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3

BUILDING MATERIALS AND STRUCTURES

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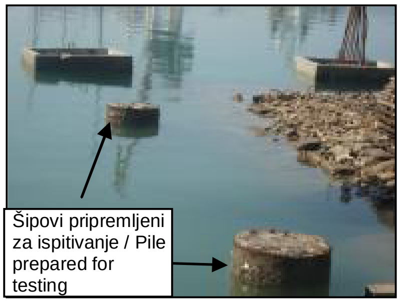
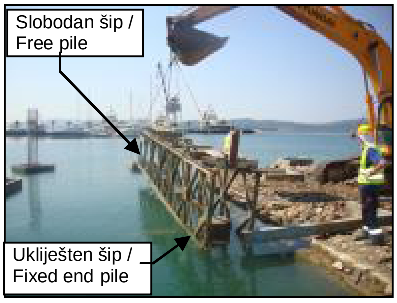
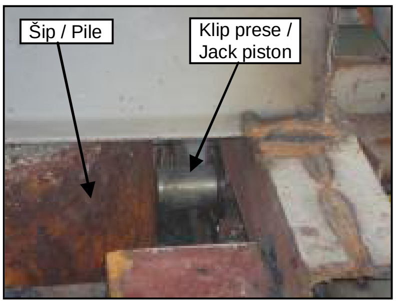
JOURNAL FOR RESEARCH OF MATERIALS AND STRUCTURES







DRUŠTVO ZA ISPITIVANJE I ISTRAŽIVANJE MATERIJALA I KONSTRUKCIJA SRBIJE
SOCIETY FOR MATERIALS AND STRUCTURES TESTING OF SERBIA

Odlukom Skupštine ***Društva za ispitivanje materijala i konstrukcija***, održane 19. aprila 2011. godine u Beogradu ime časopisa **Materijali i konstrukcije** je promenjeno i od sada će se publikovati kao **Građevinski materijali i konstrukcije**.

According to the decision of the Assembly of the ***Society for Testing Materials and Structures***, at the meeting held on 19 April 2011 in Belgrade the name of the Journal Materijali i konstrukcije (Materials and Structures) is changed into **Building Materials and Structures**.

Professor Radomir Folic
Editor-in-Chief

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AXISVM® 10 - ENHANCED CASA TOOL FOR FEM MODELING IN STRUCTURAL ANALYSIS

Dušan KOVAČEVIĆ

STRUČNI RAD
UDK: 004.42:[624.04:519.673 = 861

1 UVOD

Savremeni razvojni trendovi u oblasti građevinarstva Microsoft Windows® platformu i namenjen inženjerima konstrukterima. Zbog svojih mogućnosti (dizajniran "za inženjere od inženjera") AxisVM® se pokazao uspešnim ne samo za projekte velikih složenih sistema, već i za male i jednostavne objekte.

AxisVM® (vidi [1]) omogućava: linearnu i nelinearnu statičku i dinamičku analizu, analizu izvijanja, modalnu analizu sa spektrima odziva i "pushover" analizu. Nema ograničenja u broju elemenata (čvorova i KE) koji se slobodno kombinuju u MKE model. Koristi se za analizu bilo koje vrste konstrukcije koja sadrži ravne ili prostorne konstrukcijske elemente štapova, greda, membrana, ploča i ljuski. Postojanje biblioteke poprečnih preseka i materijala, razne vrste opterećenja i sofisticirane opcije modeliranja kontrurnih i prelaznih uslova doprinose mogućnostima rešavanja širokog spektra konstrukterskih problema.

Napredne mogućnosti za modeliranje složenih konstrukcijskih fenomena, (detalji u [2]-[4]), obezbeđuju konstrukteru moćan alat za primenu MKE tehnologije i u razvojno-istraživačkim zadacima. Osim toga, AxisVM® se koristi i u univerzitetskim sredinama, zbog mogućnosti brze i efikasne obuke u modeliranju konstrukcija.

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1 INTRODUCTION

AxisVM® is a high efficient and productive CASA FEM software tool for structural engineers developed for Microsoft Windows® platform. Due to its extensive analysis capabilities (designed "for engineers by engineers"), AxisVM® has proved to be successful, applying in design of projects ranging from large complex structures to small and simple buildings.

The AxisVM® (see [1]) performs the following type of analysis: static, buckling, modal response spectrum, dynamic, linear, pushover and nonlinear. It enables the use of an unlimited number of elements (nodes and FEs) which can be freely combined in a FEM model. In typical applications, the software is used to analyze any type of structure based on plane or spatial bar, beam, membrane, plate and shell structural elements or any combination of mentioned elements. The existence of cross-section library, material library, various type of actions and sophisticated modeling abilities of boundary and interface conditions can be used for solving a wide range of strucural engineering problems.

Advanced options in modeling of very complex structural phenomena, (details in [2]-[4]), give the designer a powerful tool for application of FEM technology in development-research tasks. Additionally, AxisVM® is widely applied in university environment, because of the possibility of quick and efficient training course.

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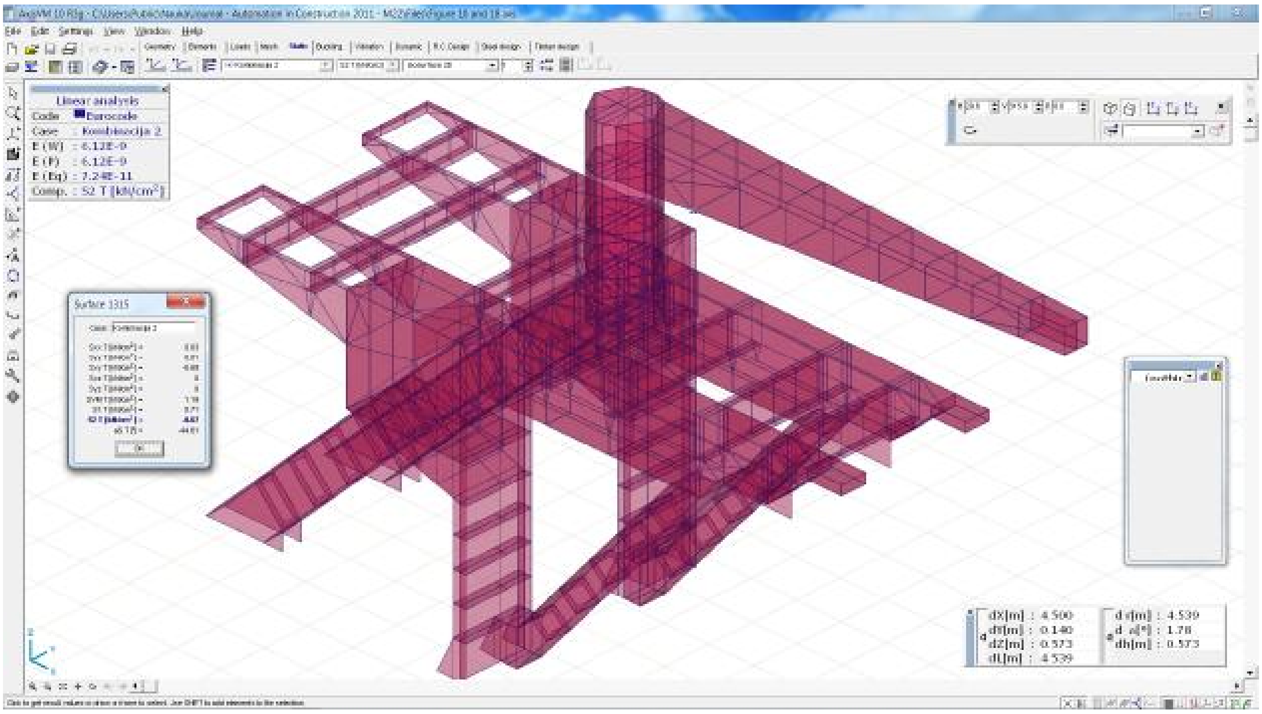
2 MODELIRANJE TOPOLOGIJE I GEOMETRIJE KONSTRUKCIJE: AXISVM® PREPROCESOR

AxisVM® (Visual Modeling) je baziran na grafički orijentisanom i intuitivnom radnom okruženju za formiranje MKE modela, sa nezavisnim postavkama svakog grafičkog prozora. U bilo kojoj fazi rada moguće je prebacivanje na bilo koji prozor za prikaz modela koji najviše odgovara potrebama korisnika. Sl. 1 pokazuje tipičnu konfiguraciju AxisVM® radnog okruženja.

2 MODELING OF STRUCTURAL TOPOLOGY: AXISVM® PREPROCESSOR

AxisVM® (Visual Modeling) provides an intuitive friendly oriented user interface with multi-window model creation and display. Each graphics window has its independent settings. During any command, it is possible to switch to the graphics window that shows the best model view or results of your action. Fig. 1 shows a typical AxisVM® working environment.



Slika 1. AxisVM® radno okruženje
Figure 1. AxisVM® working environment

Te karakteristike omogućuju da projektant radi na konstrukciji u celini i smanji vreme i moguće greške zbog odvojene analize delova konstrukcije, što je to, na žalost, uobičajeni pristup. Ne postoje ograničenja veličine i topologije modela, s obzirom na potpuno nezavisno interno preprocesiranje geometrije modela. Posebnu vrednost čini intuitivni protokol za komunikaciju korisnik-softver. Dejstva se, na primer, mogu definisati i kombinovati praktično bez ograničenja, što projektantu daje veliku slobodu u nalaženju optimuma u projektantskom rešenju, kao i realnog stepena sigurnosti.

AxisVM® editor modela, tj. preprocesor omogućava:

- modeliranje topologije i geometrije u ravni i u prostoru, primenom alata za crtanje tačke linije, poligona, pravougaonika, kružnog luka i površine,
- komande/alate za geometrijske transformacije (translacija, rotacija, simetrija i skaliranje, sa mogućnostima višestrukog kopiranja i pomeranja),
- kontekst orijentisanu i stalno dostupnu pomoć u postupcima modeliranja,
- grafičko editovanje modela za bilo koji prikaz i za perspektivu,
- primenu efikasnih alata za selektovanje sa različitim filterima,

These features allow the engineer-designer to work with an entire structure and reduce the time requirements and error potential of separate analysis processes. Independent preprocessing of the model geometry allows assigning the values to the components according to the needs and requirements of the engineer-designer, they are not restricted to pre-assigned building templates or limited to predetermined element values. Full graphic editing permits fast selection of model elements and intuitive dialog windows include the choices of all parameters for the selected element. Loads can be combined and values of the combinations assigned that enable the engineer to determine the optimum design value and the ultimate failure conditions.

AxisVM® structure editor, i.e. preprocessor enables:

- geometry modeling in 2D plane or in 3D space coordinate system by point, line, polygon, rectangle, arc and area drawing commands,
- geometry generation commands (translate, rotate, mirror, scale, …with multiple copy or move options),
- context-sensitive help though the generation processes, in conjunction with online help,
- graphic editing of the model in any view, including the perspective view,

• primenu seta alata za prikaz u razmeri sa neograničenim nivoom "poništi/ponovi" opcije,

• rad on sklopovima sa mogućnostima logičkih operacija i spratovima, što olakšava rad na veoma velikim i složenim modelima,

• definisanje radnih ravni koje se razlikuju od podrazumevanih ravni koordinatnog sistema,

• renderovani prikaz zbog uvida u detalje i bolju proveru modela (vidi Sl. 2),

• definisanje ravni i linija preseka za prikazivanje rezultata analize, što je posebno korisno kod sistema sa površinskim KE,

• slobodni razmeštaj panela sa ikonama za alate,

• pretraga po vrstama i rednom broju entiteta (čvor ili KE),

• powerful selection tools (filtered selection available),

• complete set of zoom in/out, fit to page, pan, view undo/redo commands,

• working on parts and stories (allows easy editing of most complex 3D geometries and includes advanced part management),

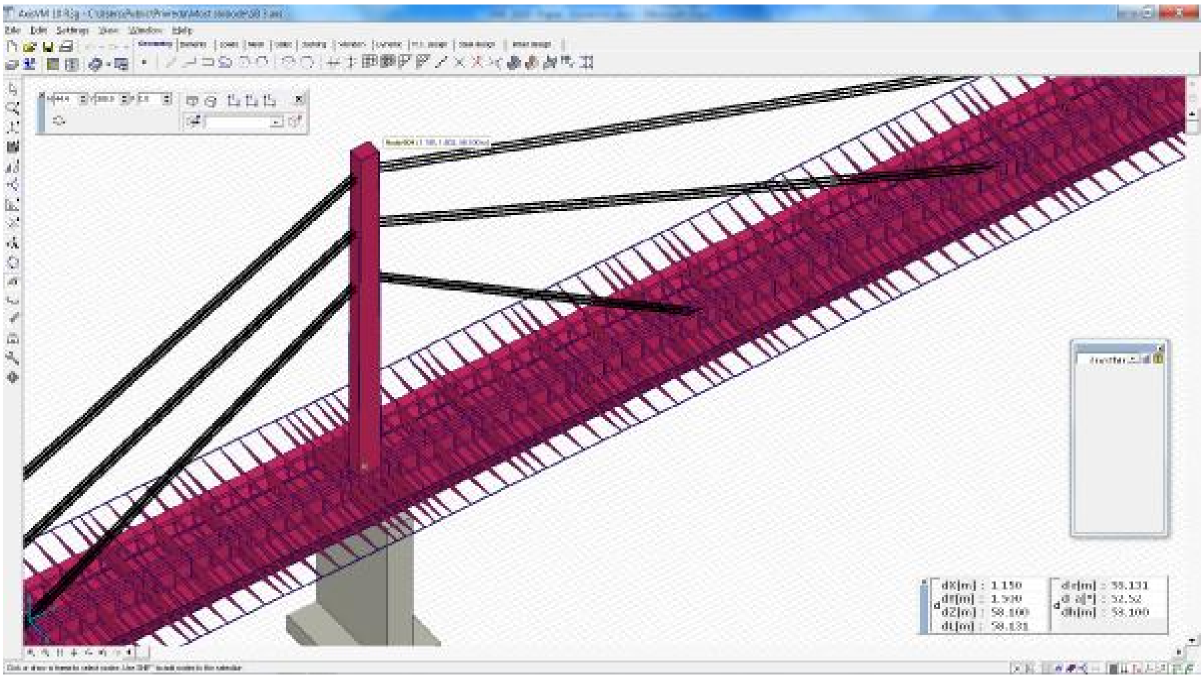
• option of making of an global section by plane,

• rendered display for better model check (see Fig. 2),

• definition of section planes and lines for surface element results display,

• free movable toolbars which can be positioned on the screen in any area, selected on a one-time basis or set to appear until no longer needed,

• search for entities by type and index,



Slika 2. AxisVM® renderovani prikaz modela (konstrukcija mosta "Sloboda"
Figure 2. AxisVM® rendered model display example ("Sloboda" bridge structure)

• automatsku proveru geometrije (označavanje suviše bliskih čvorova i izobličenih KE),

• eksternu numeraciju čvorova sistema KE,

• jednostavno definisanje karakteristika KE, oslonaca, veza i opterećenja,

• veoma fleksibilno podešavanje prikaza simbola, oznaka, kota za svaki KE ili čvor,

• definisanje rastera i koraka pointera,

• rad sa bibliotekom poprečnih preseka (prema US i EU standardima) i kreiranje sopstvenih preseka,

• rad sa bibliotekom konstrukcijskih materijala (sa parametrima svih građevinskih materijala) i kreiranje sopstvenih materijala,

• grafičko editovanje u kreiranju složenih poprečnih preseka sa automatskim izračunavanjem parametara.

Pored ostalih prednosti, ovakav pristup omogućava da se eventualne greške diskretizacije lako uoče i od strane nedovoljno iskusnih korisnika CASA softvera, čak i bez određenog nivoa znanja primene MKE.

• automatic duplication check feature and geometry check for finding of distorted geometry FEs,

• graphically created joints, members, finite elements, properties, constraints, releases and loading,

• display settings for the most appropriate model display and configure symbol and labeling display for each finite element,

• configurable 3D grid and mouse step,

• pre-loaded steel cross-section libraries with most of the available European and U.S. shapes with option of creation of custom libraries,

• pre-loaded material libraries with most of the available materials with option of creation of custom libraries,

• fully integrated graphical editor for building complex cross-section (thick- or thin-walled) shapes with automatic (based on the graphical input) calculation of cross-section properties.

In that way, unsuitable discretization issues can be easily observed even by insufficiently experienced CASA

3 MODELIRANJE PONAŠANJA KONSTRUKCIJE: AXISVM® PROCESOR

AxisVM® omogućava rad sa različitim vrstama KE sa definisanim parametrima, što obezbeđuje da model predstavlja što verniji prikaz realnog ponašanja konstrukcije. AxisVM® je zasnovan na objektno orijentisanoj arhitekturi rada sa modelima KE, što mu daje izvesne prednosti u odnosu na ostale CASA sisteme. U radu sa okvirnim i površinskim sistemima koriste se i posebni KE za modeliranje konturnih i prelaznih uslova sa parametrima koji definišu nelinearno ponašanje.

U AxisVM® su na raspolaganju:

- linijski KE: štap i greda koji se koriste za modeliranje elemenata rešetkastih i okvirnih nosača i rebro za modeliranje spojeva linijskih i površinskih KE,
- površinski KE: membrana, ploča i ljuska (isoparametarska formulacija, četvorougaoni sa devet i trougaoni KE sa sedam čvorova) koriste kvadratne interpolacione funkcije za aproksimiranje pomeranja i zadovoljavaju tzv. "patch" test. Ploča i ljuska KE zasnovani su na Reisner-Mindlinovoj teoriji o savijanju debelih ploča i na tzv. "heterozis" formulaciji, sl. 3.

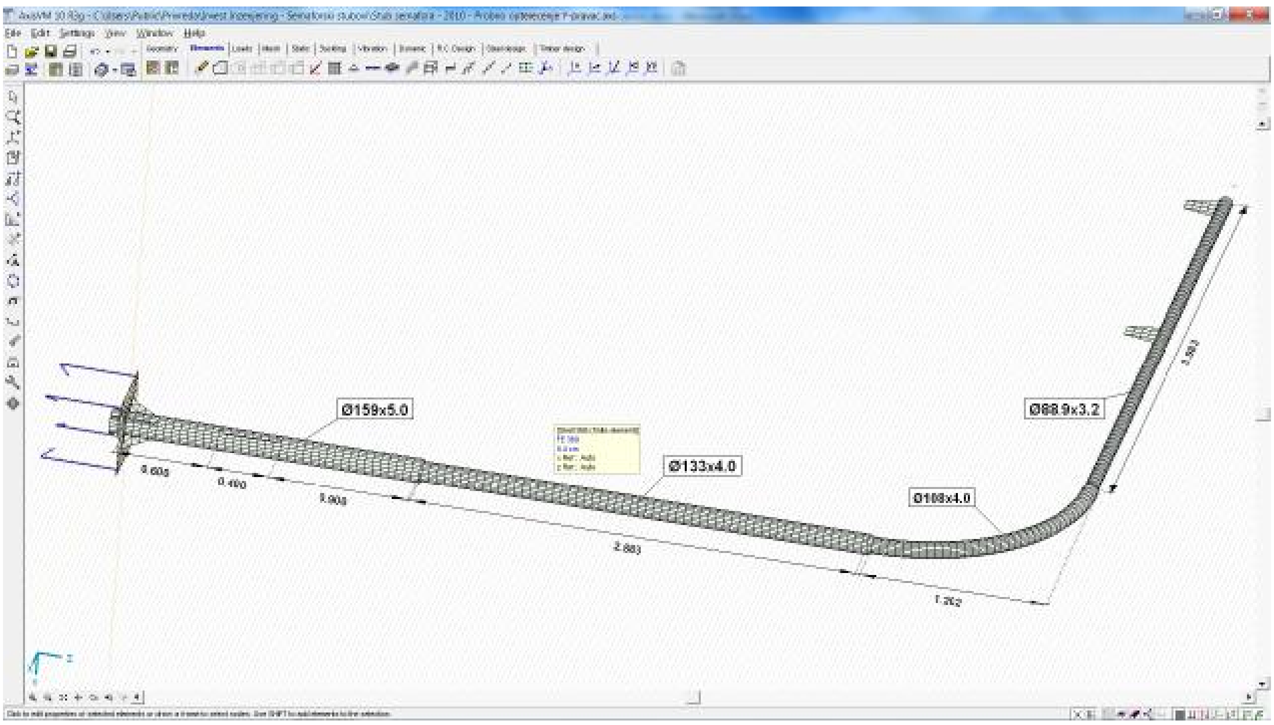
software user, without high level of knowledge about the theory of structures, i.e. FEM application.

3 MODELING OF STRUCTURAL BEHAVIOR: AXISVM® PROCESSOR

In addition to a large selection of material values and cross-sections, AxisVM® provides various types of FEs with user defined properties. A structural model can be defined by creating a mesh of user defined elements to the geometry of the model to assure that the analysis represents the most accurate representation of the structural behavior. The structural model can include different element types allowing complex structures to be accurately modeled. AxisVM® implements an object-oriented FE architecture with more consistency than many other systems. It provides a variety of FEs for modeling frames and/or surface structures, special elements for modeling boundary conditions and connections and elements with nonlinear capabilities.

FEs used in AxisVM® are following:

- line elements: truss, beam, rib (truss and the cubic beam element are the most widely used FEs for bar, beam, or column modeling. The rib element is a 3-node isoparametric FE with quadratic displacement interpolation can be used similar to the beam element (but takes into account the shear deformations) or in conjunction with surface elements for eccentric rib modeling),
- surface elements: membrane, plate, shell (isoparametric quadrilateral, 8/9-node or triangular 6/7-node FEs) use quadratic shape functions to interpolate displacements, and pass the patch test for arbitrary shape. For plate and shell FEs Reisner-Mindlin's plate assumptions is used in a so-called "heterosis" formulation, Fig. 3.



Slika 3. AxisVM® modeliranje primenom ljuska KE (analiza semaforskog stuba)
Figure 3. AxisVM® shell FEs modeling example (traffic light structure analysis)

• KE linijskih i površinskih elastičnih oslonaca Winklerovog tipa za modeliranje realnih uslova oslanjanja sa opcijom definisanja nelinearnog ponašanja (samo pritisak ili samo zatezanje) i granične nosivosti,

• čvorni oslonački KE proizvoljne orijentacije i parametara krutosti sa opcijom definisanja nelinearnog ponašanja (samo pritisak ili samo zatezanje) i granične nosivosti,

• zazor KE za modeliranje kontakta čvorova sistema KE, sa definisanjem krutosti aktivnog i pasivnog stanja i inicijalnog zazora,

• opruga KE za modeliranje linearnog/nelinearnog oslanjanja i rotaciono popustljivih veza,

• veza KE za modeliranje veza i spojeva - čvor/čvor i linija/linija za modeliranje indirektnih veza KE u čvorovima i po ivicama,

• kruto telo KE za modeliranje beskonačno krutih veza i odgovarajućeg ponašanja delova konstrukcijskog sistema.

Na raspolaganju su i različite vrste dejstava i opterećenja koje se apliciraju u čvorove, ivice i površine KE. Pri tome je neograničen broj slučajeva opterećenja i broj kombinacija. Slučajevi opterećenja mogu da se svrstaju u grupe opterećenja zbog automatskog proračuna kritične vrednosti sila u presecima za dimenzionisanje.

AxisVM® ima široki izbor opcija za numeričku analizu potrebnih u svakodnevnoj projektantskoj praksi, u razvojnim istraživanjima i u edukaciji. U pitanju su:

• linearna statička analiza,

• linearna analiza iazvijanja sa proračunom kritičnog opterećenja i oblika izvijanja (sl. 4),

• Winkler type elastic supports can model elastic foundation support conditions of line and surface elements with nonlinear characteristics - tension or compression only, limited resistance,

• joint support elements with arbitrary orientation and variable stiffness characteristics - the resulting internal forces are the support reactions with nonlinear characteristics - tension or compression only, limited resistance,

• gap elements for contact modeling can model point-to-point contact conditions and have a large stiffness when active and a small, but non-zero stiffness when in an inactive state (the active state can be for compression or for tension and initial opening can be specified for the elements),

• spring elements for linear/nonlinear support or semi-rigid connection modeling can be taken into account for linear or nonlinear elastic support or connection behavior,

• link elements for connection modeling can be node-to-node (connect nodes to nodes), or line-to-line (connect ribs, ribs to surfaces, or surface sides) and

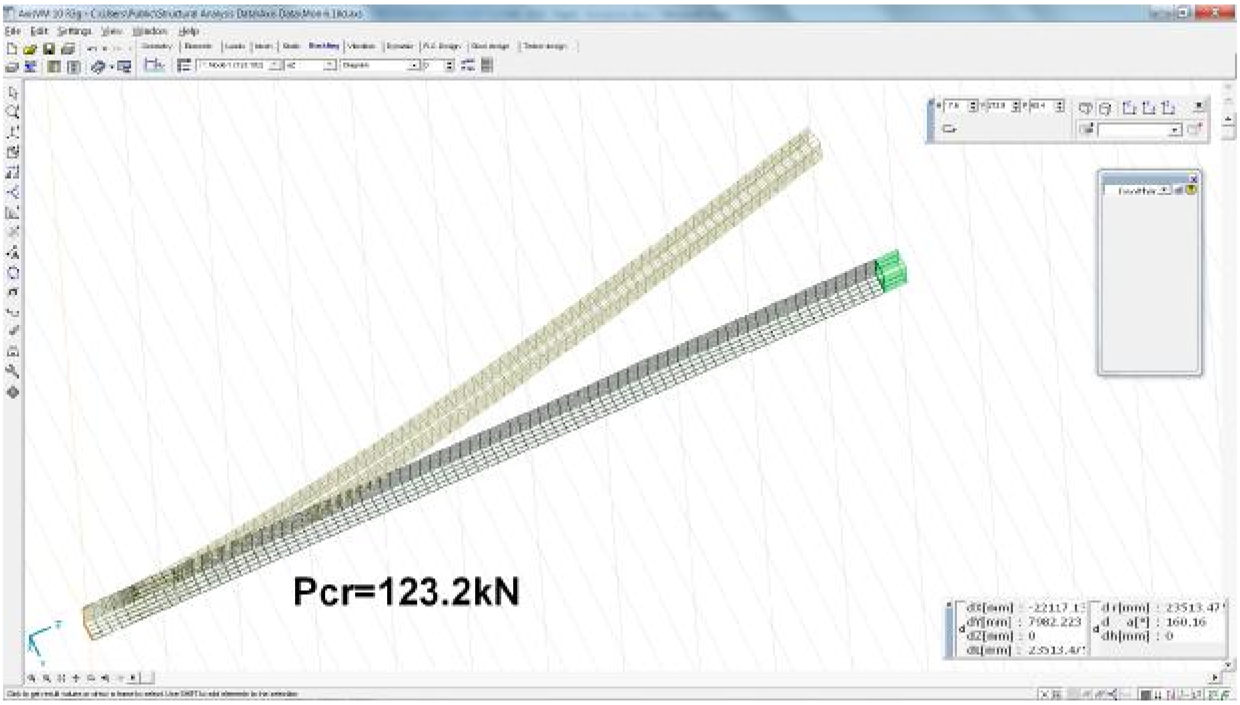
• rigid elements can model rigid parts of your structures without assigning large stiffness values to an element, that may have any number of nodes.

Various loads can be applied on the nodes and on the FEs. Unlimited number of load cases can be applied on a model and unlimited number of load combinations can be generated from these load cases. Load cases can be classified in load groups for automatic critical internal force calculations.

AxisVM® performs most of the analyses, typical in the practical design of civil engineering structures as well as in the development-research and education:

• linear static analysis,

linear buckling analysis: critical force and shape computation (Fig. 4),



Slika 4. Primer analize izvijanja u AxisVM® (teorija III reda za ljuske)
Figure 4. Example of AxisVM® buckling analysis (based on 3rd order theory of shells)

• nelinearna statička analiza sa inkrementalno-iterativnim pristupom i kontrolom konvergencije postupka preko sila ili pomeranja,

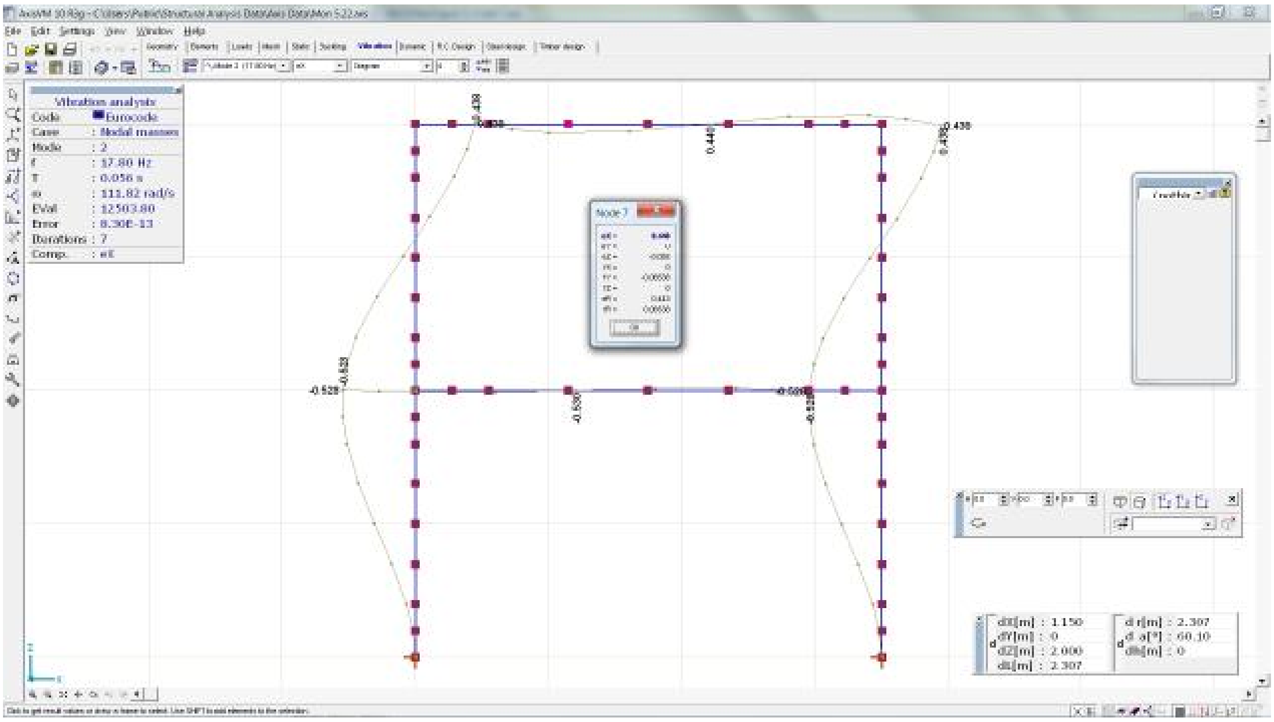
• analiza slobodnih vibracija sa proračunom svojstvenih frekvencija i oblika vibracija (sl. 5)

• seizmička analiza - modalna superpozicija sa spektrima odziva, direktna dinamička analiza i "pushover" analiza, prema EC8, ISA (Italija), STAS (Rumunija) i MSz (Mađarska) standardima.

• nonlinear static analysis: displacement/force controlled incremental-iterative solution,

• free vibration analysis: natural frequency and shape computation (Fig. 5)

• dynamic and seismic analysis - modal response spectrum, time history and pushover analysis - Eurocode 8, ISA (Italian), STAS (Romanian) and MSz (Hungarian).



Slika 5. AxisVM® analiza slobodnih vibracija
Figure 5. AxisVM® free vibration analysis example

Jasno je da primena naprednog CASA softvera zahteva dovoljna znanja o primarnom problemu (ponašanje konstrukcijskog sistema) i suštini MKE. Pored toga za kompetentno MKE modeliranje potrebno je poznavanje performansi softvera (u smislu mogućnosti i ograničenja), numeričkih metoda i kritički pristup u tumačenju i primeni dobijenih rezultata. AxisVM® nudi pomoć u ovoj oblasti i inspiriše korisnika u edukativnom smislu.

U tom smislu je veoma značajno pitanje promena u sadašnjem obrazovnom konceptu. Osim kvalitetnih znanja iz primarne struke (analiza i projektovanje konstrukcija), potrebno su znanja iz drugih tzv. "graničnih" tehničkih disciplina (numerička analiza, dizajn softvera). Autor smatra da bi svaki građevinski fakultet trebalo da svoj koncept obrazovanja prilagodi ovim potrebama.

Obrazovanje a, posebno, provera znanja u primarnoj struci trebalo bi da je prilagođena potrebi suštinskog razumevanja ponašanja konstrukcija za neko dejstvo. Sticanjem "enciklopedijskih znanja", a izučavanjem brojnih metoda za analizu, možda se postiže široko obrazovanje i tehnička kultura, ali se i smanjuje

It is clear that application of advanced CASA software requires sufficient knowledge of the basic problem (structural behavior) and main principles of the applied method (FEM). The knowledge about the software performances (its possibilities and limits), numerical methods and critical approach in interpretation and application of the obtained results are appreciated. AxisVM® offers help in this field and inspires the user for further education.

In this sense the question of changes is very important in the present educational concept. In addition to vast knowledge in the primary profession (structural analysis and design) knowledge in other technical sciences (numerical analysis, software design) is needed as well. In author's opinion every faculty of civil engineering should adjust this concept of education to the mentioned needs.

Education and, especially, testing knowledge in the primary profession should be adapted, first of all, to the need of complete understanding of the essence of structural behavior. Gaining "encyclopedia like" knowledge through studying numerous methods of analysis, possibly results in vast education and entuzijazam studenata i inženjera. Takvo znanje nije potrebno ako se MKE analiza primenom CASA softvera sprovodi na kompetentni način. Svi ovi razlozi bili su motivacija za uvođenje AxisVM® softvera u program predmeta "Modeliranje konstrukcija primenom računara" na Departmanu za građevinarstvo, Fakulteta tehničkih nauka u Novom Sadu.

4 PRIKAZ REZULTATA I DIMENZIONISANJE: AXISVM® POSTPROCESOR

Konstrukteri mogu da koriste AxisVM® za analizu konstrukcija u skladu sa specifičnim zahtevima pojedinih nacionalnih standarda. Jednostavnost izvoza rezultata analize omogućava korisniku da spaja AxisVM® dokumente u izveštaje koji su propisani nacionalnim standardima. U tom smislu se AxisVM® svakodnevno nadograđuje u nastojanju da zadovolji nove potrebe korisnika drugih programa opšte namene koji se koriste svakodnevno.

AxisVM® prikazuje rezultate analize u više prozora i sa različitim opcijama kada je u pitanju dimenzionisanje. Postoje sledeće mogućnosti:

- prikaz rezultata analize pomoću dijagrama,
- prikaz pomoću dijagrama u linijama i ravnima preseka,
- prikaz rezultata za konstrukcijske sklopove,
- prikaz rezultata pomoću 2D (Fig. 6) ili 3D izopovršina,
- dimenzionisanje elemenata čeličnih konstrukcija (sl. 7) prema EC3 i NEN 6770/74 (Holandija), dimenzionisanje spojnih sredstava u zoni veze "stub-greda" i "greda-greda",

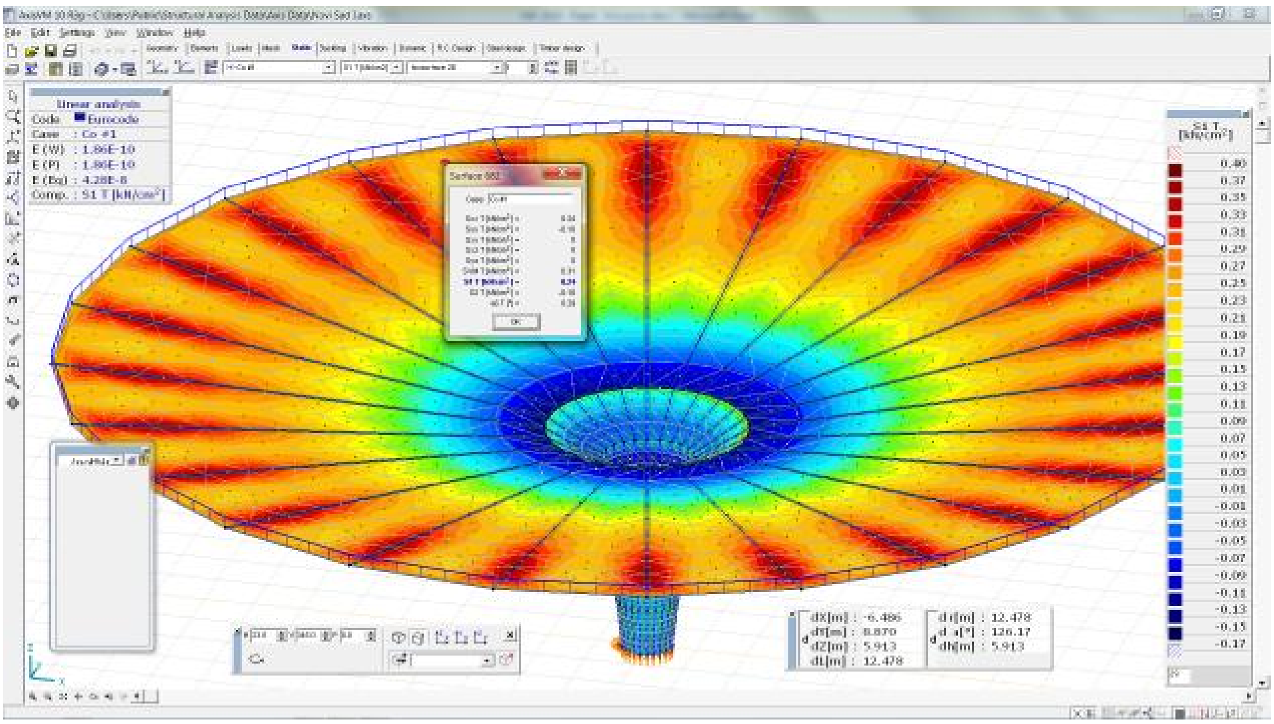
contributes to the technical culture, but it also distracts attention, wastes energy and dampens enthusiasm of students and structural engineers. This kind of knowledge is unnecessary if the FEM analysis with the use of CASA software is applied in competent manner. Therefore, the introduction of AxisVM® software in the curriculum of the course "Computer Aided Structural Modeling" in the Civil Engineering Department of the Faculty of Technical Sciences in Novi Sad was initiated by these reasons.

4 RESULTS DISPLAY AND DESIGN: AXISVM® POST-PROCESSOR

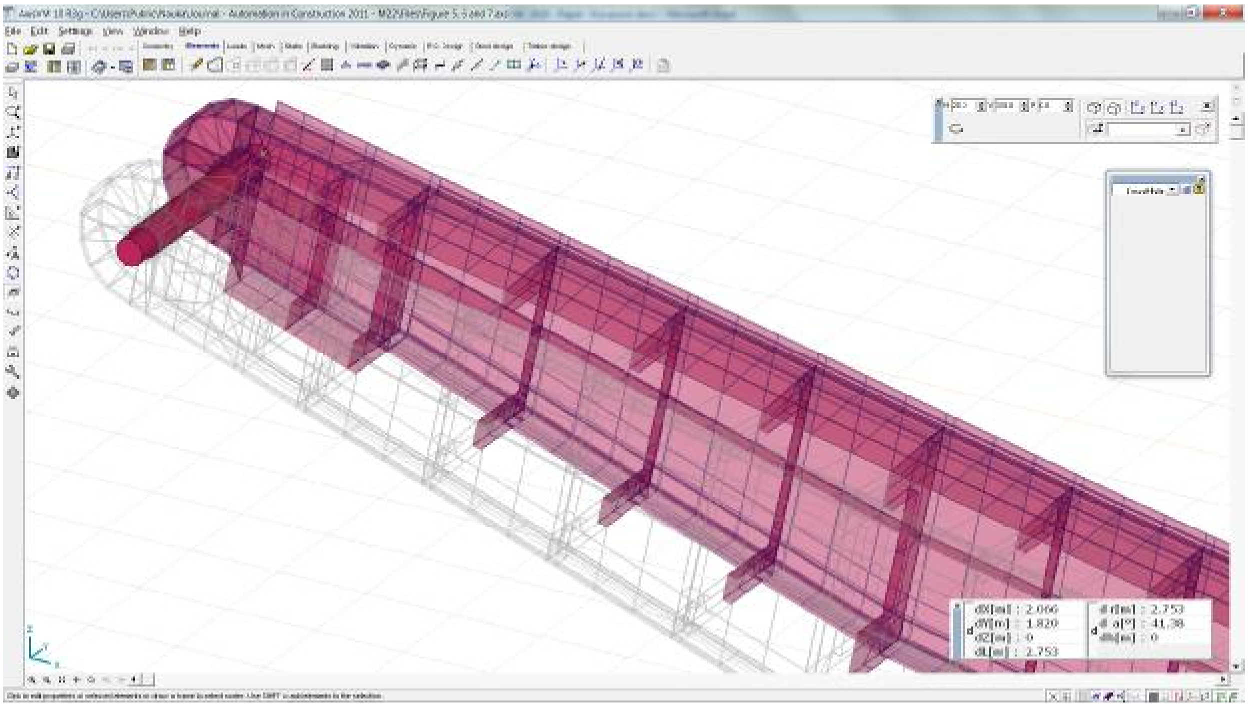
Civil engineers can use AxisVM® for the analysis of structures with confidence that their final engineering product will meet their national specific design codes. The ease of results exporting allows each user to connect AxisVM® to almost every locally produced and national code compliant design and detailing software. AxisVM® is committed to assisting each user in connecting the results of the finite element calculations to the programs they use every day.

AxisVM® provides multi-window model analysis results display and design options. Possibilities are various:

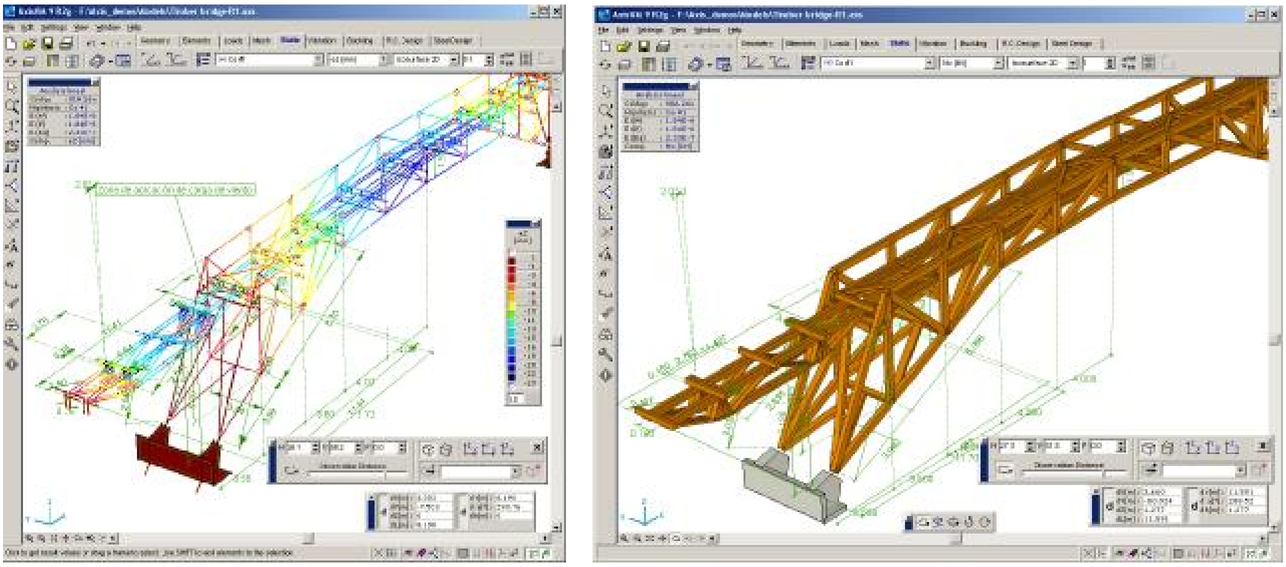
- diagram analysis results display,
- analysis results display for section lines
- analysis results display for structure parts,
- isosurface analysis results display 2D (Fig. 6) or 3D,
- steel design (Fig. 7) according to EC3, NEN 6770/74, design of bolted joints with an end plate for column-to-beam or beam-to-beam connections,



Slika 6. Prikaz rezultata analize izopovršinama (konstrukcija nadstrešnice pumpe za gorivo)
Figure 6. Isosurface display of analysis results example (gas station roof structure)



Slika 7. Dimenzionisanje elemenata čelične konstrukcije (lotra bagera vedričara)
Figure 7. Steel design example (dredger's jib crane structure)



Slika 8. Dimenzionisanje elemenata drvene konstrukcije (pešački most)
Figure 8. Some timber design example (wooden bridge structure)

- dimenzionisanje elemenata drvenih konstrukcija (sl. 8) prema EC5 EN1995-1-1:2004, za puno drvo, lamelirano lepljeno drvo i furnir,
- dimenzionisanje elemenata armiranobetonskih konstrukcija (sl. 9) - greda, stubova, ploča, membrana i ljuski shells, prema EC2, NEN, DIN i SIA (Švajcarska),
- dimenzionisanje temelja samaca prema EC7, sa proverom nosivosti na probijanje,
- proračun ugiba ploča prema EC2, NEN, MSz i

- timber design (Fig. 8) according to EC5 and EN1995-1-1:2004, solid timber (soft- and hardwood), glued-laminated timber and laminated veneer lumber,
- reinforced concrete design (Fig. 9) of beams, columns, plates, membranes, shells, according to EC2, NEN (Dutch), DIN (German), SIA (Swiss),
- pad foundations design according to EC7, with punching shear check,
- plate deflection calculation according to EC2, NEN

STAS,

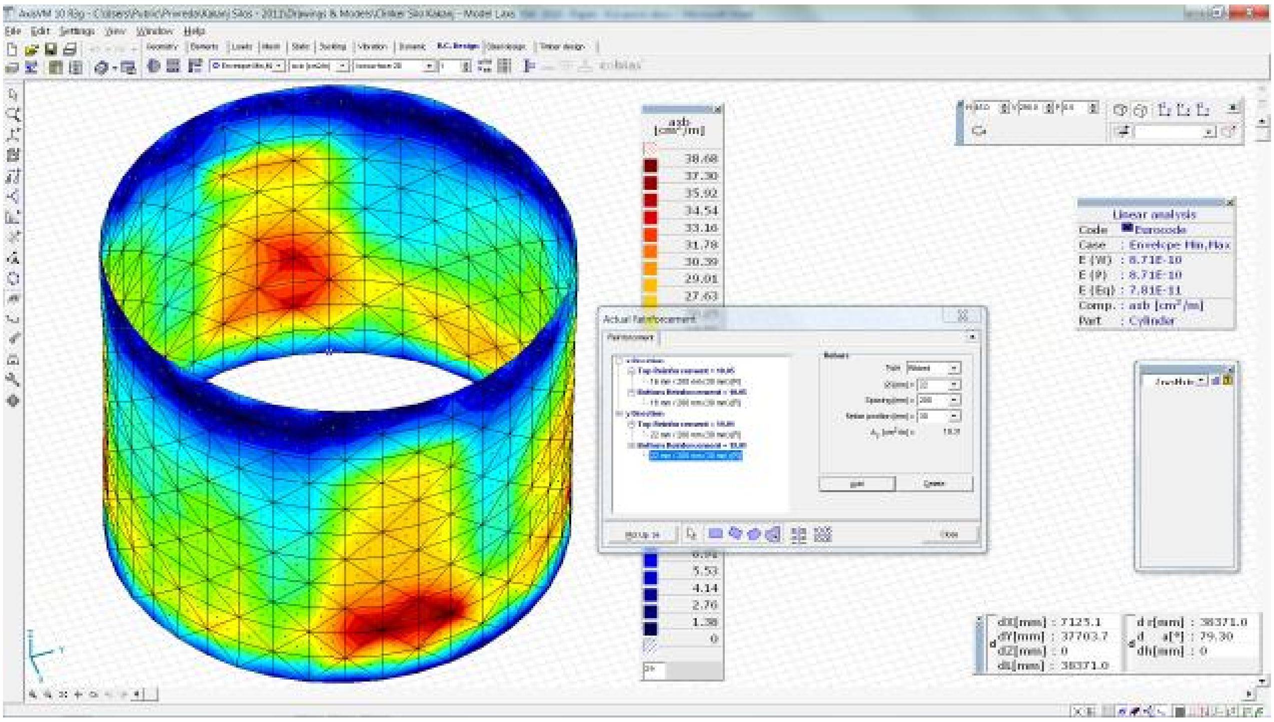
- upotreba "pretraživača tabela" za uvid u sve detalje modela, pozicija i vrednosti parametara za sve primenjene materijale, poprečne preseke, reference, čvorove, KE, oblasti i sve rezultate analize (pomeranja, naponi i sile u presecima) i

- upotreba integrisanog "formulara izveštaja" za formiranje projektne dokumentacije za svakog učesnika u procesu građenja: revidenta, razrađivača detalja, investitora, podizvođača, sa mogućnostima uvrštavanja u izveštaj bilo kog segmenta (tabele i dijagrama) baze rezultata.

(Dutch), MSz (Hungarian, STAS (Romanian),

- "Table Browser" shows complete model details, locations and values of the materials, cross-sections, references, nodes, FEs, domains and the complete result details, locations and values for the displacements, internal forces and stresses are included and

- integrated "Report Maker" for the creation of reports for every needed construction partner: design approval, steel detailer, bid estimates, component producers, and departmental specialties, with the ability to create custom reports by selecting only those model data tables and graphic results which are needed.



Slika 9. Dimenzionisanje AB konstrukcije (prikaz potrebne količine armature cilindra silosa)
Figure 9. Concrete design example (required reinforcement amount for a silo's structure)

5 AXISVM® U EVALUACIJI KONSTRUKCIJSKIH PERFORMANSI

Realno ponašanje konstrukcija (tj. stvarni odgovor za neko dejstvo) ima drugorazredni značaj u većini slučajeva standardnog projektovanja i numeričke analize. Takav pragmatički pristup je legitiman zbog okolnosti u svakodnevnoj projektantskoj praksi.

Tehnička regulativa kojom se uređuju pitanja u oblasti projektovanja konstrukcija (u građevinarstvu posebno) temelji se na pravilima koja su usmerena na ostvarivanje nosivosti, stabilnosti, upotrebljivosti i trajnosti konstrukcije. Sa navedenim uslovima su često povezani i ekonomski, odnosno financijski, kao i estetski zahtevi.

Provera konstrukcijskih performansi (testom probnog opterećenja ili drugim postupcima evaluacije) je neophodni korak u konačnoj oceni sigurnosti konstrukcijskih sistema za neke vrste objekata. Kriterijumi i zahtevi koje konstrukcije moraju da ispune, pre nego

5 AXISVM® IN EVALUATION OF A STRUCTURAL PERFORMANCES

Real behavior of structures (i.e. real response under action) is the second order fact in many cases of standard design procedures and numerical analyses. Such pragmatic approach is legitimate because of actual circumstances in everyday design office practice.

Technical codes which regulate subjects in the structural design field (in civil engineering, especially) are based on the rules which are related to achievement of structures which have bearing capacity, stability, serviceability and durability. Mentioned conditions are often associated with economic i.e. financial as well as aesthetic issues.

Structural evaluation (test by load or other evaluation procedures) are necessary steps in final assessment of capability structural systems for some type of objects. Before their full service, structures have to fulfill certain criteria and needs which are described by the technical što počne njihova puna eksploatacija, definisani su tehničkim propisima gotovo svih zemalja. Međutim, skoro da ne postoje uputstva o modeliranju realnog "odziva na dejstvo" u navedenim dokumentima. Ovo pitanje, verovatno, nema dominantan značaj u postupku standardnog projektovanja, ali za predviđanje realnog odziva potrebno je poštovati neke principe i pravila modeliranja.

Ovo poglavlje usmereno je na potvrdu značaja pravilne primene MKE tehnologije u skladu sa pomenutim pravilima i principima, a sa posebnim osvrtom na prostorne konstrukcijske sisteme koji mogu da budu najilustrativniji primer neophodnosti naprednog pristupa u modeliranju i ulogu AxisVM® u realizaciji tog koncepta.

Cilj evaluacije konstrukcijskog sistema je utvrđivanje stvarne veličine nosivosti, stabilnosti i upotrebljivosti, tj. sigurnosti sistema. Tehnički propisi se temelje na brojnim pojednostavljenjima, tj. pretpostavkama koje se uvode zbog povećanja efikasnosti projektovanja, obezbeđenja sigurnosti konstrukcije, kao i zbog realnog nivoa kompetencije projektanta. To su glavni razlozi za pojednostavljenje MKE modela, neadekvatnih za procenu stvarne sigurnosti kontrukcije. Naredni primeri bi mogli da budu ilustrativni u smislu uvažavanja značaja sofisticiranog pristupa u MKE modeliranja konstrukcija koje su predmet evaluacije realnih performansi.

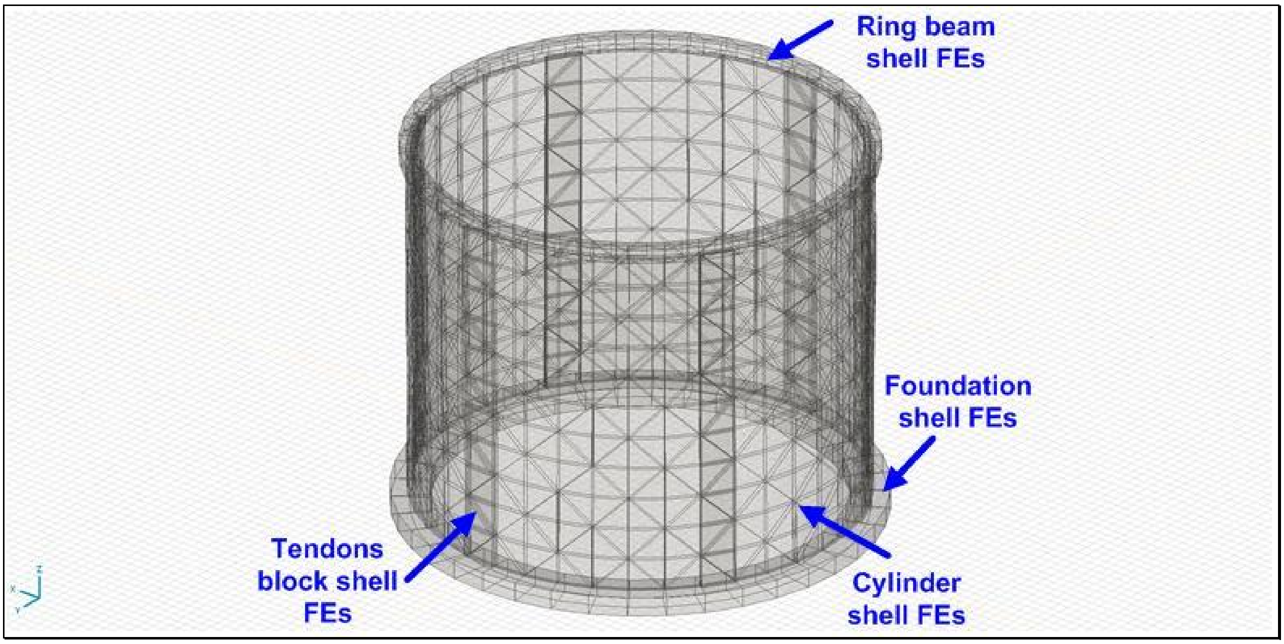
Prva grupa primera su slučajevi u kojima modeliranje geometrije (iako je izvedeno na sasvim korektan način) bitno utiče na unutrašnje sile što je objašnjeno u [5]. Tipični predstavnik ove grupe je primer cilindra konstrukcije silosa, modelirane primenom ljuska KE, sl. 10.

regulations of almost all countries. However, there lacks a detailed information about modeling of real response-under-action in almost all regulation documents. This issue is probably unimportant in the case of standard design, but for the prediction of a response caused by test load or in cases of some specific structural evaluation procedures it is necessary to follow some modeling principles and comply with the rules.

The paper emphasizes the importance of correct application of FEM technology according to these principles and rules with special attention to spatial structural systems which are the most illustrative example of the necessity of advanced approach in modeling with special attention to AxisVM® role in the advanced modeling issues.

The goal of the structural performance evaluation is to determine the real amount of structural bearing capacity, stability, safety and serviceability. Technical regulations are based on numerous assumptions which are required due to the increase of efficiency of design process, safety of designed structures and level of designer's knowledge and proficiency. This is the main reason to simplify FEM models (that comply with the regulations) which are inadequate for the evaluation of real structural performances. The following examples are illustrative in the sense of importance of very sophisticated approach in FEM modeling of structures which are the subject of mentioned evaluation.

First group of examples are the cases in which geometry modeling (although it is performed in reasonable way) strongly impacts the distribution of internal forces which is explained in [5]. Typical representative of this group is the example of silo cylinder structure modeled by shell FEs, Fig. 10.



Slika 10. Tipična konstrukcija silosa sa prstenastim temeljom, cilindrom i gornjom gredom
Figure 10. Typical silo structure with ring beam foundation, cylinder shell and ring top beam

Momenti savijanja (u tangencijalnom pravcu) javljaju se za ravnomerno raspoređeno opterećenje čak i za "dovoljan" broj KE duž obima cilindra. Prema poznatom analitičkom rešenju za ovo opterećenje ("kotlovska formula" za tanke cilindre) postoje samo membranske (normalne) sile. Ovi (zapravo nepostojeći) momenti savijanja (i odgovarajući naponi) mogu biti ili ne biti na "strani sigurnosti", što je važno, posebno za armirano-betonske konstrukcije i proračun potrebne količine zategnute ili pritisnute armature. Dva su moguća rešenja za ovaj problem: povećanje broja KE po obimu (što je pristup primenom "grube sile") ili korekcija normalnih napona u tangentnom pravcu s obzirom na činjenicu da nema momenata savijanja. Najbolje rešenje je kombinacija navedenih pristupa u skladu sa stvarnom konfiguracijom opterećenja cilindra (potpuno ravnomerna raspodela opterećenja je samo teoretski slučaj).

Isti primer bi mogao da bude ilustracija ispravnog načina modeliranja oslonaca i spojeva. sl. 11 prikazuje primenu specijalnih "veza" KE modeliranje spojeva.

Specijalni "veza" KE (vidi [6]) su jednodimenzionalni KE sa svih šest stepeni slobode i odgovarajućim parametrima krutosti koji omogućuju modeliranje gotovo svih vrsta veza. Ova činjenica ističe mogućnosti napretka u modeliranju realnog ponašanja veza u odnosu na pojednostavljene modele koji se koriste u standardnim projektima.

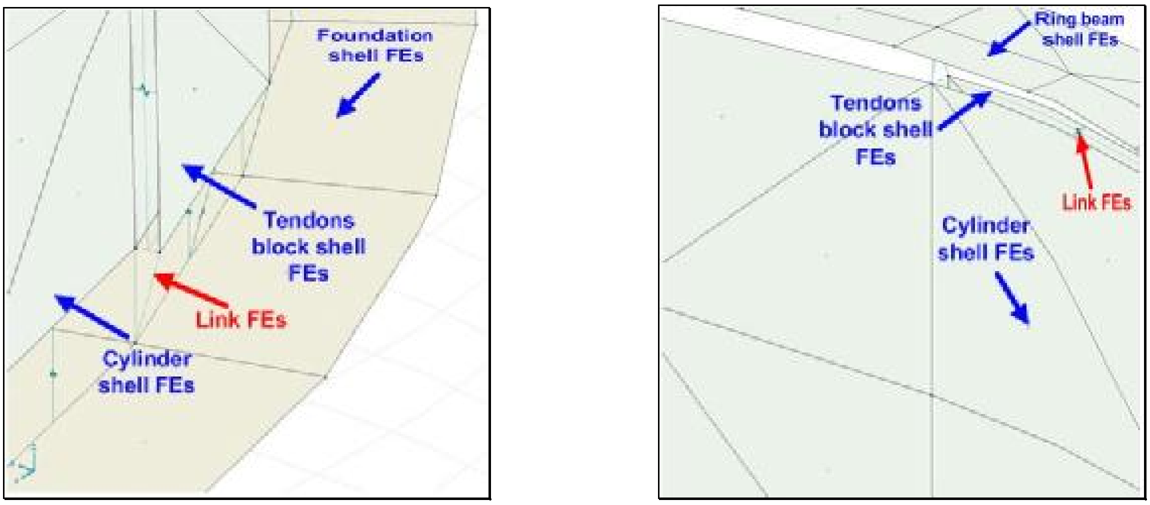
Problemi sa modeliranjem nekih dejstava (opterećenja) mogu da se ilustruju, takođe, na ovom primeru. Uobičajeni pristup za modeliranje prednaprezanja je zamena uticaja kablova ekvivalentnim opterećenjem, sl. 12, levo. Mnogo bolje rešenje je modeliranje kabela posebnim KE koji su povezani sa ljuska KE zida silosa pomoću veza KE, sl. 12, desno. Samo taj način modeliranja omogućava proveru dodatnog opterećenja kablova za dejstvo nekog drugog (obično korisnog) opterećenja.

Flexural moments (in "hoop" direction) occur in the case of uniformly distributed external load even for properly huge number of FEs through circumferences of the silo cylinder. According to the well-known analytical solution ("hoop" stress formula for the thin walled cylinders) there are only membrane stresses for this type of external load. These nonexistent flexural moments (and corresponding stresses) could be on the "safe side" or on the "non-safe side", which is important, especially for the reinforced concrete structures (in the calculation of required amount of tensioned or compressed reinforcement). There are two possible solutions for this problem: increasing the number of FEs in hoop direction ("brutal force" approach) or the correction of normal stresses in hoop direction regarding the fact that there are no moments. The best solution is the combination of mentioned approaches according to the real configuration of external forces on the silo's cylinder (pure uniform distributed circumferential load is rare or only theoretical case).

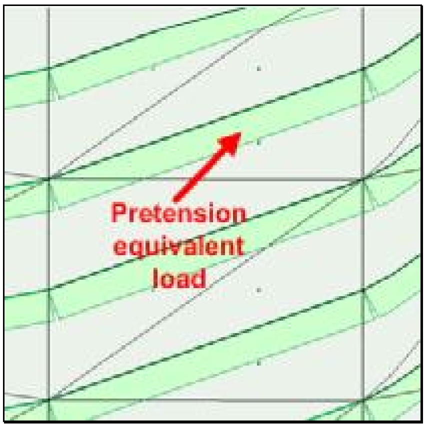
The same example could be helpful as an illustration of the correct way of modeling support and connections. Fig. 11 presents the use of special "link" FEs for connections modeling.

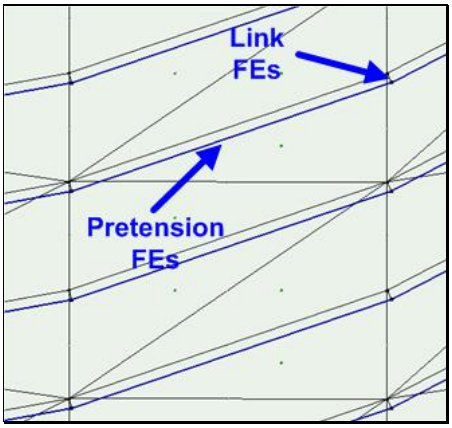
Special link elements (see [6]) are one-dimensional FEs with all six degree of freedom and corresponding stiffness parameters which make possible modeling of almost every type of connection. This fact emphasizes the advances of such type of model as more real than simplified models which are used in initial design procedures.

Problems with modeling of some actions (loads) could be illustrated on this example as well. Usual approach for modeling pretension by cables is replacement of cables influence by the equivalent uniform load, Fig 12 (left). Much better solution is consequent modeling of cables by cable or beam FEs which are connected with silo wall shell FEs by link FEs, Fig 12 (right). Only this way of modeling enables checking pretension force after the action of the other loads.



Slika 11. Detalji veza MKE modela silosa
Figure 11. Details of the connections in silo's FEM model

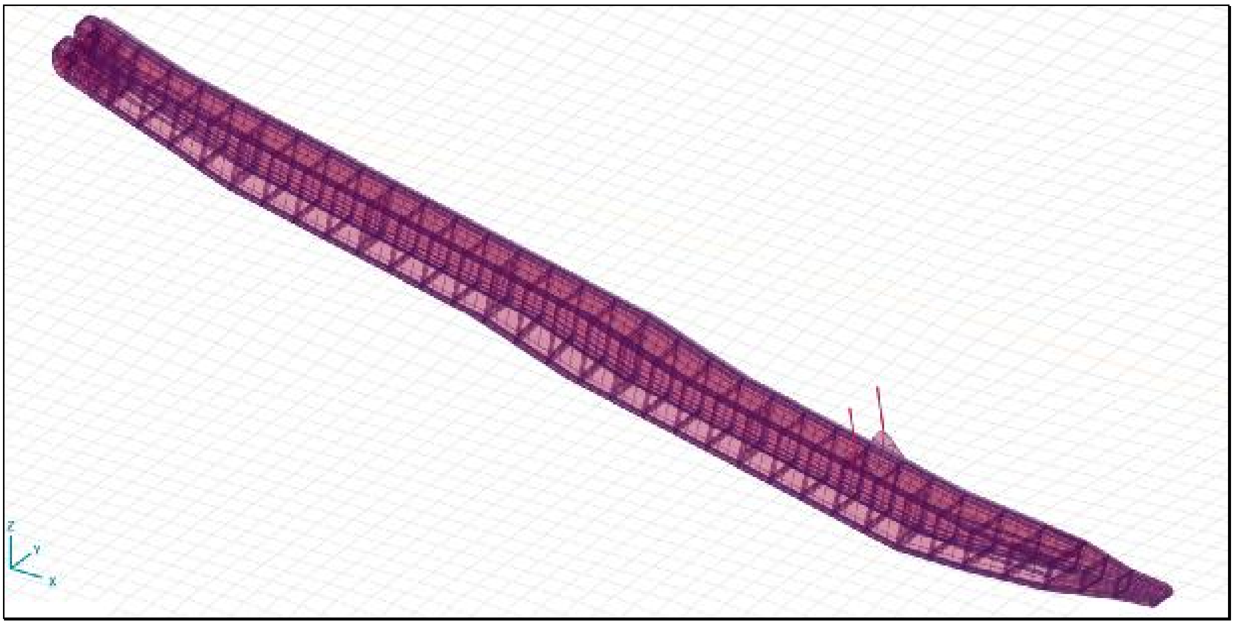




Slika 12. Prednaprezanje kao opterećenje (levo) i kao posebni KE sa veza KE (desno)
Figure 12. Pretension modeled as equivalent loads (left) or by cable/beam FEs + link FEs (right)

Drugi tip problema je uzrokovan nepravilnim izborom tipa KE. Tankozidne prostorne konstrukcije zahtevaju tretman primenom ljuska KE, [7], bez obzira na dominantnu dimenziju u topologiji konstrukcije. sl. 13 prikazuje adekvatni MKE model konstrukcije lotre, tipičnog sklopa plovnog bagera vedričara.

Another type of modeling problems is caused by improper choice of FE type. Thin walled spatial structures should be treated through the application of shell FEs, [7], regardless of the dominant dimension in the structural topology. Fig. 13 shows FEM model of a jib structure which is a typical part of the waterway dredgers facilities.



Slika 13. MKE model prostorne konstrukcije lotre
Figure 13. FEM model of spatial jib structure

Složena konstrukcija lotre ima bočna ukrućenja različitih vrsta i dimenzija, tanke zidove i elemente za oslanjanje na palubu bagera.

Jednostavan numerički test može da pokaže prednosti modela s 2D KE u odnosu na 1D KE model. Ovaj i slični "benchmark testovi" trebalo bi da postanu bitan korak u metodologiji izbora konačnog MKE modela svake složene konstrukcije.

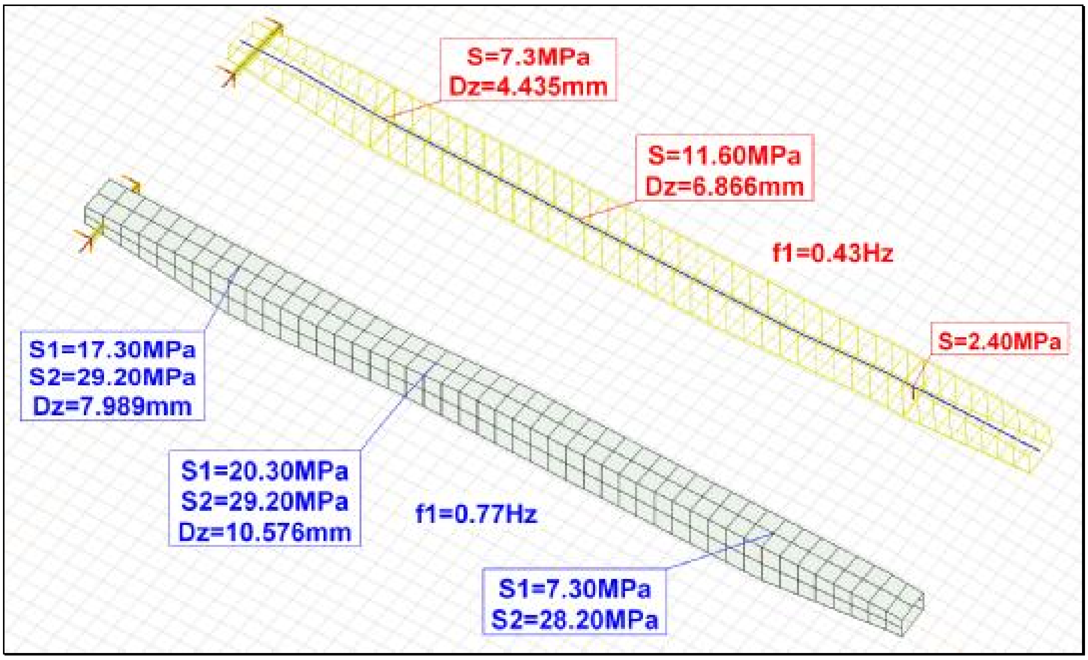
Analiza je provedena za ravnomerno podeljeno

Complex structure of jib consists of lateral stiffeners of diverse type and dimensions and thin walled cover plates, as well as parts for supporting the jib on the deck of dredger.

A simple numerical test will illustrate the advantages of a model with 2D FE in relation to the 1D FE model. This and similar "benchmark tests" should become an essential part of the final FE model choice methodology.

The analysis is performed for the uniformly opterećenje. sl. 14 prikazuje glavne napone i vertikalne ugibe u karakterističnim tačkama, kao i najniže sopstvene frekvencije 1D (gore) i 2D (dole) modela.

distributed load. Fig. 14 shows principal stresses and vertical displacements in characteristic points as well as the lowest natural frequencies for 1D (top) and 2D (bottom) models.



Slika 14. 1D i 2D model lotre: pomeranja, glavni naponi i najniže sopstvene frekvencije
Figure 14. 1D and 2D models: displacements, principal stresses and the lowest natural frequencies

1D model je sa grednim KE (kutijasti profil: 2400mmx1000mm, t=20mm) i u topološkom smislu je potpuno identičan 2D modelu sa četvorougaonim ljuska KE (izoparametarski sa devet čvorova, heterozis tipa, debljine t=20mm). Konturni uslovi su identični za oba modela i prilagođeni stvarnom stanju.

Očito je da su glavni naponi (S1 i S2) u tačnijem 2D modelu od 1.75 do 11.75 puta veći nego u jednostavnijem 1D model. Situacija sa vertikalnim ugibima (DZ) je slična. Ovde su faktori od 1.54 do 1.80 u korist složenog 2D modela. Nadalje, najniža sopstvena frekvencija (f1) u 1D modelu je gotovo 1.8 puta manja od iste frekvencije u 2D modelu.

Ovaj test vrlo jasno pokazuje da se sa naizgled sličnim modelima mogu dobiti vrlo različiti podaci o odzivu konstrukcijskog sistema, a ponekad i vrlo pogrešan utisak o nosivosti, stabilnosti i upotrebljivosti, što potvrđuje potrebu primene složenijih modela.

U tom smislu, sledeći primeri su isto tako ilustrativni. sl. 15 pokazuje MKE model mosta ispitivanog probnim opterećenjem, a sl. 16 detalje istog modela.

Spregnuta konstrukcija mosta (čelični glavni nosač+AB kolovozna ploča) pokazala je nešto veću torzionu fleksibilnost u testu sa probnim opterećenjem, što je u potpunosti potvrđeno ponašanjem prikazanog MKE modela (prvim torzionim sopstvenim oblikom). Nažalost, glavni projekat, zasnovan na jednom pojednostavljenom modelu (sa 1D KE), imao je rezultate koji nedovoljno ukazuju na ovu okolnost.

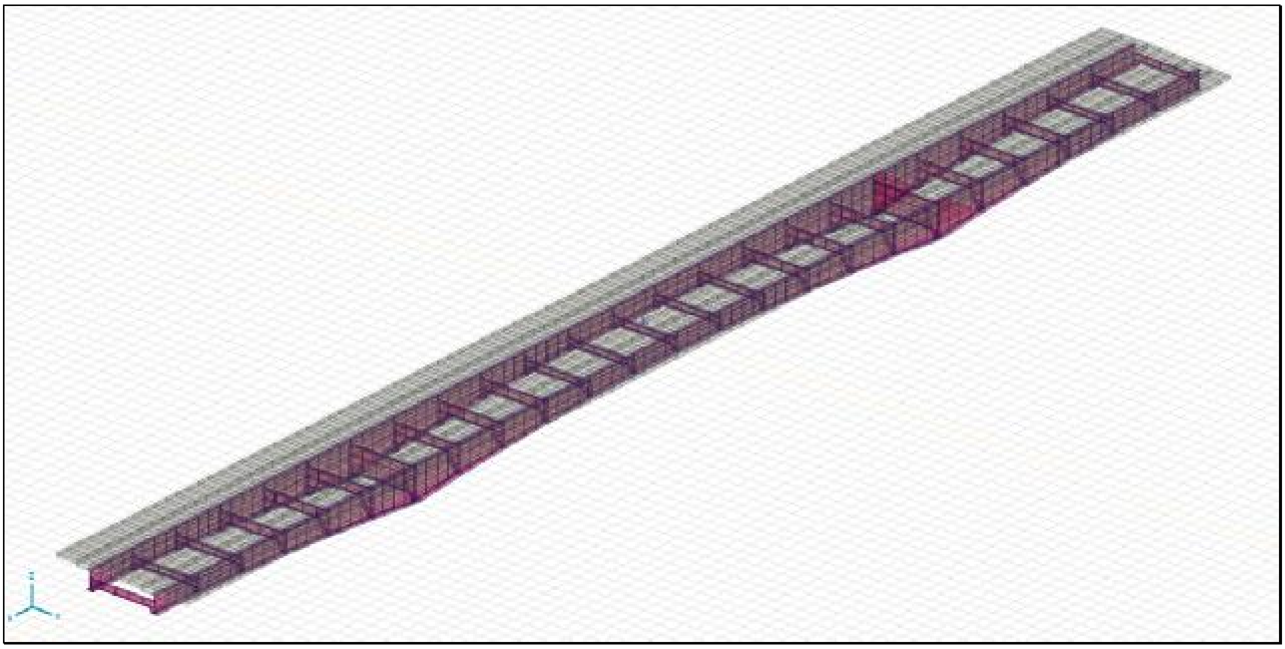
1D model is formed of the beam FE (box shape 2400mm x1000mm cross-section, t=20mm) and in the topological sense it is completely identical to the 2D model with the rectangular shell (isoparametric, nine-node, heterosis) FE (thickness t=20mm). Boundary conditions are identical for both models and adjusted to the real jib's supports conditions.

It is evident that the principal stresses (S1 and S2) in the more accurate 2D model are from 1.75 to 11.75 times greater than in a more simple 1D model. The case with the vertical displacements (Dz) is similar. Here the factors are from 1.54 to 1.80 more beneficial to the complex 2D model. Furthermore, the lowest natural frequency (f1) in a 1D model is almost 1.8 times lower than the same frequency in the 2D model.

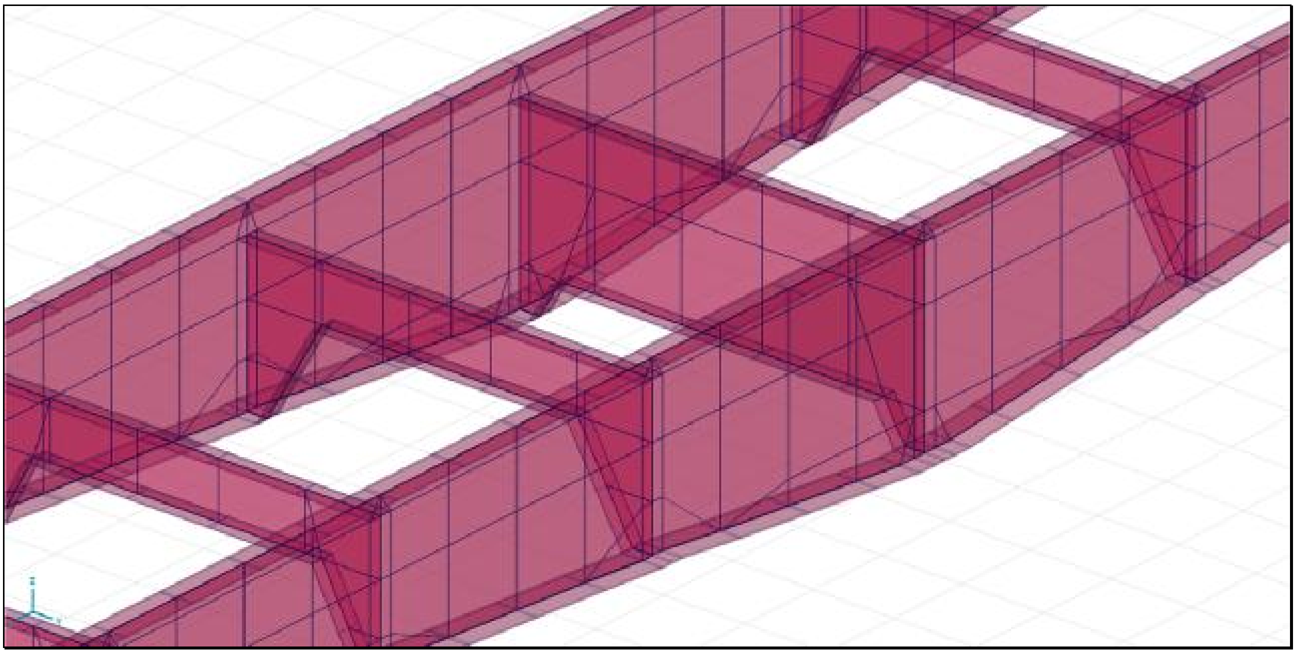
This test shows very clearly that apparently similar models can obtain very diverse data about the structure, and sometimes also make wrong impression about the bearing capacity, stability and serviceability, thus definitely confirming the demand for applying more complex models.

In this sense, the following examples are also illustrative. Fig. 15 shows FEM model of the bridge tested by load with model details given in the Fig. 16.

Composite structure of the bridge (steel main girder + concrete plate) showed torsional flexibility in the test-by-load, which is fully verified by presented FEM model, with first torsional natural shape, Fig. 11. Unfortunately, basic design analysis, based on one simplified model (built by 1D FEs), had slightly different results.



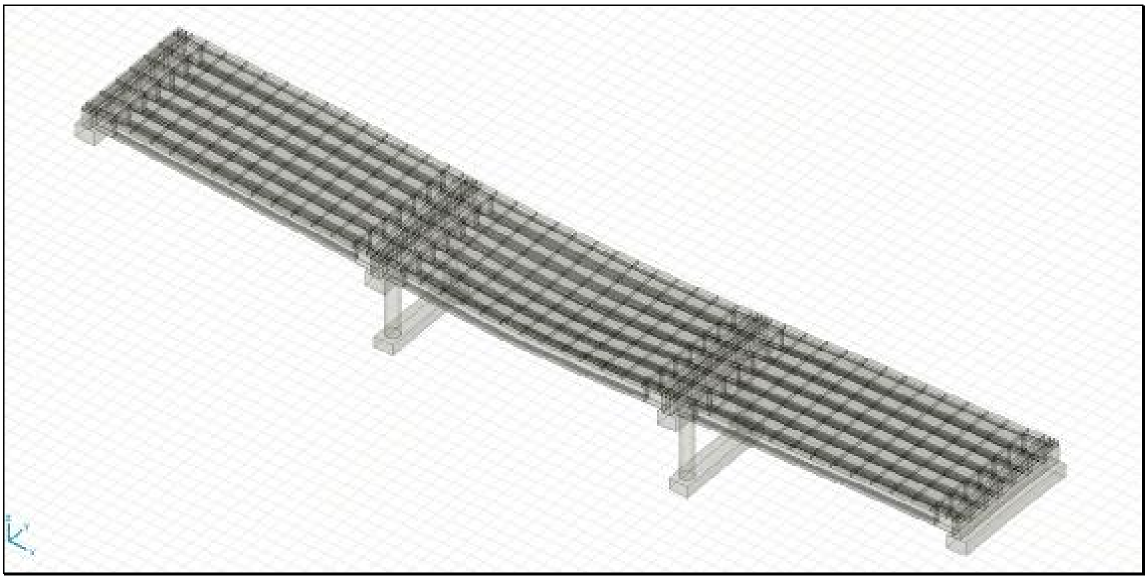
Slika 15. MKE model mosta ispitivanog probnim opterećenjem
Figure 15. FEM model of the bridge in test-by-load procedure



Slika 16. Detalji MKE modela mosta ispitivanog probnim opterećenjem
Figure 16. FEM model details of the bridge in test-by-load procedure

Ugibi konstrukcije jednog betonskog mosta (prednapregnuti linijski nosači + AB kolovozna ploča), čiji model je formulisan prema principima koji važe za konstrukcije od značaja dat je na sl. 17. Projektna dokumentacija ima za osnovu jedan pojednostavljeni model (sa 1D KE), čiji ugibi su toliko veći od realnih, da se može oceniti da je konstrukcija, u izvesnom smislu, "predimenzionisana".

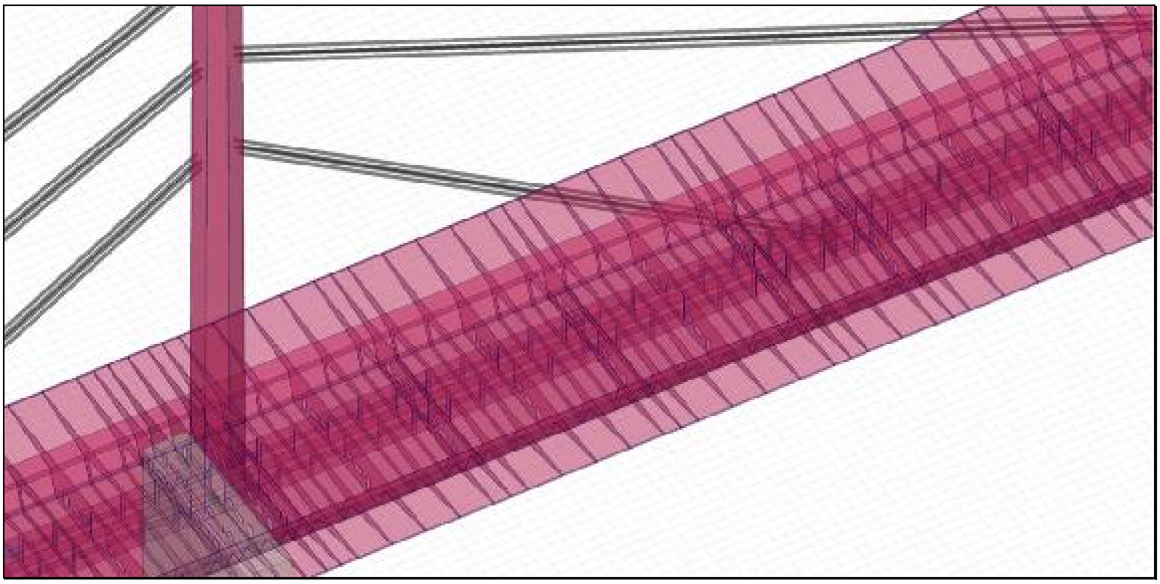
Displacements of structural system of one concrete bridge (pretensioned girders + reinforced plate) which is modeled according to the rules which should be used in the modeling of such important structures is given in the Fig. 17. Initial design analysis, based on one simplified model (built by 1D FEs), showed noticeably greater displacements and, in this sense, could be considered as "over dimensioned".



Slika 17. Ugibi modela mosta za najnepovoljniju konfiguraciuju opterećenja
Figure 17. Bridge model displacements for the most unfavorable test load position

Konačno, poslednji primer je, možda, najbolja ilustracija potrebnog pristupa u modeliranju: konstrukcije izuzetnog značaja zahtevaju poseban tretman, posebno u procedurama evaluacije njihove realne sigurnosti. sl. 18 pokazuje MKE model koji je nije bio razmatran kao glavni model u postupku dokazivanja performansi mosta obnovljenog posle razaranju bombardovanjem, a u proceduri probnog opterećenja, [8].

Finally, the last example is, maybe, the most illustrative for the preferred approach: the substantially important structures need adequate FEM modeling treatment, especially in the case of evaluation procedures. Fig. 18 shows FEM model which was omitted as the main model for test-by-load evaluation of the well-known bridge [8], reconstructed after the destruction in the bombing campaign.



Slika 18. Odgovarajući MKE model mosta izuzetnog značaja
Figure 18. Adequate FEM model for the bridge with an "out-of-categorization" importance

6 ZAVRŠNE NAPOMENE I ZAKLJUČCI

Kvalitete softverske implementacije odrežuje koliko će prednosti sofisticirane primene MKE da dođu do izražaja. U tom smislu se, kao ključno, postavlja pitanje izbora CASA softvera.

6 FINAL REMARKS AND CONCLUSIONS

High quality software implementation decides how much the advantages of FEM in modeling would be expressed. Thus, the problem of the choice of the CASA software is imposed as the key one.

Razvoj, distribucija i primena CASA softvera je polje gde su stručne kompetencije u oblasti analize konstrukcija od izuzetnog značaja, što mora da prati i optimalno obrazovanje u oblasti kompjuterskih nauka. Jasno je da ekipa koja razvija tekst-procesor, na primjer, mora da ima samo dovoljno obrazovane programere. S druge strane, tim koji radi na razvoju CASA programa mora da ima izuzetnu kompetenciju u oblasti inženjerskog projektovanja, a optimalno obrazovanje u programirskom smislu. Odgovarajuće relacije važe i kada je u pitanju distribucija i, naročito, primena. U tom smislu za AxisVM® je tipično da je razvijen od strane inženjera za inženjere.

Konceptualna zastarelost tehničkih propisa dovodi dizajnere softvera, distributeri i korisnike u situaciju da softver se koristi s nepotrebnim teškoćama. Propisi bi, dakle, trebalo da budu usklađeni sa najvažnijim tekovinom uvođenja kompjuterske tehnologije u projektiranju: eliminisanje napornih i monotonih manuelnih aktivnosti, čime se stvara više prostora za kreativno projektovanje.

The development, distribution and application of CASA software is the area where the professional competence is essential, but provided that rather high education in the field of computer sciences is also possessed. Clearly, the team that develops text-processor, for example, must have included sufficiently educated programmers. On the other hand, the team working on CASA program development must be extremely competent in engineering-structural issues, and optimally good in programming sense. Similar relations also apply when distribution and, particularly, program application are in question. AxisVM® is developed by engineers for engineers.

Conceptual "out-of-date" state of the technical regulations (eg. national design codes) brings the software developers, distributors and users into an absurd situation that software is used with avoidable difficulties. Thus, regulations should be harmonized with the most important heritage of the introduction of computer technology into a designing bureau: elimination of tiring and monotonous manual operations, and consequently providing more time for creative design.

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REZIME

AxisVM® 10 - USAVRŠENI CASA ALAT ZA MKE MODELIRANJE U ANALIZI KONSTRUKCIJA

Dušan KOVAČEVIĆ

Rad je sveobuhvatni prikaz AxisVM® 10 - CASA (Computer Aided Structural Analysis) softvera. AxisVM® je razvijen "za inženjere od strane inženjera" sa idejom da bi projektovanje konstrukcija trebalo da bude kretivni zadatak, bez obzira na ograničenja MKE, nedostatke tehničke regulative i stvarne kompetencije projektanta. AxisVM® ima preprocesor sa intuitivnim korisničkim interfejsom za jednostavno i efikasno geometrijsko modeliranje konstrukcije, moćni solver tj. procesor sa velikim mogućnostima za sofisticirano numeričko modeliranje i postprocesor sa različitim opcijama prikaza rezultata analize. Modul za dimenzionisanje obuhvata sve konstrukcijske materijale i mnoge nacionalne propise. Mogućnosti AxisVM® mogu da se koriste u svakodnevnoj projektantskoj praksi, razvojno-istraživačkom radu i u edukaciji inženjera projektanata.

Ključne reči: numeričko modeliranje, analiza konstrukcija, MKE, CASA, AxisVM

SUMMARY

AXISVM® 10 - ENHANCED CASA TOOL FOR FEM MODELING IN STRUCTURAL ANALYSIS

Dusan KOVACEVIC

The paper is a comprehensive review of AxisVM® 10 - CASA (Computer Aided Structural Analysis) software. AxisVM® is developed "for engineers by engineers" with an idea that structural design should be a creative task, regardless to the FEM limits, as well as technical regulations disadvantages and real designer's competencies. AxisVM® has a preprocessor based on an intuitive user interface for simple and efficient modeling of structural topology, powerful solver i.e. processor with sophisticated modeling possibilities and postprocessor with various options of presentation of analysis results. Design module treats all structural materials according to various national design codes. AxisVM® capabilities can be used in everyday design practice, development-scientific work and in education of structural engineers.

Key words: Numerical modeling, Structural analysis, FEM, CASA, AxisVM

STATIČKA ANALIZA KABLOVA

STATIC CABLE ANALYSIS

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1 UVOD

Kablovi, kao konstruktivni elementi, upotrebljavaju se u mnogim oblastima inženjerstva i predstavljaju vitalni noseći deo raznih konstrukcija kao što su: mostovi velikih raspona sa kablovima - viseći mostovi i mostovi sa kosim kablovima, krovnih konstrukcija sa kablovskim mrežama, komunikacijskih tornjeva sa kosim zategama, konstrukcija za eksploataciju nafte u morima sa kablovima za sidrenje, vodovi za prenos električne energije itd. Postoje generalno dva prilaza u razvoju konačnih elemenata za numeričko modeliranje kablova. Prvi prilaz je upotreba polinoma u opisu oblika kablova i polja pomeranja. Drugi prilaz je upotreba analitičkih izraza za lančanicu, koji u matematičkom smislu tačno opisuju kabl pod različitim uslovima opterećenja, a u skladu sa odgovarajućom teorijom lančanice.

U prvom prilazu, usvajaju se interpolacione funkcije koje treba da opišu nelinearno ponašanje kabla i razvijeni su konačni elementi: prosti štap sa dva čvora [2,3,9,12], prosti štap sa unutrašnjim čvorovima [1,2,13], gredni element sa dva čvora i sa unutrašnjim čvorovima [2,8,12]. Prosti štap sa dva čvora je element koji se najčešće upotrebljava kod modelovanja kablova. Ovaj elemenat je pogodan za modelovanje kablova koji su zategnuti sa visokom silom zatezanja. Da bi se u obzir uzeo i ugib kabla, moduo elastičnosti kabla se zamenjuje ekvivalentnim (Ernstovim) modulom elastičnosti, [16]. Na

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1 INTRODUCTION

Cables, as the structural elements, are being used in many fields of engineering and present the vital structural elements of various cable-supported structures, such as: the long-span bridges, like suspension and cable-stayed bridges, roof structures with cable nets, communication towers with cable stays (masts), floating off-shore oil platforms with anchoring cables, transmission power lines etc. Generally, there are two approaches in development of the finite elements related to numerical modeling of cables. The first approach is the use of polynomials to describe the shape of cable and the displacement field. The second approach is the use of analytical catenary relations, which in the mathematical sense exactly describe the cable under various loading conditions, in accordance with the corresponding catenary theory.

In the first approach, the interpolation functions which should describe the non-linear cable behavior are assumed and the finite elements are developed: truss beam with two nodes [2,3,9,12], truss beam with internal nodes [1,2,13], beam with two nodes and with internal nodes [2,8,12]. The truss element with two nodes is the element that is mostly used in modeling of cables. This element is convenient for cables that are exposed to high tension forces. In order to take into account the sag of the cable, the real modulus of elasticity of the cable is

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taj način aksijalna krutost pravolinijskog elementa postaje ekvivalentna aksijalnoj krutosti krivolinijskog elementa. Prosti štap sa unutrašnjim čvorovima uključuje efekte geometrije kabla preko uvođenja internih čvorova. Kod ovih elemenata se kao interpolacione funkcije upotrebljavaju polinomi višeg reda. Da bi se izbegao diskontinuitet u nagibu između dva prosta štapa u čvoru gde ne deluje koncentrisnao opterećenje, jer se sistem tada ponaša kao mehanizam i može da prouzrokuje numeričke probleme vezane za konvergenciju, upotrebljavaju se gredni elementi koji uspostavljaju kontinuitet u nagibu na spoju dva elementa jer sadrže i rotacione stepene slobode pomeranja u krajnjim čvorovima. Elementi zasnovani na polinomima pogodni su za modelovanje kablova sa malom strelom, odn. za tzv. plitke lančanice. Za kablove sa velikom strelom, odn. za duboke lančanice, kabl je potrebno izdeliti na veliki broj elemenata.

U drugom prilazu, analitički izrazi za lančanicu se upotrebljavaju da realno opišu ponašanje kabla [5,7,8,9,10,11,14,15]. Glavna prednost ovih elemenata je što kod statičke analize jedan kabl može da se predstavi samo jednim elementom ovoga tipa i da se pri tome dobiju rezultati visoke tačnosti. U slučaju dinamičke analize, svaki kabl treba da se modeluje sa više ovih elemenata. Konačni element, prikazan u ovome radu, je izveden na osnovu drugog prilaza i to na osnovu analitičkih izraza za elastičnu hiperboličku lančanicu. Tangentna matrica krutosti i vektor internih čvornih sila elementa su izvedeni iz tačnih analitičkih izraza za elastičnu lančanicu. Sopstvena težina kabla se razmatra direktno bez aproksimacija. Efekti predhodnog naprezanja kabla takođe su uključeni u formulaciju elementa. Sa ovim konačnim elementom može da se opiše ponašanje, kako plitkog, tako i dubokog kabla.

Opisani konačni element i metod rešavanja inkrementalnih jednačina ravnoteže su ugrađeni u razvijeni računarski program ELAN [4], koji omogućava linearnu i nelinearnu analizu konstrukcija sa kablovima, usled dejstva statičkog i dinamičkog opterećenja. Validnost formulacije konačnog elementa za kablove je proverena kroz test primere u kojima se razmatra statički odgovor kabla: pomeranja i horizontalna sila u kablu usled statičkog opterećenja: jednakopodeljenim opterećenjem i koncentrisanom silom. Vrednosti dobijene programom su upoređivane sa teorijskim vrednostima i vrednostima iz literature.

2 HIPERBOLIČKA TEORIJA DUBOKE LANČANICE - ANALITIČKA REŠENJA

2.1 Neelastična lančanica

Lančanica se definiše kao idealno savitljiva nerastegljiva materijalna linija koja ne pruža nikakav otpor promeni svog oblika. Ovo je osnovna definicija lančanice, koja je u skladu sa pretpostavkom o krutom telu. Međutim, kao što su sva tela više ili manje deformabilna, tako je i lančanica do određene mere restegljiva, ali se ipak prvo posmatra nerastegljiva, odn. neelastična lančanica. Za dalja razmatranja usvaja se dispozicija lančanice kao na slici 1. Neka je vertikalna ravan u kojoj se nalazi lančanica označena sa $x - z$, pri čemu je z osa vertikalna, sa smerom na gore. Usvaja se da je lančanica na svojim krajevima vezana za

replaced by the equivalent (Ernst's) modulus of elasticity, [16]. In such a way the axial stiffness of straight element becomes equivalent to the axial stiffness of curved (saged) element. The truss element with internal nodes includes the effects of cable geometry through internal nodes. As the interpolation functions polynomials of the higher order are being used. In order to avoid the slope discontinuity between two truss elements in the node without the concentric loading, since in that case the system is behaving as the mechanism and could produce numerical problems related to convergence, the beam elements are used, since they also have rotational degrees of freedom and enable the slope continuity between elements. Finite elements based upon polynomials are suitable for modeling of cables with small sag, the so-called shallow catenaries. For cables with large sag, i.e. for deep catenaries, the cable should be divided into the large number of elements.

In the second approach, analytical catenary expressions are being used in order to describe the realistic cable behavior [5,7,8,9,10,11,14,15]. The main advantage of such elements is that in the static cable analysis a single finite element could be used for the cable and also to obtain the results of high accuracy. In dynamic cable analysis, each cable should be modelled with more such finite elements. The cable finite element described in this paper is based upon the second approach, using analytical expressions related to elastic hyperbolic catenary. The tangent stiffness matrix and the vector of internal forces of the element are derived from the exact analytical expressions for elastic catenary. The self weight of the cable is directly considered, without approximations. The effects of pretension of the cable are also included into formulation of the element. With this finite element it is possible to describe behavior of both the shallow and the deep cable.

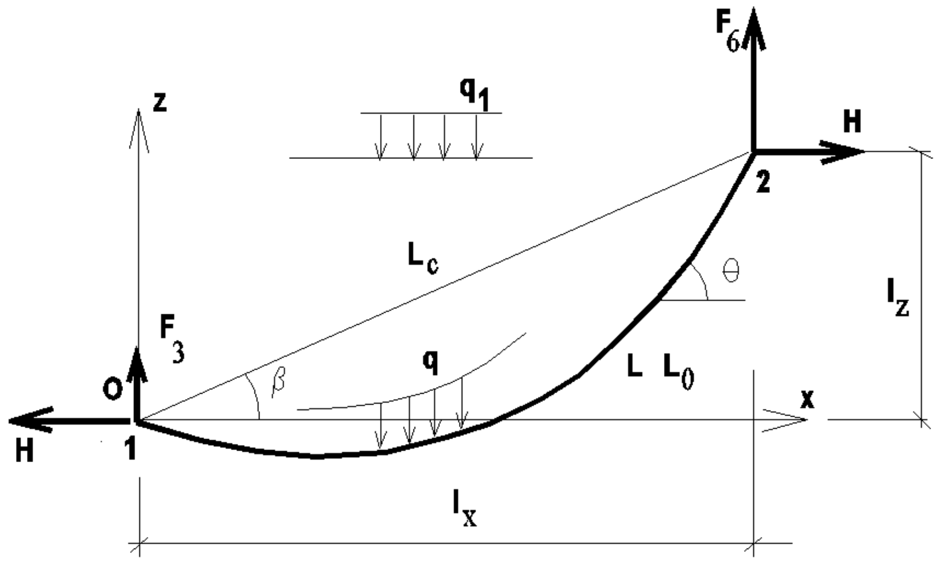
Presented finite element and the method of solution of the incremental equations of equilibrium are implemented into the computer code ELAN [4], which enables the linear and non-linear analysis of cable supported structures, due to static and also dynamic loading. Verification of the finite element formulation is checked through test examples of static cable analysis, determination of displacements and horizontal cable force due to uniformly distributed and concentrated loading. The values obtained by the program are compared with the theoretical results and the results presented in the literature.

2 HYPERBOLIC THEORY OF DEEP CATENARY – ANALYTICAL SOLUTIONS

2.1 Nonelastic catenary

The catenary is defined as an ideally flexible inextensible material line which does not resist to any change of its shape. This is the basic definition of the catenary, which corresponds to the notion of the rigid body. However, since all the bodies are more or less deformable, so the catenary is also, up to the point, extensible, but still, an unextensible, i.e. nonelastic catenary is considered first. In further discussion the catenary layout as assumed as shown in Fig. 1. The vertical plane in which the catenary belongs to is nepokretne oslonce *1* i *2*. Početak *O* koordinatnog sistema *Oxz* usvojen je u osloncu na levom kraju lančanice. Pri tome je horizontalan razmak između oslonaca, dakle raspon lančanice, označen sa l_x, dok je vertikalna denivelacija oslonaca označena sa l_z.

denoted as *x*-*z*, with *z* axis being vertical and the positive sense upwards. The ends of the catenary are connected to the fixed supports *1* and *2*. The origin *O* of the system *Oxz* is assumed at the left end of the catenary. The horizontal distance betwen the supports, i.e. the span of the catenary, is denoted as l_x, while the vertical denivelation of supports is denoted by l_z.



Slika 1 Lančanica opterećena sopstvenom težinom u koordinatnom sistemu Oxz
Figure 1 Gravitationaly loaded catenary in the coordinate system Oxz

Posmatrana lančanica opterećena je raspodeljenim opterećenjem sopstvenom težinom $q(s_0)$ duž luka s_0 nerastegljive lančanice, koji se meri od levog kraja lančanice. Predpostavlja se da je operećenje konstantno: $q(s_0) = q$ = const. Takođe se predpostavlja se da je lančanica idealno fleksibilna ($EI \equiv 0$), nerastegljiva ($AE \to \infty$), da nema torzionu krutost i da može da primi samo silu zatezanja *T*. Sila zatezanja ima pravac tangente u svakoj tački luka lančanice. Diferencijalna jednačina ravnoteže izdvojenog elementa luka lančanice glasi

Considered catenary is loaded by the distributed loading due to the self weight $q(s_0)$ along the arc s_0 of inextensible catenary, which is measured from the left end of the catenary. It is assumed that the loading is constant: $q(s_0) = q$ = const. It is also assumed that the catenary is ideally flexible ($EI \equiv 0$), inextensible ($AE \to \infty$), that lacks the torsional stiffness and can be exposed only to the tension force *T*. The tension force has the direction of the tangent in any point along the arc of the catenary. Differential equation of equilibrium of isolated arc element of the catenary is given by

$$H\,\frac{dz'}{ds_0} = q(s_0) \tag{1}$$

gde je *H* horizontalna komponenta sile zatezanja u lančanici koja ima konstantnu vrednost duž cele lančanice, jer je lančanica opterećena raspodeljenim opterećenjem stalnog (u ovom slučaju vertikalnog) pravca. Sa (..)' je označeno diferenciranje po koordinati *x.* Ako se leva i desna strana jednačine (1) podele sa *dx*, preuredi i unese da je $\frac{ds_0}{dx} = \sqrt{\left(1+z'^2\right)}$, jednačina (1) se transformiše u oblik

where *H* is the horizontal component of the tension force in the catenary, which has the constant value along entire catenary, since the catenary is loaded by distributed loading with constant (in this case vertical) direction. By (..)' the differentiation with respect to coordinate *x* is denoted. If both sides of Eq. (1) are divided by *dx*, after some transformation and considering that $\frac{ds_0}{dx} = \sqrt{\left(1+z'^2\right)}$, Eq. (1) may be transformed into

$$Hz'' = q\sqrt{\left(1+z'^2\right)} \tag{2}$$

Ako se uvedu oznake

Introducing notations

$$l = \frac{ql_x}{2H} \qquad \Phi = \operatorname{arcsin}h\left(\frac{l\,l_z}{l_x \sinh l}\right) - l = \Theta - l \tag{3}$$

konačno rešenje jednačine (2), vodeći računa o graničnim uslovima $z(0) = 0$ i $z(l_x) = l_z$, dato je sa

the final solution of Eq. (2), having in mind the boundary conditions $z(0) = 0$ and $z(l_x) = l_z$, is given as

$$z' = \sinh\left(\frac{qx}{H}+\Phi\right) = \sinh\left(2\,l\,\frac{x}{l_x}+\Phi\right) \tag{4}$$

$$z = \frac{H}{q}\left[\cosh\left(\frac{qx}{H}+\Phi\right) - \cosh\Phi\right] = \frac{H}{q}\left[\cosh\left(2\,l\,\frac{x}{l_x}+\Phi\right) - \cosh\Phi\right] \tag{5}$$

Rešenje $z=z(x)$ predstavlja jednačinu hiperbole, pa se zato ovakav pristup naziva hiperbolička teorija lančanice. Ukupna dužina luka nerastegljive hiperboličke lančanice L_0, vodeći računa o dobijenom rešenju (4) i odgovarajućim izrazima za transformaciju hiperboličkih funkcija, dobija se da je jednaka

The solution $z=z(x)$ represents the equation of the hyperbola, so this approach is called the hyperbolic theory of the catenary. The total arc length of inextensible catenary L_0, keeping in mind obtained solution (4) and the corresponding relations for transformations of hyperbolic functions, is obtained as

$$L_0 = \int_{s_0} ds_0 = \int_0^{l_x} \frac{ds_0}{dx} dx = \int_0^{l_x} \sqrt{1+z'^2}\, dx = \int_0^{l_x} \cosh\left(\frac{qx}{H}+\Phi\right) = \frac{2H}{q}\sinh l \cosh\left(l+\Phi\right) \tag{6}$$

Sile duž luka lančanice, za hiperboličko rešenje, mogu se izraziti na sledeći način

The forces along the arc of catenary, for hyperbolic solution, may be expressed as

$$\begin{bmatrix} H(x) \\ V(x) \\ T(x) \end{bmatrix} = \begin{bmatrix} H \\ Hz'(x) \\ \sqrt{H^2+V^2(x)} \end{bmatrix} = H \begin{bmatrix} 1 \\ z'(x) \\ \sqrt{1+z'^2(x)} \end{bmatrix} = H \begin{bmatrix} 1 \\ \sinh\left(2\,l\,\frac{x}{l_x}+\Phi\right) \\ \cosh\left(2\,l\,\frac{x}{l_x}+\Phi\right) \end{bmatrix} \tag{7}$$

gde je V vertikalna komponenta sile zatezanja u lančanici. Vertikalne komponente reakcija u osloncima, označene sa F_3 i F_6 i izražene preko ukupne dužine luka lančanice L_0, a dobijene transformacijom izraza (7-2), posle sređivanja se prikazuju u obliku

where V is the vertical component of the catenary tension force. The vertical components of reaction forces in supports, denoted as F_3 and F_6 and expressed by the total arc length of the catenary L_0, obtained by transformation of expression (7-2), after some transformation are presented as

$$V(0) = F_3 = -H\sinh\Phi = -\frac{q}{2}\left(l_z \coth l - L_0\right) \tag{8}$$

$$V(l_z) = F_6 = H\sinh\left(2\,l+\Phi\right) = -\frac{q}{2}\left(l_z \coth l + L_0\right) \tag{9}$$

Sile zatezanja T_1 i T_2, na krajevima lančanice, izražene preko dužine luka lančanice L_0, a dobijene transformacijom izraza (7-3), posle sređivanja glase

The tension forces T_1 and T_2, at catenary ends, expressed by the arc length of the catenary L_0, obtained by transformation of expression (7-3), might be given as

$$T(0) = T_1 = H\cosh\left(\Phi\right) = \frac{q}{2}\left(L_0 \coth l - l_z\right) \tag{10}$$

$$T(l_x) = T_2 = H\cosh\left(2\,l+\Phi\right) = \frac{q}{2}\left(L_0 \coth l + l_z\right) \tag{11}$$

Koristeći izraze (8)-(11), mogu da se izvedu sledeće jednakosti

Using expressions (8)-(11), the following relations may be derived

$$F_3 + F_6 = qL_0 \qquad F_6 - F_3 = ql_z \coth l \tag{12}$$

$$T_1 + T_2 = qL_0 \coth l \qquad T_2 - T_1 = ql_z \tag{13}$$

Iz jednačine (13-1) dobija se

From Eq. (13-1) one obtains

$$l = \coth^{-1}\frac{T_1+T_2}{qL_0} = \frac{1}{2}\ln\frac{T_1+T_2+qL_0}{T_1+T_2-qL_0} \tag{14}$$

gde je *ln* prirodni logaritam sa osnovom *e* = 2.17.... Izjednačavajući (3-1) i (14) dobija se

where *ln* is the natural logarithm with basis *e*=2.17... Equating expressions (3-1) and (14) one obtains

$$l_x = \frac{H}{q}\ln\frac{T_1+T_2+qL_0}{T_1+T_2-qL_0} \tag{15}$$

Kombinujući izraze (12-1) i (13-2), eliminacijom *q*, dobija se

Using expressions (12-1) and (13-2), after eliminating *q*, one obtains

$$l_z = \frac{T_2-T_1}{F_3+F_6}L_0 \tag{16}$$

Iz izraza (5), ako se unese da je $x = l_x$, dobija se

From expression (5), when introducing that $x = l_x$, one obtains

$$z(l_x) = l_z = \frac{H}{q}\left(\cosh\left(2l+\Phi\right)-\cosh\Phi\right) = 2\frac{H}{q}\sinh\left(l+\Phi\right)\sinh l \tag{17}$$

Kada se izrazi (6) i (17) kvadriraju i oduzmu, dobija se

If the expressions (6) and (17) are squared and added, then

$$L_0^2 - l_z^2 = \frac{4H^2}{q^2}\sinh^2 l = l_x^2\frac{\sinh^2 l}{l^2} \tag{18}$$

a posle preuređenja, dobija se da je kvadrat dužine luka nerastegljive lančanice jednak

and, after some transformation, one obtains that the square of the arc length of inextensible catenary is obtained as

$$L_0^2 = l_z^2 + l_x^2\frac{\sinh^2 l}{l^2} \tag{19}$$

Kao što se vidi, oblik luka lančanice u ravnotežnoj konfiguraciji zavisi od horizontalne komponente sile u lančanici *H*, koja je, u principu, nepoznata veličina, tako da je analiza lančanice složen statički neodređen problem. Isti zaključak sledi i iz same definicije lančanice kao idealno savitljive materijalne linije (više ili manje nerastegljive), kod koje je oblik u ravnotežnoj konfiguraciji unapred nepoznat i zavisi od apliciranog opterećenja. Jedan od načina rešavanja problema određivanja nepoznate horizontalne komponente sile u lančanici je da se iz unapred poznate početne dužine luka lančanice, date sa (19), iterativno odredi sila *H*, imajući u vidu izraz (3-1) za parametar λ u kome figuriše i sila *H*.

2.2 Elastična lančanica

Stvarna lančanica ima konačnu aksijalnu krutost. Usvaja se da se materijal od kojeg je napravljena lančanica ponaša linearno elastično, odn. da zadovoljava Hooke-ov zakon, što je sasvim prihvatljivo za većinu realnih kablova u praksi. Jednačine ravnoteže dela kabla (od početka kabla, do neke proizvoljne dužine luka s_0), u horizontalnom i vertikalnom pravcu su, videti sliku 2,

As may be seen, the shape of the arc of the catenary in its equilibrium position depends on the horizontal component *H* of the catenary tension, which is, in principle, the unknown quantity, so the catenary analysis is the complex statically indetermined problem. The same conclusion follows also from the very definition of the catenary as ideally flexible material line (more or less inextensible), whose shape in the equilibrium position is unknown in advance and depends on the applied loading. One of the ways to deal with the problem to determine the unkonwn horizontal component of the catenary tension force is that from the initially known total arc length of the catenary, given by (19), the force *H* is iteratively determined, having in mind the expression (3-1) for the parameter λ, which also contains the unknown force *H*.

2.2 Elastic catenary

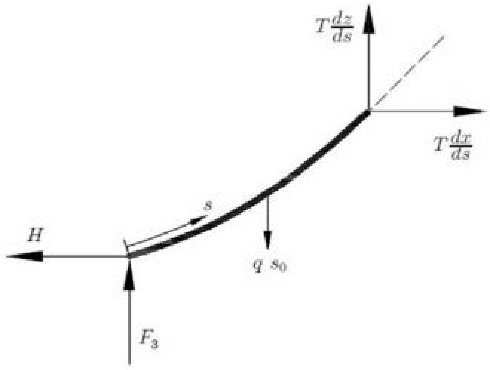
The actual catenay has the finite axial stiffness. It is assumed that the material properties of the catenary are lineraly elastic, i.e. to obey the Hooke’s law, which is quite acceptable for most real cables in engineering practice. Equilibrium equations of the part of the catenary (from the begining of the cable up to some arbitrary arc length s_0), in horizontal and vertical directions, are, see Fig. 2,

$$T\frac{dx}{ds}=H \qquad T\frac{dz}{ds}=qs_0-F_3 \tag{20}$$

Može da se vidi da se zbog konzervacije mase ukupna težina dela lančanice ne menja usled izduženja kabla [14]. Takođe, geometrijsko ograničenje

It could be seen that, due to conservation of mass, the total weight of the part of the catenary unchanged due to lengthening of the cable [14]. Also, the geometric restraint

$$\left(\frac{dx}{ds}\right)^2+\left(\frac{dz}{ds}\right)^2=1 \tag{21}$$



Slika 2 Segment elastične lančanice
Figure 2 Segment of elastic catenary

mora da bude zadovoljeno. Kako je dilatacija elementa luka lančanice (približno) jednaka

must be satisfied. Since the dilatation of the arc element of the catenary is (approximately) equal to

$$e=\frac{ds-ds_0}{ds_0}=\frac{ds}{ds_0}-1 \tag{22}$$

kao i pošto materijal lančanice zadovoljava Hook-ov zakon, dobija se

and also since the catenary material is obeys the Hooke's law, one obtains

$$T=As=AEe=AE\left(\frac{ds}{ds_0}-1\right) \tag{23}$$

U izrazu (23) sa *A* je označena površina poprečnog preseka neopterećene lančanice, σ je napon u poprečnom preseku i *E* je Young-ov moduo elastičnosti.

Ako se jednačine (20) kvadriraju i zamene u jednačini (21), dobija se sila zatezanja u bilo kojoj tački s_0 lančanice, u zavisnosti od njene horizontalne *H* i vertikalne komponente F_3, kao

In expression (23) *A* is the cross-sectional area of unloaded catenary, σ stress in the cross-sectional area and *E* is the Young's modulus of elasticity.

If Equations (20) are squared and substituted into Eq. (21), one obtains the tension force in any point s_0 of the catenary, in dependance of its horizontal *H* and vertical component F_3, as

$$T(s_0)=\left(H^2+(qs_0-F_3)^2\right)^{1/2} \tag{24}$$

Vodeći računa da je

Having in mind that

$$\frac{dx}{ds_0}=\frac{dx}{ds}\frac{ds}{ds_0} \qquad \frac{dz}{ds_0}=\frac{dz}{ds}\frac{ds}{ds_0} \tag{25}$$

i koristeći jednačine (20) i (21), dobijaju se parametarske jednačine lančanice u obliku

and using Eqs. (20) and (21), one obtains the parametric catenary equations in the form

$$x(s_0)=\frac{Hs_0}{AE}+\frac{H}{q}\left[\sinh^{-1}\left(\frac{qs_0-F_3}{H}\right)-\sinh^{-1}\left(-\frac{F_3}{H}\right)\right] \tag{26}$$

$$z(s_o)=\frac{F_3\,s_0}{AE}\left(\frac{qs_0}{2F_3}-1\right)+\frac{H}{q}\left[\left(1+\left(\frac{qs_0-F_3}{H}\right)^2\right)^{1/2}-\left(1+\left(\frac{F_3}{H}\right)^2\right)^{1/2}\right] \tag{27}$$

Ako se u jednačinama (26) i (27) stavi da je $s_0 = L_0$, i vodeći računa o vezi hiperboličkih i logaritamskih funkcija, kao i o izrazima (12) i (13), dobijaju se pogodniji izrazi za raspon i vertikalnu denivelaciju oslonaca lančanice u obliku

If one introduces $s_0 = L_0$ into Eqs. (26) and (27), keeping in mind relations between hyperbolic and logarithmic functions, as well as expressions (12) and (13), one obtains the more convenient expressions for the span and the vertical denivelation of supports in the form

$$x(L_0)=l_x=H\left(\frac{L_0}{EA}+\frac{1}{q}\ln\frac{F_6+T_2}{T_1-F_3}\right) \qquad z(L_0)=l_z=\frac{T_2-T_1}{q}+\frac{1}{2AEq}\left(T_2^2-T_1^2\right) \tag{28}$$

U relacijama (28) su raspon i vertikalna denivelacija oslonaca lančanice izraženi preko sila na krajevima, kao i drugih podataka o lančanici (modul elastičnosti *E*, površina poprečnog preseka *A*, gravitaciono opterećenje *q* i ukupna početna dužina luka lančanice L_0). Ove relacije su značajne u izvođenju elemenata matrice fleksibilnosti, odn. matrice krutosti, u numeričkom pristupu na bazi metode konačnih elemenata.

In Eqs. (28) the span and vertical denivelation of supports of the catenary are expressed through the forces at catenary ends, as well as through some other catenary data (modulus of elasticity *E*, cross-sectional area *A*, gravitational loading *q* and the total initial arc length of the catenary L_0). This relations are important in deriving the elements of the flexibility matrix in the numerical approach using the finite element method.

3 PARABOLIČKA TEORIJA LANČANICE - ANALITIČKA REŠENJA

3.1 Neelastična lančanica

U osnovi prikazane hiperboličke teorije lančanice se usvaja da je gravitaciono opterećenje *q* ravnomerno raspoređeno po luku lančanice, *q=const*, slika 1, što predstavlja realnu situaciju, jer je kabl celom svojom dužinom istog preseka i od istog materijala. U slučaju tzv. plitkih lančanica, gde je odnos strele lančanice prema rasponu relativno mali, obično $f/l_x<0.125$, (pod strelom *f* se podrazumeva vertikalan ugib na sredini lančanice, mereno od tetive luka), može da se usvoji da je gravitaciono opterećenje konstantno, ali raspoređeno po horizontalnoj projekciji luka lančanice: $q_1=const$. Diferencijalna jednačina ravnoteže izdvojenog elementa luka lančanice (2), je jednostavnija, videti, npr.[4], i data je sa

3 PARABOLIC CATENARY THEORY – ANALYTICAL SOLUTIONS

3.1 Nonelastic catenary

Within presented hyperbolic catenary theory it is assumed that the gravitational loading *q* is uniformly distributed along the arc length of the catenary, *q=const*, Fig. 1. In the case of the so-called shallow catenary, where the ratio of the sag and the span is relatively small, usually $f/l_x<0.125$ (the sag *f* of catenary is the vertical deflection measured in the middle of the span from the chord to the arc), it is assumed that the gravitational loading is constant, but when expressed as distributed along the horizontal projection of the arc length (i.e. span): $q_1=const.$ In that case the differential equation of equilibrium of isolated arc element of the catenary (2) is more simple [4]

$$Hz''=q_1 \tag{29}$$

Imajući u vidu granične uslove $z(0)=0$ i $z(l_x)=l_z$, dobijaju se rešenja diferencijalne jednačine (29) u obliku

Having in mind the boundary conditions $z(0)=0$ and $z(l_x)=l_z$, the solution of differential equation (29) is obtained in the form

$$z'=\frac{q_1}{2H}(2x-l_x)+\frac{l_z}{l_x} \tag{30}$$

$$z=\frac{q_1}{2H}(x^2-l_x x)+\frac{l_z}{l_x}x \tag{31}$$

Kao što se vidi, rešenje $z=z(x)$ je dobijeno u obliku kvadratne parabole, za razliku od hiperboličkih relacija datih sa (4) i (5). Rešenje (31) predstavlja oblik luka

As may be noticed, the solution $z=z(x)$ is obtained in the form of quadratic parabola, as opposed to hyperbolic relations given by (4) and (5). The solution (31) nerastegljive paraboličke, odn. plitke, lančanice koji odgovara sopstvenoj težini lančanice q_1 koja je konstantno raspodeljena po horizontalnoj projekciji luka lančanice. Naravno, kao i u slučaju duboke lančanice i hiperboličkih relacija, u paraboličkom rešenju figuriše i nepoznata horizontalna komponenta sile H u lančanici, koja se, kao i kod duboke lančanice, može da odredi iterativnim putem iz poznate dužine luka lančanice. Dužina luka lančanice je data sa integralom (6), koji se, unoseći paraboličke relacije (30) i (31), nešto složenije rešava, za razliku od hiperboličkih relacija. Kao rezultat, dobija se prihvatljivo približno rešenje za dužinu luka paraboličke (odn. plitke) lančanice u obliku:

represents the arc of the parabolic or shallow catenary, which corresponds to the self-weight q_1 which is uniformly distributed along the horizontal projection of the arc of the catenary. Of course, the same as in the case of deep catenary and hyperbolic relations, the parabolic solution is expressed through unknown horizontal component of the catenary tension force. As in the case of deep catenary, the unknown force H may be determined in iterative fashion from the known arc length of the catenary. The total arc length of the cable is given by the integral (6), which, when introducing the parabolic relations (30) and (31), is somewhat more complicated than in the case of hyperbolic relations. As the result, an acceptably good approximate solution for the total arc length of the parabolic (or shallow) catenary is given in the form

$$L_0 = \int_{s_0} ds_0 = \int_0^{l_x} \frac{ds_0}{dx} dx = \int_0^{l_x} \sqrt{1+z'^2}\, dx \cong \int_0^{l_x} \left(1 + \frac{z'^2}{2}\right) dx = l_x \left[1 + \frac{1}{6}\left(\frac{q_1 l_x}{2H}\right)^2 + \frac{1}{2}\left(\frac{l_z}{l_x}\right)^2\right] \tag{32}$$

3.2 Elastična lančanica

Za opterećenje usled sopstvene težine lančanica zauzima položaj opisan sa (31). Ako se na lančanicu aplicira neko dodatno gravitaciono opterećenje, onda se lančanica pomera iz prvobitne ravnotežne konfiguracije date sa (31) u neku novu ravnotežnu konfiguraciju (smatra se da se dodatno opterećenje aplicira dovoljno polako, tako da inercijalne sile mogu da se zanemare). Sve tačke luka lančanice usled dodatnog opterećenja dobijaju neka dodatna pomeranja u i w u pravcima osa x i z i dilatacija ε elementa luka lančanice može da se prikaže u obliku

3.2 Elastic catenary

For the loading due to the self-weight the catenary takes the position described by Eq. (31). If an additional gravitational loading is applied, then the catenary is displaced from the initial equilibrioum configuration given by (31) into another new equilibrium configuration (it is considered that the additional loading is applied sufficently slowly, so the inertial forces may be neglected). All points of the arc of the catenary due to additioal loading obtain some additional dispalcements u and w in direction of axes x and z and the dilatation ε of the arc element may be presented in the form

$$e = \frac{ds - ds_0}{ds_0} = \frac{dx}{ds_0}\frac{du}{ds_0} + \frac{dz}{ds_0}\frac{dw}{ds_0} + \frac{1}{2}\left(\frac{dw}{ds_0}\right)^2 \tag{33}$$

gde su uključene i male veličine drugog reda. U slučaju zanemarivanja malih veličina drugog reda, poslednji član u jedn. (33) može da se zanemari. Ako se sa τ obeleži nastali priraštaj sile zatezanja kabla T, koji se javlja usled dodatnog opterećenja, onda je horizontalna komponenta priraštaja sile zatezanja lančanice data sa

where the small quantities of the second order are included too. In the case when small quantities of the second order are being neglected, the last term in Eq. (33) may be neglected. If by τ one denotes the additional increment of the catenary tension force T, which is developing due to additional loading, then the horizontal component of increment of the catenary tension force is given by

$$h = t\,\frac{dx}{ds_0} = t\,\cos q \approx t\,\cos b \tag{34}$$

jer je, za plitku lančanicu, nagib tangente na luk približno jednak nagibu tetive luka. Imajući u vidu pretpostavku da se materijal lačanice ponaša u skladu sa Hooke-ovim zakonom, onda je

since, for the shallow catenary, the slope of the tangent to the arc is approximately equal to the slope of the arc chord. Having in mind that it is assumed that the catenary material is behaving according to the Hooke's law, and then it is

$$\frac{t}{EA} = e \tag{35}$$

pri čemu se ne posmatraju dilatacije usled moguće promene temperature. Unoseći relacije (33) i (34) u (35),

under the assumption that dilatations due to the temperature change are disregarded. Introducing the dobija se, posle množenja sa $(\frac{ds_0}{dx})^2$

relations (33) and (34) into (35), after multiplying by $(\frac{ds_0}{dx})^2$, one obtains

$$\frac{h(\frac{ds_0}{dx})^3}{EA} = \frac{du}{dx} + \frac{dz}{dx}\frac{dw}{dx} + \frac{1}{2}(\frac{dw}{dx})^2 \quad (36)$$

Jedn. (36) se naziva jednačina promene stanja plitke paraboličke lančanice u diferencijalnom obliku, [4,6]. Ako se jednačina (36) integrali po x duž raspona lančanice, dobija se jednačina promene stanja plitke paraboličke lančanice u integralnom obliku

Equation (36) is the so-called catenary equation of the shallow parabolic catenary in the differential form, [4,6]. If Eq. (36) is integrated by x along the catenary span, one obtains the catenary equation of the shallow parabolic catenary in the integral form

$$\frac{hL_e}{EA} = u(l_x) - u(0) + \int_0^{l_x} z'w'dx + \frac{1}{2}\int_0^{l_x} (w')^2 dx \quad (37)$$

gde je uvedana oznaka za tzv. virtuelnu dužinu lančanice L_e

where the notation for the so-called virtual catenary length L_e is introduced

$$L_e = \int_0^{l_x} (\frac{ds_0}{dx})^3 dx \cong l_x \left\{ 1 + 8\left(\frac{f}{l_x}\right)^2 + \frac{96}{5}\left(\frac{f}{l_x}\right)^4 + \frac{3}{2}\left[1 + 8\left(\frac{f}{l_x}\right)^2 + \frac{1}{4}tg^2 b\right] tg^2 b \right\} \quad (38)$$

Virtuelna dužina L_e je definisana kao određeni integral, a u slučaju paraboličnih relacija se dobija prikazana približna vrednost. Parcijalnom integracijom prvog integrala u jedn. (37), uz uzimanje u obzir graničnih uslova o nepokretnosti oslonačkih tačaka lančanice, jednačina promene stanja u integralnom obliku može da se prikaže kao

The virtual length L_e is defined as the definite integral, and in the case of the parabolic relations, one obtains the approximate value given by (38). By the partial integration of the first integral given in Eq. (37), taking into account the boundary conditions related to prevented displacements of the end points of the catenary (fixed supports), the catenary equation in the integral form may be presented as

$$\frac{hL_e}{EA} = \frac{q_1}{H}\int_0^{l_x} w dx + \frac{1}{2}\int_0^{l_x} (w')^2 dx \quad (39)$$

Pri tome, ako se zanemari uticaj malih veličina drugog reda u izrazu za dilataciju, u jednačini promene stanja (39) figuriše samo prvi integral, dok se drugi zanemaruje, odn. u jednačini (36) se poslednji član na desnoj strani zanemaruje. Time se dobija jednačina promene stanja u okviru linerane teorije plitke parabolične lančanice.

Also, if one neglects the effect of the small quantities of the second order in expression for dilatation, in the catenary equation (39) only the first integral remains, while the second one is neglected, or, in Eq. (36), the last term on the right-hand side is neglected. In such a way the obtained catenary equation corresponds to the linear theory of the parabolic catenary.

3.2.1 Uticaj dodatnog raspodeljenog gravitacionog opterećenja

Na lančanicu deluje gravitaciono opterećenje (sopstvena težina) $q_1(x)=q_1=const$, usled kojeg lančanica zauzima oblik dat sa relacijom (31). Pri tome se podrazumeva da je horizontalna komponenta sile zatezanja lančanice H takođe poznata, odn. određena. Posmatra se slučaj kada je lančanica opterećena još i sa dodatnim statičkim gravitacionim opterećenjem $p(x)=p=const$, koje je takođe ravnomerno raspoređeno po horizontalnoj projekciji luka lančanice, tako da se primenjuje parabolička teorija lančanice. Usled ovog dodatnog gravitacionog opterećenja lančanica zauzima novi ravnotežni položaj koji je definisan sa dodatnim pomeranjem u vertikalnom pravcu $w(x)$, koje se meri od položaja prvobitne ravnotežne konfiguracije $z(x)$. Ovom

3.2.1 The effect of the additional gravitational loading

Gravitational loading (self-weight) $q_1(x)=q_1=const$ is acting upon the catenary, due to which the catenary takes the position as defined by Eq. (31). It is understood that the horizontal component of the catenary tension force H is also known, i.e. previously determined. The case is considered when the catenary is loaded by the additional static gravitational distributed loading $p(x)=p=const$, which is also uniformly distributed along the horizontal projection of the catenary arc length, so the parabolic catenary theory is applied. Due to the additional gravitational loading the catenary takes up the new equilibrium position which is defined by the additional displacement in the vertical direction $w(x)$, meassured from the initial equilibrium position $z(x)$. As the consequence of the additional loading $p(x)$ there is dodatnom opterećenju *p(x)* odgovara takođe i promena sile zatezanja lančanice, tako da je horizontalna komponenta sile zatezanja u novoj ravnotežnoj konfiguraciji jednaka H_1=H+h, gde je sa h obeležena promena horizontalne komponente zatezanja lančanice. Pri tome je i h konstantno duž lančanice jer je rezultat delovanja dodatnog opterećennja p koje je konstantnog pravca.

Diferencijalna jednačina ravnoteže izdvojenog elementa luka lančanice, posle apliciranog dodatnog opterećenja, je data, analogno sa jednačinom (29), kao

also the corresponding change of the catenary tension force, so the horizontal component of the tension force in the new equilibrium position is equal to H_1=H+h, where h denotes the change of the horizontal component of the catenary tension. Also, h is constant along the catenary since it is the result of action of the additional loading p, which has the constant direction.

Differential equation of equilibrium of the isolated catenary arc element, after application of the additional loading, is given, in analogy with Eq. (29), as

$$(H+h)(z''+w'')=(q_1+p) \tag{40}$$

Imajući u vidu dif. jednačinu ravnoteže (29) lančanice u prvobitnoj ravnotežnoj konfiguraciji, jednačina (40) dobija oblik

Having in mind the differential equation (29) of the catenary in its initial configuration, Eq. (40) obtains the form

$$(H+h)w''=p-\frac{hq_1}{H} \tag{41}$$

pri čemu je moguće i da se još zanemari proizvod *hw"*, kao relativno mala veličina. Kako je horizontalna komponenta dodatnog zatezanja lančanice h nepoznata veličina, ali konstantna, diferencijalna jednačina (41) može da se prikaže u obliku

where it is also possible to neglect the term *hw"*, as the relatively small quantity. Since the horizontal component of the additional catenary tension h is unknown quantity, but which is constant, the differential equation (41) may be presented in the form

$$w''=A_*=\frac{p}{H+h}-\frac{hq_1}{H(H+h)}=const \tag{42}$$

Rešenje diferencijalne jednačine (42), uz granične uslove $w(0)=w(l_x)=0$, dobija se kao parabola

The solution of the differential equation (42), with the boundary conditions $w(0)=w(l_x)=0$, is obtained as the parabola

$$w(x)=\frac{1}{2}A_*(x^2-xl_x) \tag{43}$$

Konstanta A_* data sa (42), koja ima dimenziju dužina^{-1}, može da se prikaže u obliku

The constant A_*, as given by (42), with the dimension length^{-1}, may be presented in the form

$$A_*=\frac{p}{H+h}-\frac{hq_1}{H(H+h)}=\frac{q_1}{H(1+a)}\left(\frac{p}{q_1}-a\right) \tag{44}$$

gde je α oznaka za relativnu (bezdimenzionalnu) promenu horizontalne komponente sile zatezanja lančanice h usled dodatnog opterećenja, normirano u odnosu na silu H

where α denotes the relative (non-dimensional) change of the horizontal component of the catenary tension h due to additional loading, normalized with respect to the force H

$$a=\frac{h}{H} \tag{45}$$

U rešenju (43) konstanta A_* je nepoznata veličina, jer je nepoznata dodatna sila h, odnosno, nepoznata je relativna promena horizontalne sile data sa koeficijentom α. Međutim, rešenje (43) može da se unese u jednačinu promene stanja (39), koja predstavlja jednačinu kompatibilnosti elastične lančanice pri dodatnom opterećenju i u kojoj figuriše nepoznata dodatna sila h. Integrali na desnoj strani jednačine promene stanja (39) se, posle unošenja rešenja (43), dobijaju kao

In the solution (43) the constant A_* is the unknown quantity, since the additional force h is unknown, or, rather, unknown quantity is the relative change of the horizontal tension force given by the coefficient α. However, the solution (43) may be inserted into the catenary equation (39), which represents the compatibility equation of elastic catenary, containing the unknown additional force h. The integrals on the right-hand side of the catenary equation (39), after inserting the solution (43), are obtained as

$$\int_0^{l_x} w dx = -\frac{1}{12} A_* l_x^3 \qquad \int_0^{l_x} (w')^2 dx = \frac{1}{12} A_*^2 l_x^3 \tag{46}$$

pa se, posle daljeg transformisanja jednačine promene stanja, dobija kubna jednačina po bezdimenzionalnoj promeni horizontalne sile u lančanici (u normalizovanom obliku po α)

After further transformation, the catenary equation (39) is reduced to the cubic equation in the unknown change of the horizontal catenary tension (in the normalized form α)

$$a^3 + \left(2 + \frac{l_*}{24}\right) a^2 + \left(1 + \frac{l_*}{12}\right) a = \frac{l_*}{24}\left[2\left(\frac{p}{q_1}\right) + \left(\frac{p}{q_1}\right)^2\right] \tag{47}$$

U jednačinu (47) je uneta i oznaka za bezdimenzionalan parametar lančanice λ* dat sa

The non-dimensional catenary parameter λ*, introduced into Eq. (47), is given by

$$l_* = \frac{q_1^2 l_x^3 EA}{H^3 L_e} \tag{48}$$

Prema tome, dodatna horizontalna komponenta sile zatezanja u lančanici, u bezdimenzionalnom obliku α, određuje se rešavanjem kubne jednačine promene stanja (47), čiji se koeficijenti određuju preko bezdimenzionalnog parametra lančanice λ*, datim sa (48), kao i u zavisnosti od relativnog dodatnog opterećenja *p/q₁*. Bezdimenzionalan parametar lančanice λ* karakteriše mehaničko ponašanje lančanice i predstavlja osnovni parametar elastične lančanice. On uzima u obzir efekte početne geometrije lančanice i elastičnosti lančanice. Ako je parametar λ* relativno veliki broj, onda to predstavlja slučaj nerastegljive lančanice, dok slučaj kada je λ* relativno mali broj znači da se lančanica ponaša kao zategnuta žica. Izraz za parametar λ* može da se prikaže i u obliku u kome figuriše strela lančanice

Therefore, the additional horizontal catenary tension force, in the non-dimensional form α, is determined as the solution of the cubic catenary equation (47), whose coefficients are determined through the non-dimansional catenary parameter λ*, given by (48), and also depending upon the relative additional loading p/q_1. The non-dimensional catenary parameter λ* characterizes the mechanical behavior of the catenary. If the catenary parameter λ* is the relatively large number, then it represents the case of inextensible catenary, while the case when λ* is relatively small number means that the catenary behaves as the taut wire. The expression for the catenary parameter λ* may be presented in the form where the catenary sag is explicitly introduced

$$l_* = \left(\frac{8f}{l_x}\right)^3 \frac{EA}{q_1 L_e} \tag{49}$$

Rešavanjem kubne jednačine (47) se dobija promena horizontalne komponente zatezanja lančanice, odnosno konačna horizontalna sila zatezanja lančanice usled dodatnog opterećenja

Upon solution of the cubic equation (47) one obtains the change of the horizontal component of the catenary tension, or the final horizontal catenary tension due to the additional loading

$$H_1 = H + h = (1 + a)H \tag{50}$$

a zatim, prema izrazima (44) i (43), dodatan ugib lančanice usled dodatnog gravitacionog opterećenja *p(x)=const*. Vidi se da je zavisnost dodatne sile zatezanja lančanice usled dodatnog opterećenja, prikazana kubnom jednačinom (47), nelinearna, kao i da ta nelinearnost bitno zavisi od parametra λ*. Može da se utvrdi da je nelinearnost više izražena ukoliko je parametar lančanice λ* manji, a da je za veće vrednosti λ*, npr. λ* > 5000, nelinearnost sve manja, pa je granična vrednost dodatnog zatezanja lančanice, sa porastom parametra λ*, data sa

and then, according to the expressions (44) and (43), the additional catenary deflection due to the additional gravitational loading *p*. It might be seen that the dependence of the additional catenary tension to the additional loading, as given by Eq. (47), is nonlinear, and that nonlinearity strongly depends upon the catenary parameter λ*. It could be established that the nonlinearity is more emphasized if the catenary parameter λ* is smaller and that for greater values of λ*, for example λ* > 5000, nonlinearity is smaller. It maight be established that the limit value of the additional catenary tension, with the increase of the catenary parameter λ*, is given as

$$\lim_{l_* \to \infty} (a) = \frac{p}{q_1} \tag{51}$$

(asimptotsko približavanje je sa donje strane odnosa p/q_1).

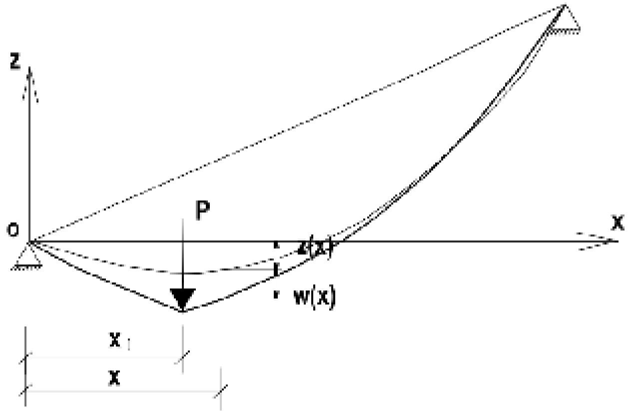
(asymptotic approximation is from the lower side of the ratio p/q_1).

3.2.2 Uticaj dodatne koncentrisane gravitacione sile

Za razliku od predhodnog slučaja raspodeljenog dodatnog opterećenja (deo 3.2.1), posmatra se lančanica koja je, osim sopstvenom težinom, opterećena još i sa dodatnom koncentrisanom gravitacionom silom inteziteta P na rastojanju x_1 od levog kraja lančanice, slika 3.

3.2.2 The effect of additional concentrated gravitational force

As opposed to the previous case of distributed additional loading (section 3.2.1), the catenary is considered which is, besides the self-weight, also loaded by the additional concentrated gravitational force of the intensity P at the distance x_1 from the left end of the catenary, Fig. 3.



Slika 3 Lančanica opterećena dodatnom koncentrisanom gravitacionom silom
Figure 3 Catenary loaded by the additional concentrated gravitational force

Ako su dodatna pomeranja lančanice mala, profil lančanice je i dalje plitak, a ravnoteža sila u pravcu ose z koje deluju na izdvojeni deo lančanice proizvoljne (konačne) dužine x na delu levo od sile P, odn. na delu $0 \le x < x_1$ glasi

If the additional displacements of the catenary are small, the shape of the catenary is still shallow, and the equilibrium of forces in direction of z acting upon the isolated part of an arbitrary (finite) length x of the catenary on the left side of the force P, i.e. at $0<x<x_1$, reads

$$(H+h)(z'+w') = P\left(\frac{x_1}{l_x}-1\right)+\frac{q_1 l_x}{2}\left(\frac{2x}{l_x}-1\right) \qquad 0 \le x < x_1 \tag{52}$$

Desna strana jednačine predstavlja izraz za transverzalnu silu proste grede u preseku x na delu $0 \le x < x_1$ usled sopstvene težine i koncentrisane sile, odn. zbir gravitacionih sila na tom delu lančanice, od oslonca u x=0, pa do beskonačno blisko sa leve strane preseka x. Leva strana jedn. (52) je vertikalna projekcija sile zatezanja lančanice u posmatranom proizvoljnom preseku x na delu $0 \le x < x_1$, koja je prikazana preko konstantne horizontalne komponente i tangensa ugla nagiba luka lančanice prema horizontali. Razvojem izraza (52) i eliminisanjem, odn. skraćivanjem članova koji zavise od sopstvene težine, dobija se

The right-hand side of Eq. (52) represents the expression for the shear force of the simply supported beam in the cross-section x at the part $0 \le x < x_1$ of the beam due to the self-weight and the concentrated force. Alternatively, it represents the sum of all gravitational forces at that part of the catenary, from the support at x=0, up to the infinitely close to the left side of the cross-section x. The left-hand side of Eq. (52) is the vertical projection of the catenary tension force at considered arbitrary cross-section x at the part $0 \le x < x_1$, which is presented by the constant horizontal component and the tangent of the slope angle with respect to the horizontal axis. By expanding the expression (52) and upon eliminating the members that depend upon the self-weight, one obtains

$$(H+h)w' = P\left(\frac{x_1}{l_x}-1\right) - hz' \qquad 0 \le x < x_1 \tag{53}$$

Slično se dobija da je ravnoteža sila u vertikalnom

In the similar way one obtains the equilibrium of pravcu na izdvojenom delu lančanice proizvoljne (konačne) dužine od desnog kraja lančanice pa do proizvoljnog preseka x na delu desno od koncentrisane sile P, dakle na delu $x_1 < x \le l_x$, data u obliku

forces in the vertical direction acting upon the isolated part of the catenary of the arbitrary (finite) length from the right end of the catenary up to an arbitrary section x on the right side of the concentrated force P, i.e. for the part $x_1 < x \le l_x$. The equilibrium of vertical forces may be written in the form

$$(H+h)w' = P\frac{x_1}{l_x} - hz' \qquad x_1 < x \le l_x \tag{54}$$

Integraljenjem jednačina (53) i (54), uz zadovoljenje graničnih uslova $w(0)=w(l_x)=0$, dobijaju se relacije

Upon integration of Eqs. (53) and (54) and satisfying the boundary conditions $w(0)=w(l_x)=0$, one obtains the following relations

$$w = -\frac{Pl_x}{H(1+a)}\left\{\frac{1}{2}\frac{a}{P_*}\left(\left(\frac{x}{l_x}\right)^2 - \frac{x}{l_x}\right) - \left(\frac{x_1}{l_x}-1\right)\frac{x}{l_x}\right\} \quad 0 \le x < x_1 \tag{55}$$

$$w = -\frac{Pl_x}{H(1+a)}\left\{\frac{1}{2}\frac{a}{P_*}\left(\left(\frac{x}{l_x}\right)^2 - \frac{x}{l_x}\right) - \left(\frac{x}{l_x}-1\right)\frac{x_1}{l_x}\right\} \quad x_1 < x \le l_x \tag{56}$$

gde je uveden izraz za bezdimenzionalnu gravitacionu koncentrisanu silu

where the expression for the non-dimensional gravitational concentrated force is introduced

$$P_* = \frac{P}{q_1 l_x} \tag{57}$$

U slučaju kada se problem analize uticaja dodatne koncentrisane sile posmatra kao nelinearan, da bi se odredila vrednost parametra α, koristi se nelinearna jednačina promene stanja (39). U preseku x_1, gde deluje koncentrisano opterećenje, pa postoji prekid prve vrste u dijagramu transverzalnih sila, u drugom integralu jednačne (39) postoji diskontinuitet nagiba, pa se za nalaženje tog integrala primenjuje parcijalna integracija iz dva dela

In case when the problem of analysis of the action of an additional concentrated force is treated as non-linear, in order to determine the value of the parameter α, the non-linear catenary equation (39) is used. At the section x_1, where the concentrated force is acting, so there is the discontinuity of the first kind in the shear force diagram, in the second integral of Eq. (39) there is the discontinuity of slope, so, in order to calculate that integral, the partial integration in two steps is preformed

$$\int_0^{l_x} (w')^2 dx = -\left\{ w'w\Big|_{x_1^-}^{x_1^+} + \left(w''\right)^2 \int_0^{x_1} w dx + \left(w''\right)^2 \int_{x_1}^{l_x} w dx \right\} \tag{58}$$

Posle zamene izraza (55), (56) i (58) u izrazu (39) i integraljenja, dobija se bezdimenzionalna kubna jednačina po relativnoj promeni horizontalne sile u lančanici (u normalizovanom obliku po a)

After introducing expressions (55), (56) and (58) into Eq. (39) and upon integration, one obtains the non-dimensional cubic equation in the relative change of the horizontal catenary force (in the normalized form in α)

$$a^3 + \left(2 + \frac{l_*}{24}\right)a^2 + \left(1 + \frac{l_*}{12}\right)a = -\frac{l_*}{2}\left(\left(\frac{x_1}{l_x}\right)^2 - \frac{x_1}{l_x}\right)P_*\left(1+P_*\right) \tag{59}$$

Ako se želi linearizovana analiza uticaja koncentrisane dodatne gravitacione sile, potrebno je da se zanemare mali članovi višeg reda (*hw'*) koji se pojavljuju u diferencijalnim jednačinama ravnoteže sila (53) i (54) na izdvojenim konačnim elementima luka lančanice. Integraljenjem jednačina (53) i (54), uz zanemarivanje malih članova višeg reda i uz

If one wants to linearize the analysis of the action of the additional concentrated gravitational force, it is necessary to neglect the small terms of the higher order (*hw'*) which appear in the differential equations of equilibrium of forces (53) and (54), acting upon the isolated finite lengths of the catenary arc. Upon integrations of Eqs. (53) and (54), neglection of small zadovoljenje graničnih uslova $w(0)=w(l_x)=0$, dobija se

terms of the higher order and upon satisfaction of the boundary conditions $w(0)=w(l_x)=0$, one obtains

$$w=-\frac{Pl_x}{H}\left\{\frac{1}{2}\frac{a}{P_*}\left(\left(\frac{x}{l_x}\right)^2-\frac{x}{l_x}\right)-\left(\frac{x_1}{l_x}-1\right)\frac{x}{l_x}\right\} \qquad 0\le x<x_1 \tag{60}$$

$$w=-\frac{Pl_x}{H}\left\{\frac{1}{2}\frac{a}{P_*}\left(\left(\frac{x}{l_x}\right)^2-\frac{x}{l_x}\right)-\left(\frac{x}{l_x}-1\right)\frac{x_1}{l_x}\right\} \qquad x_1<x\le l_x \tag{61}$$

Ako se izrazi (60) i (61) unesu u jednačinu promene stanja u okviru linearizovane teorije parabolične lančanice, posle integraljenja i sređivanja se dobija linearna relacija po α

If expressions (60) and (61) are introduced into the catenary equation corresponding to the linearized theory of the parabolic catenary, upon integration and some transformation, one obtains the linear relation in α

$$a=-\frac{1}{\left(1+\frac{12}{l_*}\right)}6P_*\left(\left(\frac{x_1}{l_x}\right)^2-\frac{x_1}{l_x}\right) \tag{62}$$

Prema tome, dodatna horizontalna komponenta sile zatezanja u lančanici, u bezdimenzionalnom obliku α, određuje se rešavanjem ili kubne jednačine promene stanja (59) kod primene nelinearne teorije parabolične lančanice, ili linearne jednačine (62) kod linearizovane teorije parabolične lančanice. I jedna i druga jednačina su funkcije bezdimenzionalnog parametra lančanice λ_*, datog sa (48), i bezdimenzionalnog koncentrisanog dodatnog opterećenja P^* datog sa (57). Linearizovano rešenje će biti prihvatljivo tačno u odnosu na nelinearno samo za relativno male vrednosti P^*. Ako je λ_* veliko, P^* ne bi trebalo da bude veće od 10^{-1} da bi se dobilo rešenje u granicama tačnosti od 10%. Ako je λ_* relativno malo, dozvoljene su i veće vrednosti za P^* da bi se dobilo prihvatljivo rešenje i u okviru linearizovanog pristupa, [6].

Therefore, the additional horizontal component of the catenary tension, in the non-dimensional form α, is determined by solution of the cubic catenary equation (59), applying the non-linear theory of the parabolic catenary, or by solution of the linear equation (62), using the linearized theory of parabolic catenary. Both equations are the functions of the non-dimensional catenary parameter λ_*, given by (48), and the non-dimensional concentrated additional loading P^* given by (57). The linearized solution will be acceptably exact with respect to the non-linear approach only for the relatively small values of P^*. If λ_* is large, P^* should not be greater then 10^{-1} in order to obtain the solution within the 10% accuracy limit. If λ_* is relatively small, one could have larger values of P^* and still obtain the acceptable solution within the linearized approach, [6].

4 KONAČNI ELEMENTI ZA ELASTIČNU HIPERBOLIČKU LANČANICU

Konačni elementi, zasnovani na analitičkim relacijama za elastičnu hiperboličku lančanicu, mogu da se upotrebljavaju za analizu kablova sa bilo kojim odnosom strela-raspon. Ovakvim elementima, sa veoma visokom tačnošću, mogu da se analiziraju i labavi i zategnuti kablovi. U literaturi se mogu naći ovakva rešenja kako za lančanicu u ravni [7,8], tako i za prostornu lančanicu [10,11].

Čvorne sile i čvorna pomeranja prostorne lančanice data su na slici 4. Lančanica je opterećena jednako-podeljenim gravitacionim opterećenjem pravcu vertikalne *z* ose. Prvo se izvode koeficijenti matrice fleksibilnosti za lančanicu u ravni *xOz* . Koriste se izrazi (3-1), (8), (12-1), (19) i (28) u donekle modifikovanom obliku

4 THE FINITE ELEMENTS FOR ELASTIC HYPERBOLIC CATENARY

The finite elements, based upon the analytical expressions for elastic hyperbolic catenary, might be used for the cable analysis with any sag-span ratio. Using these elements, with very high accuracy, one could analyze both the loose and taut cables. Such solutions might be found in the literature both for the planar catenary [7,8] and for the spatial catenary [10,11].

The nodal forces and the nodal displacements of the spatial catenary are given in the Fig. 3. The catenary is loaded by the uniformly distributed gravitational loading in direction of the vertical *z* axis. At first, the coefficients of the flexibility matrix for the planar catenary in *xOz* plane are derived. Expressions (3-1), (8), (12-1), (19) and (28), in the modified form, are used:

$$L^2=l_z^2+l_x^2\frac{\sinh^2 l}{l^2} \qquad l=\frac{q|l_x|}{2|F_1|} \tag{63}$$

$$F_3=\frac{q}{2}\left[-l_z\frac{\cosh l}{\sinh l}+L\right] \qquad F_6=qL_0-F_3 \tag{64}$$

$$l_x = -F_1\left(\frac{L_0}{AE}+\frac{1}{q}\ln\frac{F_6+T_2}{T_1-F_3}\right) \qquad l_z = \frac{T_2-T_1}{q}+\frac{1}{2AEq}\left(T_2^2-T_1^2\right) \tag{65}$$

Koriste se i sledeći izrazi

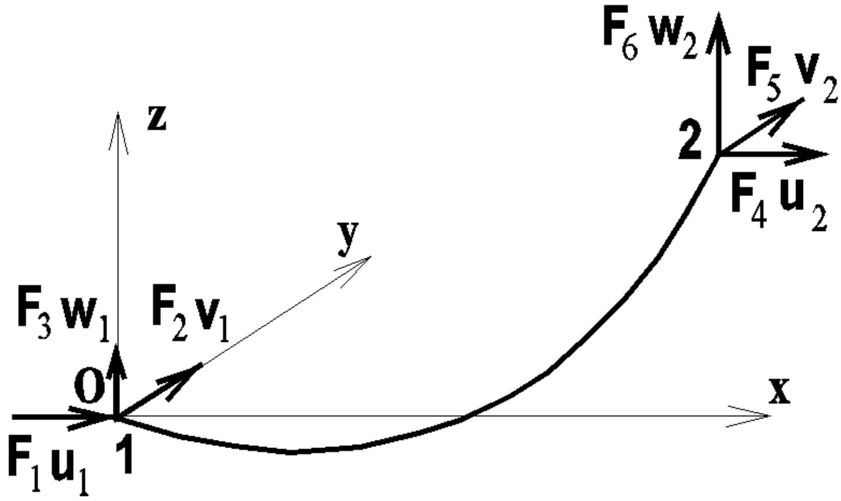
The following expressions are also used

$$F_4 = -F_1 \qquad T_1 = \sqrt{F_1^2+F_3^2} \qquad T_2 = \sqrt{F_4^2+F_6^2} \tag{66}$$

Ako se izrazi (64-2) i (66) zamene u relacijama (65), vidi se da izrazi (65) za horizontalni raspon i vertikalnu denivelaciju mogu da se prikažu kao funkcije sila na levom kraju, tj.

If expressions (64-2) and (66) are substituted into relations (65), it might be seen that expressions (65) for the horizontal span and the vertical denivelation could be expressed as functions of the forces at the left end, i.e.

$$l_x = l_x(F_1, F_3) \qquad l_z = l_z(F_1, F_3) \tag{67}$$



Slika 4 Čvorne sile i čvorna pomeranja lančanice
Figure 4 Nodal forces and nodal displacements of the catenary

Diferencijali dužina l_x i l_z datih simbolično sa izrazima (67), mogu da se prikažu u obliku

Differentials of the lengths l_x and l_z given symbolically with expressions (67) could be presented in the form

$$\begin{bmatrix} dl_x \\ dl_z \end{bmatrix} = \begin{bmatrix} \dfrac{\partial l_x}{\partial F_1} & \dfrac{\partial l_x}{\partial F_3} \\ \dfrac{\partial l_z}{\partial F_1} & \dfrac{\partial l_z}{\partial F_3} \end{bmatrix} \begin{bmatrix} dF_1 \\ dF_3 \end{bmatrix} = \begin{bmatrix} f_{11} & f_{13} \\ f_{31} & f_{33} \end{bmatrix} \begin{bmatrix} dF_1 \\ dF_3 \end{bmatrix} = \mathbf{f}_{2x2} \begin{bmatrix} dF_1 \\ dF_3 \end{bmatrix} \tag{68}$$

U izrazu (68) $\mathbf{f}_{2x2}$ je matrica fleksibilnosti lančanice u ravni, reda 2, čiji koeficijenti mogu da se izvedu u obliku

In expression (68) $\mathbf{f}_{2x2}$ denotes the flexibility matrix of the planar catenary, of order 2, whose coefficients might be derived as

$$f_{11} = \left[\frac{1}{q}\left(\frac{F_6}{T_2}+\frac{F_3}{T_1}-\ln\frac{F_6+T_2}{T_1-F_3}\right)-\frac{L_0}{AE}\right] \qquad f_{13} = f_{31} = \left[\frac{F_1}{q}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)\right] \qquad f_{33} = -\left[\frac{L_0}{AE}+\frac{1}{q}\left(\frac{F_6}{T_2}+\frac{F_3}{T_1}\right)\right] \tag{69}$$

Za lančanicu u trodimenzionalnom prostoru postoje tri komponente sile u čvorovima na krajevima lančanice. Matrica fleksibilnosti trodimenzionalne lančanice može da se izvede direktno iz matrice fleksibilnosti dvodimenzionalne lančanice kada joj se doda koeficijent

For the catenary in the three-dimensional space there are three force components at each end of the catenary. The flexibility matrix of the spatial catenary could be derived directly from the flexibility matrix of two-dimensional catenary, when adding the flexibility fleksibilnosti f_{22} za pomeranja van ravani lančanice, videti [7],

coefficient f_{22} corresponding to displacements in out-of-plane direction of the catenary, see [7],

$$f_{22} = -\frac{l_x}{F_1} = \left(\frac{L_0}{AE} + \frac{1}{q} \ln \frac{F_6 + T_2}{T_1 - F_3} \right) \quad (70)$$

Matrica krutosti **k** trodimenzionalne lančanice jednaka je inverznoj matrici fleksibilnosti **f** trodimenzionalne lančanice i jednaka je

The stiffness matrix **k** of the three-dimensional catenary is equal to the inverse flexibility matrix of the three-dimensional catenary and is given as

$$\mathbf{k} = \mathbf{f}^{-1} = \begin{bmatrix} f_{11} & & f_{13} \\ & f_{22} & \\ f_{31} & & f_{33} \end{bmatrix}^{-1} = \frac{1}{D} \begin{bmatrix} k_{11} & & k_{13} \\ & k_{22} & \\ k_{31} & & k_{33} \end{bmatrix} \qquad \begin{aligned} & k_{11} = f_{33} \;\; k_{13} = k_{31} = -f_{13} \\ & k_{22} = \frac{D}{f_{22}} \;\; k_{33} = f_{11} \\ & D = f_{11} f_{33} - f_{13}^2 \end{aligned} \quad (71)$$

Tangentna matrica krutosti $\mathbf{K}_T$ lančanice predstavlja vezu između vektora inkrementalnih internih čvornih sila $\Delta\mathbf{f}_{\text{int}}$ i vektora inkrementalnih čvornih pomeranja $\Delta\mathbf{q}$. Ova veza je data sa

The tangent stiffness matrix $\mathbf{K}_T$ of the catenary represents the connection between the vector of the incremental internal nodal forces $\Delta\mathbf{f}_{\text{int}}$ and the vector of incremental nodal displacements $\Delta\mathbf{q}$. This relation is given by

$$\begin{aligned} & \mathbf{K}_T \Delta\mathbf{q} = \Delta\mathbf{f}_{\text{int}} \\ & \Delta\mathbf{f}_{\text{int}}^T = [\Delta F_1 \;\; \Delta F_2 \;\; \Delta F_3 \;\; \Delta F_4 \;\; \Delta F_5 \;\; \Delta F_6] \\ & \Delta\mathbf{q}^T = [\Delta u_1 \;\; \Delta v_1 \;\; \Delta w_1 \;\; \Delta u_2 \;\; \Delta v_2 \;\; \Delta w_2] \end{aligned} \qquad \mathbf{K}_T = \begin{bmatrix} -\mathbf{k} & \mathbf{k} \\ \mathbf{k} & -\mathbf{k} \end{bmatrix} \quad (72)$$

4.1 Procedura određivanja tangentne matrice krutosti

Da bi se odredila tangentna matrica krutosti $\mathbf{K}_T$ moraju prvo da se odrede vrednosti čvornih sila F_1 i F_3. Te sile su usvojene kao redundantne sile i određuju se, u odnosu na datu poziciju krajnjih čvorova lančanice, upotrebom iterativne procedure. Osim osnovnih podataka o lančanici: q, E, A, kao i položaja drugog čvora, odn. raspona i vertikalne denivelacije l_x^0 i l_z^0, što je, načelno, uvek zadato, može da bude poznata još ili dužina nerastegljive lančanice L_0, ili horizontalna sila F_1. U zavisnosti od toga da li je još poznato L_0 ili F_1, bira se odgovarajuća iterativna procedura.

(A) U prvom slučaju, kada su za lančanicu poznate vrednosti q, E, A, položaj drugog čvora l_x^0 i l_z^0, kao i nerastegljiva dužina L_0, postupak određivanja tangentne matrice krutosti i vektora internih čvornih sila je sledeći:

1. Vrednost promenjive λ^0 određuje se iz izraza (63-1), kada se dužina L rastegljivog elementa zameni sa dužinom L_0 nerastegljivog elementa i zadrži prvi član u razvoju funkcije $\sinh^2\lambda/\lambda^2$ u red. To je poslednji slučaj u izrazu (73) za λ^0, dok prvi slučaj u (73) predstavlja vertikalanu lančanicu $l_x^0 = 0$, a drugi slučaj se odnosi na veoma plitku lančanicu, pa se usvaja da je λ^0 mala vrednost. Ukupan izraz za λ^0 glasi, videti, npr. [9],

4.1 The procedure of determination of the tangent stiffness matrix

In order to determine the tangent stiffness matrix $\mathbf{K}_T$ the values of nodal forces F_1 and F_3 should be determined first. These forces are assumed as the redundant forces and are determined, with respect to the given position of the end nodes of the catenary, using the iterative procedure. Besides the basic catenary data: q, E, A, as well as the position of the second node, i.e. the span and the vertical denivelation l_x^0 and l_z^0, which is, in principle, always given, the known quantity might be also either the length of the inextensible cable L_0, or the horizontal force F_1. Depending on what is additionaly known, L_0 or F_1, the corresponding iterative procedure is selected.

(A) In the first case, when the known catenary data are q, E, A, position of the other node l_x^0 and l_z^0, as well as the inextensible length L_0, the procedure to determine the tangent stiffness matrix and the vector of the internal nodal forces, is as follows:

1. The value of the variable λ^0 is determined from expression (63-1), when the length L of the extensible element is substituted with the length L_0 of inextensible element and keeping the first term in development of the function $\sinh^2\lambda/\lambda^2$ into series. That is the last case in expression (73) for λ^0, while the first case in (73) represents the vertical catenary $l_x^0 = 0$, and the second case corresponds to the very

shallow catenary, so one assumes the small value for λ^0. The complete expression for λ^0 is given by, see [9],

$$l^0 = \begin{cases} 10^6 & za \quad l_x^0 = 0 \\ 0.2 & za \quad L_0^2 \le \left(l_x^0\right)^2 + \left(l_z^0\right)^2 \\ \sqrt{6\left(\dfrac{L_0^2 - \left(l_z^0\right)^2}{\left(l_x^0\right)^2} - 1\right)} & za \quad L_0^2 > \left(l_x^0\right)^2 + \left(l_z^0\right)^2 \end{cases} \tag{73}$$

2. Inicijalizuju se čvorne sile: F_1^0 prema (63-2) kada se u izraz unesu poznate vrednosti za: $\lambda=\lambda^0$, $l_x = l_x^0$ i q; sila F_3^0 prema (64-1) kada se u izraz unesu poznate vrednosti za: q, $l_z = l_z^0$, $\lambda=\lambda^0$ i $L= L_0$

3. Započinje se iterativni proces, sa brojačem i, gde je $i = 0,1,2,3,...,$ u kome se određuje vektor nekompatibilnosti relativnog rastojanja $\Delta\mathbf{l}^i$ u iteracijama. Naime, ako je nova projekcija lančanice l_x^{i+1} i l_z^{i+1} data prema izrazima (65), koji odgovaraju silama F_1^i i F_3^i u posmatranoj iteraciji, a vodeći računa o izrazima (66) i (64), tada je

2. The nodal forces are initialized: F_1^0 according to (63-2), inserting into expression the known values for: $\lambda=\lambda^0$, $l_x = l_x^0$ and q; the force F_3^0 according to (64-1), introducing into expression the known values for: q, $l_z = l_z^0$, $\lambda=\lambda^0$ and $L= L_0$

3. Iterative process begins, with the couner i, where $i = 0,1,2,3,...,$ in which the vector of non-compatibility of the relative distance $\Delta\mathbf{l}^i$ is iteratively determined. Namely, if the new catenary projections l_x^{i+1} and l_z^{i+1} are given by expressions (65), corresponding to forces F_1^i and F_3^i in considered iteration, and also taking into account expressions (66) and (64), then

$$\Delta\mathbf{l}^i = \begin{bmatrix} \Delta l_x^i \\ 0 \\ \Delta l_z^i \end{bmatrix} = \begin{bmatrix} l_x^i - l_x^{i+1} \\ 0 \\ l_z^i - l_z^{i+1} \end{bmatrix} \tag{74}$$

gde Δl_x^i i Δl_z^i predstavljaju razlike projekcija lančanice između dve uzastopne iteracije.

4. Vektor korekcije internih čvornih sila i vektor korigovanih internih čvornih sila mogu da se prikažu kao\

where Δl_x^i and Δl_z^i represent the differences of cable projections between the two consecutive iterations.

4. The correction vector of the internal nodal forces and the vector of corrected internal nodal forces may be presented as

$$\begin{bmatrix} \Delta F_1^i \\ 0 \\ \Delta F_3^i \end{bmatrix} = \mathbf{k}^i \begin{bmatrix} \Delta l_x^i \\ 0 \\ \Delta l_z^i \end{bmatrix} = \mathbf{k}^i \Delta\mathbf{l}^i \qquad \begin{bmatrix} F_1^{i+1} \\ 0 \\ F_3^{i+1} \end{bmatrix} = \begin{bmatrix} F_1^i \\ 0 \\ F_3^i \end{bmatrix} + \begin{bmatrix} \Delta F_1^i \\ 0 \\ \Delta F_3^i \end{bmatrix} \tag{75}$$

gde je $\mathbf{k}^i$ dato sa (71). Iterativna procedura veoma brzo konvergira. Iterativni proces (koraci 3 i 4) se nastavlja sve dok ne bude $\left\|\Delta\mathbf{l}^i\right\| < e$, gde je ε neka unapred zadata, odn. usvojena, mala vrednost.

5. Sa dobijenim krajnjim vrednostima internih čvornih sila F_1^{i+1} i F_3^{i+1}, na kraju iterativnog procesa, i sa ostalim zadatim podacima, računaju se konačne

where $\mathbf{k}^i$ is given by (71). Iterative procedure converges very quickly. Iterative process (steps 3 and 4) is continued until one obtains that $\left\|\Delta\mathbf{l}^i\right\| < e$, where ε is some initially given, i.e. assumed, small quantity.

5. Upon obtaining the final values of the internal nodal forces F_1^{i+1} and F_3^{i+1}, at the end of the iterative procedure, together with all other given catenary data,

vrednosti koeficijenata tangentne matrice krutosti $\mathbf{k}^{i+1}$ lančanice koje se koriste za dalji proračun konstrukcije, prema relacijama (71) i (72).

(B) U drugom slučaju, kada su za lančanicu poznate vrednosti *q*, *E*, *A*, položaj drugog čvora l_x^0 i l_z^0 kao i horizontalna sila F_1, postupak određivanja tagentne matrice krutosti i vektora čvornih sila je sledeći:

1. Inicijalizuju se vrednosti za:

- λ prema (63-2) .
- L_0 prema (63-1) kada se stavi da je $L= L_0$ i kada se u izraz unesu poznate vrednosti za: $l_x = l_x^0$, $l_z = l_z^0$ i λ.
- Čvorna sila F_3^0 prema (64-1) kada se u izraz unesu poznate vrednosti za: *q*, $l_z = l_z^0$, λ i $L= L_0$

2. Zatim se započinje iterativni proces sa brojačem *i*, gde je $i = 0,1,2,3,....$ u kome se određuje vektor nekompatibilnosti relativnog rastojanja prema (71). Ako je $\left\|\Delta\mathbf{l}^i\right\| < e$, vrednost L_0^i je dužina lančanice u neopterećenom stanju i prelazi se na korak 4, a ako ne, prelazi se na korak 3

3. Ako se elementi matrice $\mathbf{\Psi}$ definišu kao

the final values of the coefficients of the catenary tangent stiffness matrix $\mathbf{k}^{i+1}$ are calculated and used in the further calculation, according to relations (71) and (72).

(B) In the second case, when the known catenary data are *q*, *E*, *A*, position of the second node l_x^0 and l_z^0 as well as the horizontal catenary force F_1, the procedure of determination of the tangent stiffness matrix and the vector of the nodal forces is the following:

1. The values for the following quantities are initialized:

- λ according to (63-2) .
- L_0 according to (63-1) when inserting that $L= L_0$ and when the known data for: $l_x = l_x^0$, $l_z = l_z^0$ and λ are inserted into expresion,
- Nodal force F_3^0 according to (64-1) when inserting into expression the known values for: *q*, $l_z = l_z^0$, λ and $L= L_0$

2. Iterative process begins, with the counter *i*, where $i = 0,1,2,3,....$ in which the vector of non-compatibility of the relative distance $\Delta\mathbf{l}^i$ is iteratively determined according to (71). If $\left\|\Delta\mathbf{l}^i\right\| < e$, the value L_0^i is the catenary length in unloaded state and the process continues with the step 4. If not, the process continues with the step 3.

3. If the elements of the matrix $\mathbf{\Psi}$ are defined as

$$d\mathbf{l} = \begin{bmatrix} dl_x \\ dl_z \end{bmatrix} = \begin{bmatrix} \dfrac{\partial l_x}{\partial F_3} & \dfrac{\partial l_x}{\partial L_0} \\ \dfrac{\partial l_z}{\partial F_3} & \dfrac{\partial l_z}{\partial L_0} \end{bmatrix} \begin{bmatrix} dF_3 \\ dL_0 \end{bmatrix} = \Psi \begin{bmatrix} dF_3 \\ dL_0 \end{bmatrix} \tag{76}$$

tada se ispravka za F_3^{i+1} i L_0^{i+1} računa prema

then the correction for F_3^{i+1} and L_0^{i+1} is determined according to

$$\begin{bmatrix} F_3^{i+1} \\ L_0^{i+1} \end{bmatrix} = \begin{bmatrix} F_3^i \\ L_0^i \end{bmatrix} + \begin{bmatrix} \Delta F_3^i \\ \Delta L_0^i \end{bmatrix} \qquad \begin{bmatrix} \Delta F_3^i \\ \Delta L_0^i \end{bmatrix} = \left[\Psi^i\right]^{-1} \Delta\mathbf{l}^i \tag{77}$$

i prelazi se na korak 2 i sledeću iteraciju.

4. Sa dobijenim krajnjim vrednostima F_3^{i+1} i L_0^{i+1}, na kraju iterativnog procesa, kao i sa ostalim zadatim vrednostima, računaju se konačne vrednosti koeficijenata tangentne matrice krutosti $\mathbf{k}^{i+1}$ lančanice koja se koriste za dalji proračun konstrukcije.

and the process is continued with step 2 and the next iteration.

4. With the final values of F_3^{i+1} and L_0^{i+1} obtained, at the end of the iterative procedure, as well as with other given catenary data, the final values of the coefficients of the tangent stiffness matrix $\mathbf{k}^{i+1}$ of the catenary are calculated and used in the further calculation.

5 JEDNAČINE RAVNOTEŽE U STATIČKOJ ANALIZI

Ako se umesto generalisanih pomeranja, za osnovne parametre u čvorovima usvoje priraštaji pomeranja, dobija se inkrementalna formulacija osnovnih jednačina ravnoteže. Za razliku od jednačina ravnoteže sa parametrima pomeranja kao nepoznatim veličinama,

5 EQUILIBRIUM EQUATIONS IN THE STATIC ANALYSIS

If, instead of the generalized nodal displacements, as the basic unkowns one assumes the increments of displacements, incremental formulation of the koje su nelinearne, inkrementalne jednačine ravnoteže su linearne i u njima su nepoznati inkrementi pomeranja.

Posmatra se proizvoljno telo u toku deformacije. Sa ${}^{0}C$ je označena početna, sa ${}^{m}C$ tekuća, a ${}^{m+1}C$ naredna konfiguracija tela. U korigovanoj Lagrange-ovoj formulaciji referentna konfiguracija je tekuća konfiguracija ${}^{m}C$. Rešenje inkrementalnih jednačina ravnoteže sistema, izvedenih korigovanim Lagrange-ovim postupkom, primenom metode konačnih elemenata glasi [4]

$$ {}_{m}^{m}\mathbf{K}_T \Delta\mathbf{q} = {}^{m+1}\mathbf{r} - {}_{m}^{m}\mathbf{f}_{\text{int}} \tag{78} $$

U jednačini (78) ${}_{m}^{m}\mathbf{K}_T$ predstavlja tangentnu matricu krutosti sistema u ${}^{m}C$, $\Delta\mathbf{q}$ vektor inkrementalnog pomeranja sistema iz trenutne u narednu konfiguraciju, ${}^{m+1}\mathbf{r}$ vektor ekvivalentnog čvornog opterećenja sistema u ${}^{m+1}C$, a ${}_{m}^{m}\mathbf{f}_{\text{int}}$ je vektor internih čvornih sila sistema.

Za rešavanje inkrementalnih jednačina ravnoteže (78) korišćen je modifikovani Newton Raphson-ov iterativni postupak gde umesto jednačine (78) važi jednačina

$$ {}^{m}\mathbf{K}_T \Delta\mathbf{q}^{(i)} = {}^{m+1}\mathbf{r} - {}^{m+1}\mathbf{f}_{\text{int}}^{(i-1)} \tag{79} $$

pri čemu indeks *i* označava iteraciju.

6 NUMERIČKI PRIMERI

U kompjuterski program ELAN, [4], ugrađen je, između ostalog, prikazani konačni elemenat koji je zasnovan na analitičkim izrazima za elastičnu hiperboličku lančanicu i inkrementalno-iterativni postupak za rešavanje jednačina ravnoteže. Razvijeni program ELAN omogućava linearnu i nelinearnu analizu konstrukcija sa kablovima usled statičkog i dinamičkog opterećenja. U svim primerima, u ovome delu rada, kablovi se aproksimiraju samo sa po dva konačna elemenata za elastičnu hiperboličku lančanicu. Analiziraju se plitki kablovi tj. kablovi kod kojih je odnos f / l_x, koji predstavlja odnos strele slobodno obešenog kabla usled sopstvene težine i horizontalnog rastojanja oslonaca, relativno mali, $f / l_x < 0.125$. Kod plitkog kabla uzima se da je $q \cong b$ (slika 1). Da bi se rezultati dobijeni programom verifikovali, upoređivani su sa teorijskim (analitički dobijenim) vrednostima i vrednostima dobijenim iz literature.

Primer 1: Posmatraju se dva kabla, sa osloncima na istoj visini, (odn. kabl sa „horizontalnim rasponom") čije su karakteristike date u tabeli 1. Koriste se uobičajene oznake: *A* je površina poprečnog preseka kabla, *E* Young-ov moduo elastičnosti materijala i *q* je sopstvena težina kabla. Primer je prikazan u literaturi [6].

equilibrium equations is obtained. As opposed to the equilibrium equations with unknown nodal displacements, which are the non-linear equations, incremental equilibrium equations are linear, with increments of displacements as unknowns.

An arbitrary body during deformation is considered. With ${}^{0}C$ the initial configuration is denoted, ${}^{m}C$ represents the current, and ${}^{m+1}C$ is the next configuration of the body. In the Updated Lagrangian formulation the reference configuration is the current one ${}^{m}C$. The solution of the incremental equations of equilibrium, derived by using the Updated Lagrangian formulation and the finite element method, is given by, see [4],

where ${}_{m}^{m}\mathbf{K}_T$ represents the tangent stiffness matrix of the system in ${}^{m}C$, $\Delta\mathbf{q}$ is the vector of incremental displacements of the system from the current to the next configuration, ${}^{m+1}\mathbf{r}$ is the vector of equivalent nodal loading of the system in ${}^{m+1}C$, while ${}_{m}^{m}\mathbf{f}_{\text{int}}$ is the vector of internal nodal forces of the system.

The solution of incremental equations of equilibrium (78) is obtained by using the modified Newton-Raphson's iterative method, where, instead of Eqs. (78), the following equation is used

where the index *i* represents the current iteration.

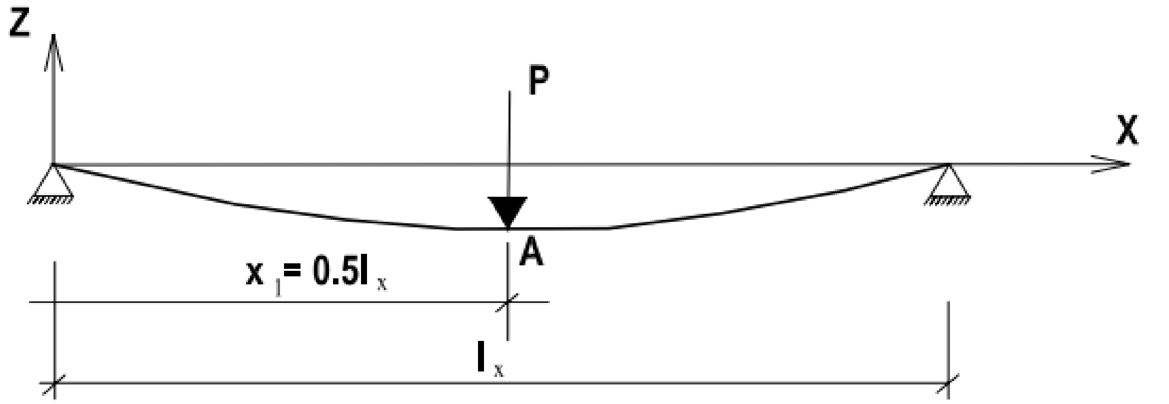
6 NUMERICAL EXAMPLES

The computer code ELAN [4] contains, besides other features, also the finite element related to the elastic hyperbolic catenary and the incremental iterative procedure to solve the equilibrium equations. Developed code ELAN enables the linear and non-linear analysis of cable structures due to static and dynamic loading. In all examples in this paper the cables are approximated only by the two finite elements for elastic hyperbolic catenary, The shallow cables are analyzed, i.e. the cables where the ratio f / l_x, which represents the ratio of a sag and span of the cable due to the self weight, is relatively small, $f / l_x < 0.125$. For the shallow cable one assumes that $q \cong b$ (Fig.1). In order to verify obtained results using the program, they are compared with the theoretical (analytically obtained) results and results obtained from the literature.

Example 1: The two cables are considered, with supports at the same level, whose characteristics are given in the Table 1. The following notation is used: *A* is the cross- sectional area, *E* the Young's modulus of elasticity and *q* is the self weight of the cable. The example is presented in the literature [6].

Tabela 1 Karakterisike kablova u prvom primeru
Table 1 Cable characteristics in the 1st example

Svojstva (Property)	Kabl 1 (Cable 1)	Kabl 2 (Cable 2)
$A[m^2]$	0.161	$5.06x10^{-4}$
$E[kN/m^2]$	$1.81x10^8$	$1.04x10^8$
$l_x[m]$	915	91.5
f/l_x	1:12	1:50
$q[kN/m']$	4.4	0.0388



Slika 5 Plitki kabl opterećen koncentrisanom silom u sredini
Figure 5 Shallow cable loaded by the concentrated force in the middle of the span

Kao što može da se vidi u Tabeli 1, primer je isti: plitki kabl sa horizontalnim rasponom, opterećen koncentrisanom silom u sredini raspona, jedino su karakteristike kablova međusobno različite, pa se zato i govori o dva kabla. Na deformisanom obliku kabla 1 i 2, usled sopstvene težine, počinje da deluje koncentrisana sila *P* u tački A na sredini raspona (slika 5). Intenzitet koncentrisane sile, koja deluje u tački A na kablu 1, je dat u više koraka opterećenja *P*=*n* x 178*kN* (*n*=0,1,2,3,4,5), a na kablu 2 *P*=*n* x 4.45*N* (*n*=0,1,2,3,4,5). Traži se vertikalno pomeranje tačke A kabla i horizontalna sila zatezanja u kablu.

Kontrola dobijenih vrednosti ugiba i horizontalne sile, dobijenih programom, vrši se upoređivanjem sa vrednostima ugiba i horizontalne sile dobijenim iz jednačine promene stanja za plitku paraboličnu lančanicu opterećenu koncentrisanom silom prema nelinearnoj i linearnoj teoriji (poglavlje 3.2.2). Za posmatrani kabl 1 se dobija da je parametar lančanice jednak $\lambda_* = 2000$, a za kabl 2 je $\lambda_* = 60.2$.

Kao što je rečeno, oba kabla su aproksimirani sa po dva konačna elementa koja su međusobno povezani u tački A. Dobijeni rezultati za kabl 1 su prikazani u tabeli 2. Može da se vidi sledeće: vrednosti horizontalne sile dobijene programom, za različite nivoe dodatnog opterećenja, dobro se slažu sa računskim vrednostima sile dobijene prema nelinearnoj i linearnoj teoriji; ugibi dobijeni programom, za različite nivoe dodatnog opterećenja, dobro se slažu sa računskim vrednostima ugiba dobijenih prema nelinearnoj teoriji. Sa slike 6a se vidi da je kriva $a(P^*)$ dobijena programom linearna i da se dobro slaže sa krivom dobijenom prema linearnoj i neli-

As may be seen in the Table 1, the example is the same: a shallow cable with the horizontal span, loaded by the concentrated force in the middle of the span, only the properties of cables are mutually different. After the deformed shape of cables 1 and 2, due to the self weight is achieved, the concentrated force *P* in the point A at the middle of the span starts to act (Figure 5). The intensity of the force acting upon the cable 1 is presented in the form of several loading steps *P*=*n* x178kN (*n*=0,1,2,3,4,5), and upon the cable 2 in the form *P*=*n* x 4.45N (*n*=0,1,2,3,4,5). The vertical deflection of the point A and the horizontal tension force in cables are determined.

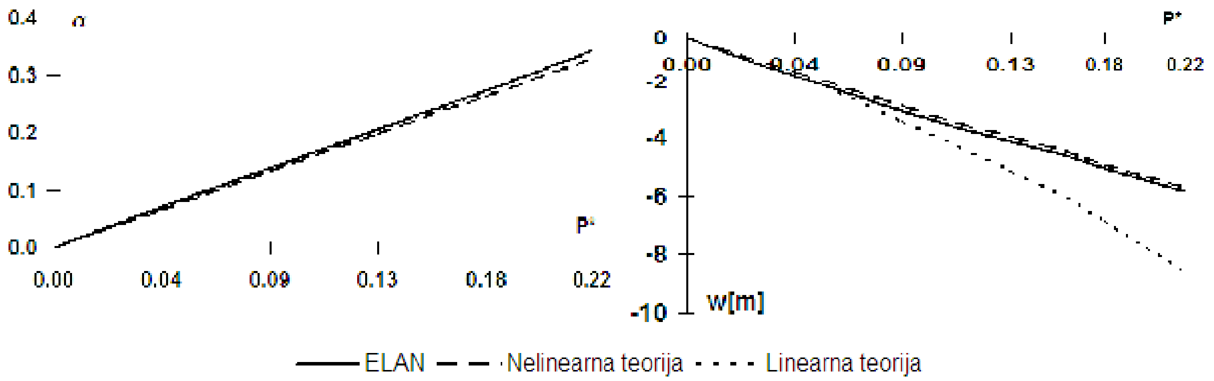
The control of the results for deflection and the horizontal force obtained by the code is done by comparison with deflections and horizontal force as obtained by the cable equation for the shallow parabolic catenary loaded by the concentrated force, according to the non-linear and the linear theory (section 3.2.2). For the cable 1 one obtains $\lambda_* = 2000$, and for the cable 2, $\lambda_* = 60.2$.

As previously stated, both cables were approximated by the two finite elements that are mutually connected at point A. Obtained results for cable 1 are presented in the Table 2. The following could be seen: values of the horizontal force for various levels of additional loading, obtained by the code, are in the good agreement with horizontal forces obtained according to non-linear and linear theory; deflections obtained by the code, for various levels of additional loading, are in good agreement with the numerical values of deflections obtained according to the non-linear theory. From the nearnoj teoriji. Na slici 6b se vidi da je kriva ugiba kabla $w(P^*)$ dobijena programom nelinearna i da se dobro slaže sa krivom dobijenom prema nelinearnoj teoriji.

Fig. 6a one could see that the curve $\alpha(P^*)$ obtained by the code is linear and that it is in a good agreement with curves obtained by the linear and non-linear theories. Fig. 6b shows that the deflection curve $w(P^*)$ obtained by the code is non-linear and that it is in a good agreements with the corresponding curve according to the non-linear theory.

Tabela 2: Kabl 1 - Horizontalna sila i ugib u sredini kabla
Table 2: Cable 1 - Horizontal force and deflection in the middle

P[*kN*]	Ukupna sila u kablu (The total cable force) *H*(1+α) [*kN*]			Pomeranje (Deflection) *w* [*m*]		
	Računsko rešenje (Numerical solution)		ELAN	Računsko rešenje (Numerical solution)		ELAN
	Linearno (Linear)	Nelinearno (Non-linear)		Linearno (Linear)	Nelinearno (Non-linear)	
0	6039	6039	6039	0	0	0
178	6437	6440	6472	-1.72	-1.57	-1.75
356	6835	6848	6873	-3.43	-2.88	-3.05
534	7233	7264	7279	-5.15	-3.95	-4.14
712	7631	7681	7690	-6.86	-4.90	-5.06
890	8030	8104	8102	-8.58	-5.69	-5.85



a) b)

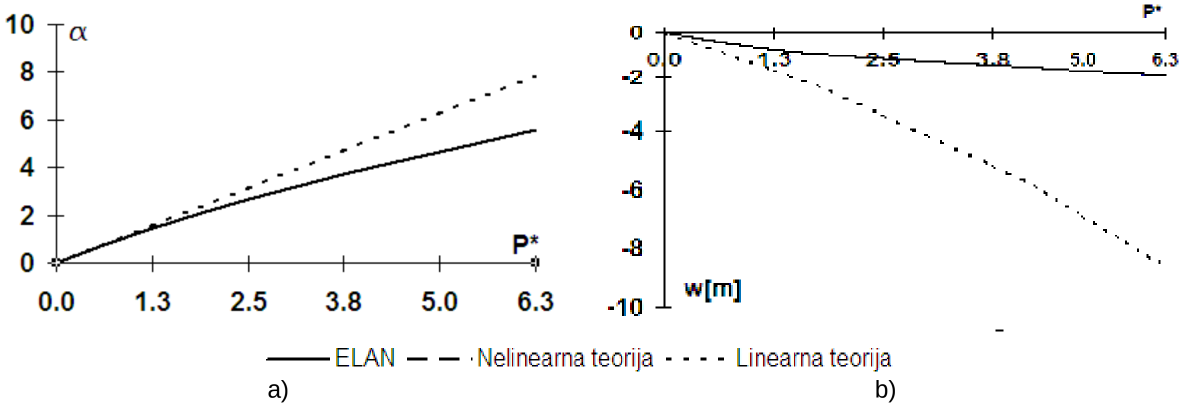
Slika 6 Kabl 1 opterećen koncentrisanom silom u sredini raspona u više koraka a) promena inkrementa horizontalne sile u kablu b) relativna promena ugiba u sredini raspona
Figure 6 Cable 1 loaded in several steps by the concentrated force in the middle: a) the change of increment of the horizontal cable force b) relative change of deflection in the middle of the span

Rezultati za kabl 2 su dati u tabeli 3. Može da se vidi da se vrednosti horizontalne sile i ugiba dobijene programom, za različite nivoe dodatnog opterećenja, dobro slažu sa računskim vrednostima sile i ugiba dobijenih prema nelinearnoj teoriji. Sa slike 7a se vidi da je kriva $\alpha(P^*)$ dobijena programom nelinearna i da se dobro slaže sa krivom dobijenom prema nelinearnoj teoriji. Na slici 7b se vidi da je kriva ugiba kabla $w(P^*)$ dobijena programom nelinearna i da se dobro slaže sa krivom dobijenom prema nelinearnoj teoriji.

Obtained results for cable 2 are presented in the Table 3. The following could be seen: values of the horizontal force and deflections, for various levels of additional loading, obtained by the code, are in the good agreement with horizontal forces and deflections obtained according to the non-linear theory. From Fig. 7a one could see that the curve $\alpha(P^*)$ obtained by the code is non-linear and that it is in a good agreement with curve obtained by the non-linear theory. Fig. 7b shows that the deflection curve $w(P^*)$ obtained by the code is non-linear and that it is in a good agreements with the corresponding curve according to the non-linear theory.

Tabela 3 Horizontalna sila i ugib u sredini kabla 2
Table 3: Cable 2 - Horizontal force and deflection in the middle

P[kN]	Ukupna sila u kablu (The total cable force) H(1+α) [kN]			Pomeranje (Deflection) *w [m]*		
	Računsko rešenje (Numerical solution)		ELAN	Računsko rešenje (Numerical solution)		ELAN
	Linearno (Linear)	Nelinearno (Non-linear)		Linearno (Linear)	Nelinearno (Non-linear)	
0.00	22.5	22.15	22.2	0	0	0
4.45	56.9	54.4	54.6	-1.7	-0.787	-0.803
8.90	91.6	81.0	81.0	-3.4	-1.185	-1.200
13.35	126.3	104.2	104.4	-5.2	-1.488	-1.510
17.80	161.0	125.1	126.0	-6.9	-1.745	-1.760
22.25	195.8	146.1	145.8	-8.6	-1.928	-1.980



Slika 7 Kabl 2 opterećen koncentrisanom silom u sredini raspona u više koraka a) promena inkrementa horizontalne sile u kablu b) relativna promena ugiba u sredini raspona
Figure 7 Cable 2 loaded in several steps by the concentrated force in the middle: a) the change of increment of the horizontal cable force b) relative change of deflection in the middle of the span

Primer 2: Kao drugi primer, posmatra se horizontalni kabl (bez vertikalne denivelacije oslonaca), kao što je prikazano u literaturi [7], videti sliku 8. Krajnje tačke kabla fiksirane su na horizontalnom rastojanju od $l_x = 304.8m$. Površina poprečnog preseka kabla je A=54.8 x10$^{-5}m^2$ i dužina kabla u neopterećenom stanju je L_0 = 301.752m, tako da je kabl inicijalno prednapregnut. Young-ov moduo elastičnosti materijala kabla E iznosi $E = 1.30x10^8 kNm^{-2}$, dok je sopstvena težina kabla jednaka $q = 4.6x10^{-2} kNm^{-1}$. Kao i pre, kabl se aproksimira sa dva konačna elementa koja su međusobno povezana u tački A.

U prvom slučaju, na kabl počinje da deluju istovremeno sopstvena težina q i sila P=35.4kN u tački A. Vertikalno pomeranje w tačke A dobijeno programom je w = -4.117m, a prema [7] je w= -4.126m. Vidi se da se rezultati dobijeni programom veoma dobro slažu sa vrednostima datim u literaturi (**D**=-0.22%).

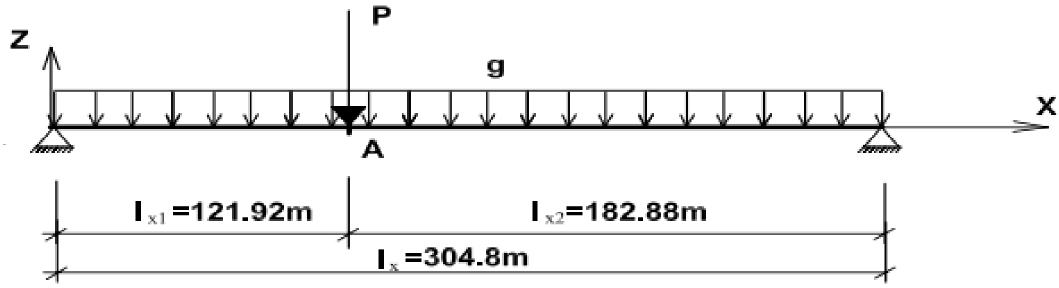
U drugom slučaju, na kabl u ravnotežnom položaju usled sopstvene težine, počinje da deluje i dodatno jednakopodeljeno opterećenje $p = 4.6x10^{-2} kNm^{-1}$. Vertikalno pomeranje tačke A dobijeno programom je w=-0.698m. Kontrola dobijenih vrednosti ugiba, dobijenih programom, izvršena je u odnosu na vrednost ugiba

Example 2: As the second example, a horizontal cable (without the vertical denivelations of supports) is considered, as found in the literature [7], see Fig. 8. The end joints of the cable are fixed at the horizontal distance of l_x = 304.8m. Cross-sectional area of the cable is A=54.8 x10$^{-5}m^2$ and the length of the cable in the unloaded condition is L_0 = 301.752m, so the cable is initially pre-tensioned. The Young's modulus of elesticity of the cable is equal to E = 1.30x10$^8 kNm^{-2}$. The self-weight of the cable is q = 4.6x10$^{-2} kNm^{-1}$. As previously, the cable is approximated by the two finite elements connected at the joint A.

In the first case, the cable is simultaneously loaded by the self-weight q and the concentrated force P=35.4kN at the joint A. The vertical deflection w of the joint A obtained by the code is w = -4.117m, while, according to [7], deflection is w = -4.126m. The result obtained by the code is in excellent agreement with the literature (**D**=-0.22%).

In the second case, the cable is in its equilibrium position due to the self-weight and then the additional uniformly distributed loading p = 4.6x10$^{-2} kNm^{-1}$ is applied. Vertical displacement of the joint A, obtained by the code is w = -0.698m. The control of deflections obtained by the code is preformed using the cable equation for the cable loaded by the additional dobijenu iz jednačine promene stanja, za kabl opterećen jednakopodeljenim opterećenjem, prema nelinearnoj teoriji (poglavlje 3.2.1) i iznosi w=-0.699*m*. Vidi se da se rezultati dobijeni programom veoma dobro slažu sa računskim vrednostima.

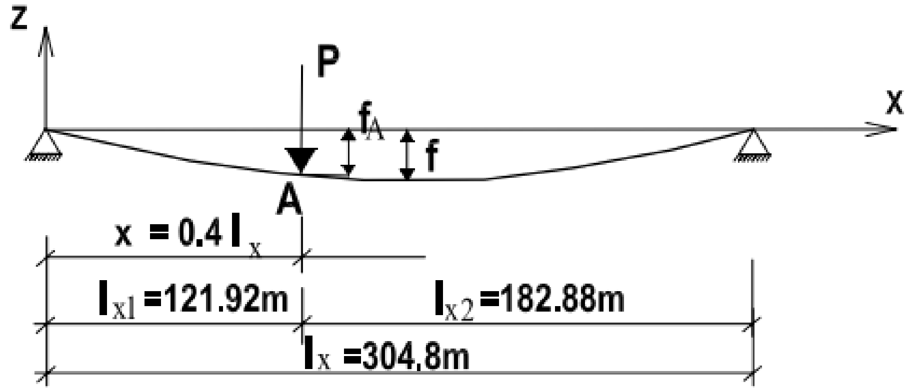
distributed loading, according to the non-linear theory (see section 3.2.1), and is obtained as w = -0.699*m*. It is obvious that the results obtained by the computer code ELAN are in excellent agreement with the calculated values.



Slika 8 Prednapregnuti kabl opterećen sopstvenom težinom i koncentrisanom silom
Figure 8 Pretensioned cable loaded by its self weight and the concentrated force

Primer 3: Treći primer je takođe prikazan u literaturi [7]: to je takođe kabl sa horizontalnim rasponom od l_x = 304.8*m*, slika 9. Usled sopstvene težine q kabl je dobio ugib f u sredini raspona. Na tako deformisanom kablu počinje da deluje vertikalna koncentrisana sila P na udaljenosti od 0.4l_x od levog oslonca, u tački A. Početni ugib kabla, na mestu dejstva koncentrisane sile, je f_A. Potrebno je naći horizontalno u i vertikalno w pomeranje tačke A. Poznato je: površina poprečnog preseka kabla A=0.000548m^2, Young-ov moduo elastičnosti E=130*GPa*, sopstvena težina q=0.046*kN/m*, P=35.6*kN*, f = 30.5*m* i f_A = 29.276*m*. Opet je kabl aproksimiran sa dva konačna elementa koji se sustiču ispod napadne tačke A sile P. Na osnovu poznatog q i f mogu da se izračunaju početne dužine delova kabla i one iznose L_{01}=125.847*m* i L_{02}=186.855*m*. Pomeranja tačke A, dobijena programom, su: u = −0.833*m* i w = −5.32*m,* dok pomeranja tačke A prema [7] iznose: u = −0.859*m* i w = −5.62*m*. Vidi se da se rezultati dobijeni programom ELAN prihvatljivo dobro slažu sa vrednostima datim u literaturi ($\mathbf{D}_u$ = -3.0%, $\mathbf{D}_w$ = -5.3%).

Example 3: The third example is also presented in the literature [7]: it is also the cable with horizontal span of l_x = 304.8*m*, Fig. 9. Due to its self weight, the cable obtained the sag f at the middle of the span. Upon deformed cable then begins to act the concentrated vertical force P at the distance 0.4 l_x from the left support (Fig. 9), at point A. The initial cable deflection, at the position of the concentrated force, is f_A. Both the horizontal u and the vertical displacement w of the point A should be determined. The known data are: cross-sectional cable area A=0.000548m^2, the Young's modulus of elasticity is E=130*GPa*, the self-weight is q=0.046*kN/m*, intensity of the concentrated force is P = 35.6*kN*, and deflections are f = 30.5*m* and f_A = 29.276*m*. Again, the cable is approximated by the two finite elements which are connected at the joint A, where the force is acting. Based upon the known q and f one could calculate the initial lengths of the parts of the cable that are connected at point A. The lengths are L_{01}=125.847*m* and L_{02}=186.855*m*. Displacements of the point A, obtained by the code, are u = −0.833*m* and w = −5.32*m,* while displacements of the point A according to [7] are u = −0.859*m* i w = −5.62*m*. It could be seen that the results obtained by the code ELAN are acceptably in a good agreement with the calculated values presented in the literature ($\mathbf{D}_u$ = -3.0%, $\mathbf{D}_w$ = -5.3%).



Slika 9 Kabl na koga deluje koncentrisana sila
Figure 9 Cable under the action of the concentrated force

7 ZAKLJUČAK

U radu je prikazana statička analiza lančanice, prvo analitički pristupi zasnovani na hiperboličkim i paraboličkim relacijama nerastegljive ali i elastične lančanice, a zatim i numerički pristup na bazi metode konačnih elemenata. Numerički model konstrukcija sa kablovima, korišćenjem konačnih elementa zasnovanih na hiperboličkim izrazima za lančanicu, koji je prikazan u radu, može da se koristi za nelienarnu analizu kablova sa bilo kojim odnosom strela-raspon, koristeći pri tome veoma malo takvih konačnih elemenata. Nelinearna statička analiza je prikazana u vidu inkrementalne korigovane Lagrange-ove formulacije, a za rešavanje dobijenih jednačina ravnoteže u statičkoj analizi koristi se modifikovani Newton Raphson-ov iterativni postupak.

Numerički model konačnih elemenata za prikazivanje i analizu samostalnih kablova, ali i konstrukcija sa kablovima uopšte, dakle konstrukcija kod kojih su kablovi samo deo sistema, kao i postupak za rešavanje nelinearnih jednačina ravnoteže, ugrađeni su u razvijeni računarski program ELAN, [4]. Program ELAN može da se koristi za linearnu i nelinearnu analizu konstrukcija sa kablovima usled statičkog, ali i dinamičkog opterećenja. Ovde je prikazana samo statička analiza kablova.

Verifikacija programa je urađena preko više prikazanih numeričkih primera u kojima su analizirana pomeranja i horizontalne sile u kablovima opterećenih sopstvenom težinom, dodatnim jednakopodeljenim opterećenjem i koncentrisanim silama. Dobijene vrednosti pomeranja i horizontalnih sila primenom programa ELAN se veoma dobro slažu sa teorijskim vrednostima na bazi analitičkih relacija, kao i na vrednostima iz literature.

Napomena:
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7 CONCLUSION

The paper is presented static analysis of the catenary, first the analytical approaches based upon hyperbolic and parabolic relations for unextensible and also elastic catenary, and then the numerical approach based upon the finite element method. Numerical model of the cable structures using the finite elements based upon the hyperbolic expressions for the catenary, as presented in this work, may be used in the non-linear cable analysis with any sag-span ratio, using very small number of such catenary finite elements. The non-linear static analysis is presented in the form of the incremental updated Lagrangian formulation and the solution of obtained equations of equilibrium is performed by the modified Newton-Raphson iterative procedure.

Numerical model of the finite elements convenient for numerical presentation and analysis of isolated cables, but also for the cable supported structures in general, that is for structures where cables are part of the whole system, as well as the procedures to solve the non-linear equilibrium equations are implemented in developed computer code ELAN [4]. The code ELAN might be used for the linear and non-linear analysis of the cable supported structures, due to the static and dynamic loading. In this paper only the static analysis is presented.

Verification of the computer code is done through the several numerical examples in which displacements and horizontal tension forces of cables loaded by self-weight, additional distributed loading and concentrated forces were analysed. Obtained values of displacements and horizontal cable forces obtained by the code ELAN are in a very good agreement with theoretical values based upon analytical solutions and the values obtained from the literature.

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REZIME

STATIČKA ANALIZA KABLOVA

Špiro GOPČEVIĆ
Stanko BRČIĆ
Ljiljana ŽUGIĆ

Kablovi, kao konstruktivni elementi, upotrebljavaju se u mnogim oblastima inženjerstva i predstavljaju vitalni noseći deo raznih konstrukcija. Posle kraćeg prikaza analitičke analize lančanice, zasnovane na hiperboličnim, ali i paraboličnim relacijama, u radu je prikazana formulacija konačnih elemenata, upotrebljena za modeliranje kablova, a koja je izvedena upotrebom analitičkih izraza za nerastegljivu, kao i za elastičnu hiperboličku lančanicu. U radu je prikazana statička analiza kabla preko numeričke analize pomeranja i unutrašnjih sila u kablu opterećenog jednakopodeljenim opterećenjem i koncentrisanim silama. U postupku rešavanja inkrementalnih jednačina ravnoteže korišćen je metod kontrole sile i modifikovani Newton-Raphson-ov metod. U cilju numeričke realizacije ovoga problema, razvijen je odgovarajući kompjuterski program ELAN, koji omogućava linearnu i nelinearnu analizu konstrukcija sa kablovima, usled dejstva statičkogi dinamičkog opterećenja i pomoću kojega je sprovedena analiza. Vrednosti dobijene programom ELAN upoređivane su sa teorijskim vrednostima dobijenim analitičkim pristupom i vrednostima iz literature. U svim razmatranim primerima dobijeni rezultati se dobro međusobno slažu.

Ključne reči: nelinearna analiza, statička analiza, lančanica, kabl, numerička analiza

SUMMARY

STATIC CABLE ANALYSIS

Špiro GOPČEVIĆ
Stanko BRČIĆ
Ljiljana ŽUGIĆ

The cables, as structural elements, are used in many fields of engineering and represent the vital support to various structures. After the short overview of the analytical analysis of the catenary, based upon hyperbolic, but also the parabolic relations, the paper presents the finite element formulation, used for modeling of cables, derived from the analytical expressions for inextensible, as well as for the elastic hyperbolic catenary. Static analysis of cables based upon the numerical analysis of displacements and internal forces in the cable loaded by the uniformly distributed loading and concentrated forces is presented in the paper. Incremental equations of equilibrium are solved by using the force control and the modified Newton-Raphson method. In order to implement the numerical method, the corresponding computer code ELAN is developed, which enables the linear and non-linear analysis of cable supported structures due to the static and dynamic loading. Numerical analysis is preformed using the ELAN code. The results obtained by ELAN are compared with theoretical values obtained by analytical approach and with the values obtained in the literature. In all considered examples the results are in a good agreement.

Key words: nonlinear analysis, static analysis, catenary element, cable, numeric analysis

UTICAJ PUTNIH PROJEKATA NA ŽIVOTNU SREDINU TOKOM ŽIVOTNOG CIKLUSA I INSTITUCIONALIZACIJA UPRAVLJAČKOG OKVIRA

IMPACT OF ROAD PROJECTS ON ENVIRONMENT DURING THE LIFE CYCLE AND INSTITUTIONALIZATION OF A MANAGEMENT FRAMEWORK

Igor JOKANOVIĆ

PREGLEDNI RAD
UDK: 502/504:625.7/.8 = 861

1 UVOD

Putna infrastruktura predstavlja osnovu za formiranje planskog razvoja aktivnosti, odnosno planiranje prostora, bilo da se radi o problemu koji se pojavljuje na relativno malim područjima kao što su naselja i gradovi, ili na kompleksnoj teritoriji regiona ili država.

Putevi su, generalno, namenjeni, i često donose, značajne ekonomske i društvene koristi. Povećanje kapaciteta puta i poboljšano stanje kolovoza mogu skratiti vreme putovanja i smanjiti troškove korišćenja vozila, povećavajući sa druge strane pristup tržištima, poslovima, obrazovanju i zdravstvenim uslugama, a smanjujući troškove prevoza putnika i roba.

Pored svih pozitivnih aspekata koje donose, putni projekti takođe mogu imati i značajan negativan uticaj na lokalne zajednice i prirodnu okolinu (Slika 1). Ljudi i njihova imovina se mogu naći na direktnom koridoru u kome se izvode radovi i biti njima pogođeni u značajnoj meri. Ljudi, takođe, mogu biti indirektno pogođeni realizacijom projekata, kroz poremećaje u životnom okruženju, kroz gubitak uobičajenih putanja kretanja i veza u okviru lokalne zajednice, kroz povećanje respiratornih problema zbog zagađenosti vazduha ili povećanje broja povreda usled saobraćajnih udesa. Narušavanje prirodnog okruženja može obuhvatiti eroziju tla, promene tokova reka i podzemnih voda i ugrožavanje životinjskog i biljnog sveta.

Putevi dovode ljude, a ljudi iniciraju ili podstiču razvoj. Novi putevi mogu podstaći razvoj u prethodno nerazvijenim oblastima, ponekad značajno utičući na osetljiva okruženja i način života lokalnog stanovništva.

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1 INTRODUCTION

Road infrastructure represents the basis for forming a planned development of activities, meaning spatial planning, whether it involves a problem which emerges in relatively small areas such as settlements or towns, or within a complex territory of a region or country.

Roads are generally intended and often bring significant economic and social benefits. Increased road capacity and improved pavements can reduce travel times and lower costs of vehicle utilization, while, on the other hand, they increase access to markets, business centers, education and health services and thus, decrease transport costs for both freight and passengers.

Aside from all the positive aspects, road projects can also have a significant adverse impact on local communities and natural environment (Fig. 1). People and their property can be situated in the direct vicinity of construction works and thus, be significantly affected by them. People can also be indirectly affected by the realization of a project through disturbances in the environment, loss of normal paths of movement and connections within the local community, increased respiratory problems due to air pollution or an increased number of injuries as a result of traffic accidents. Disturbance of natural environment can encompass erosion of soil, changes in the flow of rivers and ground waters and endanger animal and plant life.

Roads gather people and people initiate or stimulate development. New roads can stimulate development in previously undeveloped areas, sometimes significantly

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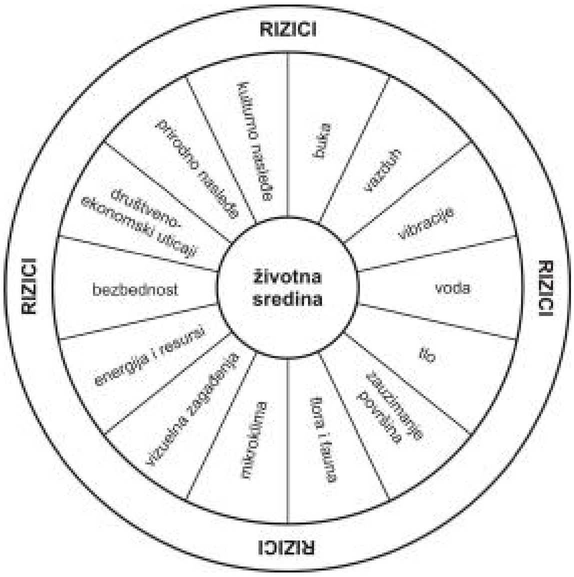
Putevi su pokretači promena i mogu biti odgovorni kako za koristi, tako i za štete u postojećoj ravnoteži između ljudi i okruženja u kome žive.

affecting the sensitive environment and the way of life of local population. Roads are initiators of changes and can be responsible for both benefiting and harming the existing balance between people and the environment in which they live.



Slika 1. Uticaji putnih projekata na životnu sredinu
Fig. 1. Environmental impacts of road projects

Kako postajemo svesniji ovih uticaja, rastu i zahtevi za tehnikama i veštinama potrebnim da se prilikom planiranja, projektovanja, izgradnje i eksploatacije puteva uzmu u obzir razmatranja u vezi zaštite životne sredine.

Dosta toga se može učiniti da bi se izbegli, ublažili ili kompenzovali negativni efekti putnih projekata na životnu sredinu, ali je izuzetno važno da se potencijalni uticaji identifikuju u ranim fazama planiranja i da se preduzmu mere za izbegavanje ili ublažavanje ovih efekata, gde god je to moguće. Ukoliko se na vreme ne uoče potencijalni negativni uticaji, to može dovesti do kašnjenja i povećanja troškova u kasnijim fazama razvoja projekta. Zanemarivanje uticaja može takođe prouzrokovati da upravljač saobraćajne infrastrukture usvoji rešenja koja ugrožavaju životnu sredinu.

Cilj rada je da se, uvažavajući osnovne faze životnog ciklusa puta, odnosno putne mreže (od početnih zamisli, preko izgradnje, do rehabilitacije/obnove), ukaže na glavne elemente analize uticaja na životnu sredinu, u smislu najbolje prakse, te analiziraju i prikažu mogućnosti za uspostavljanje sistema za upravljanja uticajima na životnu sredinu kroz preporuke međunarodnih standarda upravljanja uticajima.

2 ŽIVOTNI CIKLUS PROJEKTA

U našem okruženju, termin „projekat" je tradicionalno prihvaćen kao imenica koja označava projektnu dokumentaciju sastavljenu od različitih komponenti. Tek od nedavno, za ovo se koristi pojam „projektna dokumentacija", prvenstveno da bi se napravila razlika između koncepta koji predstavlja sveukupne aktivnosti

As we are becoming more aware of these effects, there is a growing requirement for introducing techniques and skills which are indispensible for environmental protection, and thus, should be taken into consideration when planning, designing, constructing and exploiting roads.

Much can be done to avoid, mitigate or compensate for the adverse effects of road projects on the environment, but it is particularly important to identify potential impacts in early phases of planning and take measures to avoid or mitigate these effects wherever possible. If potential adverse impacts are not detected on time, it could lead to delays and increased costs in subsequent project development phases. Ignoring the impacts could also cause the transportation infrastructure manager to adopt solutions which threaten the environment.

The objective of this paper is to specify the main elements of the environmental impact assessment, in the sense of best practice, and analyze and present possibilities of establishing an environmental management system through the recommendations of international environmental management standards while considering the basic phases of the road life cycle, or road network (from initial concepts, through construction, to rehabilitation/ reconstruction).

2 PROJECT LIFE CYCLE

In our surrounding, the term „project" is traditionally accepted as a noun which describes design documentation composed of various components. Only recently has the term „design documentation" has been used primarily to primarily to differentiate between the concept na realizaciji rešenja radi postizanja određenog cilja u ograničenom vremenskom okviru, od koncepta projektne dokumentacije koji predstavlja samo deo velikog skupa aktivnosti. Istovremeno, veoma je važan uticaj iz stranih jezika u kojima „projekat“ ima šire značenje od onog koje ima u našem jeziku. U drugim jezicima taj termin predstavlja širi skup aktivnosti organizovanih da reše određene potrebe ili, kako je definisano u „Larousse“ enciklopediji: „projekat je nešto što nameravamo da izgradimo ili napravimo“.

Životni ciklus projekta se može opisati kao skup različitih aktivnosti koje se odvijaju u fazama ili koracima, kroz koje projekat ili plan mora da prođe. Tipičan životni ciklus projekta se sastoji iz serije faza od iskopa prirodnih materijala, kroz projektovanje i osmišljavanje, obradu, proizvodnju ili izgradnju, pakovanje, distribuciju, do korišćenja, održavanja, ponovnog korišćenja, recikliranja, rekonstrukcije i, na kraju, rastavljanja ili uklanjanja i odlaganja otpada.

Analiza životnog ciklusa se koristi kao sredstvo za planiranje, analizu, procenu i poboljšanje procesa i aktivnosti koje se izvode za vreme postojanja projekta. Može se reći da je to sredstvo koje se koristi od strane raznih specijalista ili stručnjaka za upravljanje celim projektom, od ideje do uklanjanja, a ne samo u određenim fazama razvoja i realizacije projekta [1, 6, 13]. Ovaj proces je moguće ugraditi u većinu oblasti i disciplina ljudskih aktivnosti, samo se predmet i obim problema razlikuju.

2.1 Analiza životnog ciklusa

Procena životnog ciklusa (Life Cycle Assessment-LCA) uključuje procenu određenih aspekata, često aspekata uticaja projekta na životnu sredinu kroz sve faze njegovog životnog ciklusa. Ponekad se, takođe, naziva „analiza životnog ciklusa”, „analiza od nastanka do ukidanja/uklanjanja” ili „ekobalans” i predstavlja naglo rastuću porodicu sredstava i tehnika osmišljenih da pomognu u upravljanju uticajima na životnu sredinu i, dugoročno, u osiguranju održivog razvoja [13].

Među novijim konceptima u LCA procesu se ističe “upravljanje životnim ciklusom” (Life Cycle Management-LCM), koje predstavlja integrisan pristup minimiziranju ekoloških uticaja kroz životni ciklus projekta, sistema, usluga ili proizvoda.

Kompletna LCA studija bi, uobičajeno, zahtevala veliku količinu podataka i rezultat bi bio utrošak velike količine vremena i novca. U ekstremnim slučajevima, takva studija bi mogla trajati nekoliko godina i koštala bi milione evra. Puna LCA studija daje najbolju osnovu za donošenje odluka, ali su one često relevantne samo za značajne projekte velikog obima i za proizvode koji se prodaju u velikim količinama, koji se ne menjaju tako često.

LCA je sredstvo koje pomaže pri donošenju odluka. Ako se koristi na pravi način, može pomoći da odluke koje se naprave budu zasnovane na zaštiti i unapređenju životne sredine, bilo tokom razrade, pri proizvodnji ili eksploataciji projekta ili sistema.

Na globalnom nivou, već nekoliko godina, se dosta očekuje od LCA. Na evropskom nivou, Parlament je sugerisao da Komisija razvije okvir za integrisanu politiku orijentisanu prema životnom ciklusu [13].

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which represents all activities in the realization of a solution to achieve a certain goal within a limited time-frame and the concept of design documentation which represents only a part of the large set of activities. At the same time, there is a very important influence from foreign languages in which „project” has a wider meaning from that in our language. In other languages that term represents a wider set of activities organized to solve certain needs or, as defined in the „Larousse” encyclopedia: „a project is something which we intend to build or create”.

The life cycle of a project may be described as the set of various activities taking place in phases or steps, which the project or plan should go through. The typical life cycle of a project consists of a series of phases from excavation of natural materials, through planning and formulation, processing, manufacturing or construction, packaging, distribution, use, maintainance, re-use, recycling, reconstruction and, at the end, dismantling or commissioning and waste disposal.

The life cycle analysis is used as mean for planning, analysis, evaluation and improvement of processes and activities which take place during the project. It can be said that it is a resource which is used by various specialists or experts to manage the entire project, from idea to removal, and not only in certain phases of development and realization of the project [1, 6, 13]. This process can be implemented in a majority of fields and disciplines of human activity; only the subject and scope of the problem are different.

2.1 Life cycle assessment

The Life Cycle Assessment (LCA) includes evaluation of certain aspects, often the aspects of environmental effects of the project through all phases of its life cycle. Sometimes, the life cycle assessment is also referred to as the „life cycle approach”, „cradle to grave analysis” or „ecobalance” and represents a rapidly growing family of resources and techniques devised to help in the management of environmental effects and, over the long term, ensure sustainable development [13].

Life cycle management (LCM) is one of the recent concepts within the LCA process, and represents an integrated approach to minimizing ecological impacts throughout the life cycle of a project, system, service or product.

A complete LCA study would normally require a great deal of data and the result would be expenditure of large quantities of time and money. In extreme cases, such a study could last several years and cost millions of euros. A full LCA study provides the best basis for decision making, but they are often relevant only for significant projects of a large scope and products which are sold in large quantities, and are not often replaced.

The LCA is a resource which helps when making decisions. If it is used properly, it can help to make decisions based on protection and improvement of the environment while designing, manufacturing or operating a project or system.

On the global level, much has been expected of the LCA for several years now. On the European level, the Parliament suggested that the Commission develops a framework for integrated policy oriented towards the life cycle [13].

projekata, proizvoda i materijala treba da bude zasnovana na konceptu procene životnog ciklusa. Poslovni i industrijski sektori su svesni zahteva korisnika i prepoznaju mogućnosti LCA u očuvanju prirodnih resursa i energije, kao i u minimiziranju zagađenja i otpada.

2.2 Životni ciklus puta

Procesi i aktivnosti koje se odvijaju za vreme trajanja životnog ciklusa puta se grupišu u šest faza (Slika 2). Ova raspodela je zasnovana na komponentama upravljačkog ciklusa u oblasti puteva, kao i na činjenici da su saobraćajnice trajno javno vlasništvo/dobro sa funkcijom koja se ne menja kroz vreme. Umesto toga, izvode se unapređenja i rehabilitacije konstrukcije da bi se unapredio ili zadržao nivo usluge koji se nudi korisnicima. Svaka faza se može i mora deliti u ulazne elemente, procese, rezultate, ključne aktivnosti, itd. Ove faze se mogu preklapati u određenoj meri, ali nije dozvoljeno preskakanje bilo koje od njih.

Sa inženjerskog aspekta, razvoj projekta, uopšteno, prati dobro definisan proces koji obuhvata planiranje, generalni, idejni i glavni projekat sa prethodnom studijom opravdanosti i studijom opravdanosti, zatim finansiranje, nabavke i izgradnju.

Ove aktivnosti su praćene eksploatacijom i održavanjem završenog projekta, a krug se završava sa rekonstrukcijom ili rehabilitacijom, koje su ustvari početak novog životnog ciklusa. U zavisnosti od prirode projekta, konsultacije sa različitim vladinim agencijama, zainteresovanim stranama, javnošću ili sa svim tim stranama, mogu biti komponenta od najvećeg značaja tokom nekoliko ranih faza procesa.

The design and production-construction of new projects, products and materials should be based on the concept of the life cycle assessment. Business and industrial sectors are aware of the needs of the user and recognize the possibilities of the LCA in protecting natural resources and energy, as well as in minimizing pollution and waste.

2.2 Road life cycle

Processes and activities which take place during the road life cycle are grouped into six phases (Fig. 2). This division is based on the components of the management cycle in the field of roads, as well as on the fact that roads are permanent public property with a function which does not change over time. Instead, improvements and rehabilitation of the structure are carried out in order to improve or maintain the level of service provided to the user. Each phase can and should be divided into input elements, processes, results, key activities, etc. These phases can overlap to a certain measure, but none of them may jump in front of another.

From an engineering aspect, project development generally follows a well-defined process which encompasses planning, conceptual, preliminary and detail design, with prefeasibility and feasibility study, then financing, procurement and construction.

These activities are followed by operation and maintenance of the completed project, and the circle is completed with reconstruction or rehabilitation, which in fact are the beginning of a new life cycle. Depending on the nature of the project, consultations with various government agencies, stakeholders, public, or with all the parties together can be the most significant component during the several early phases of the process.

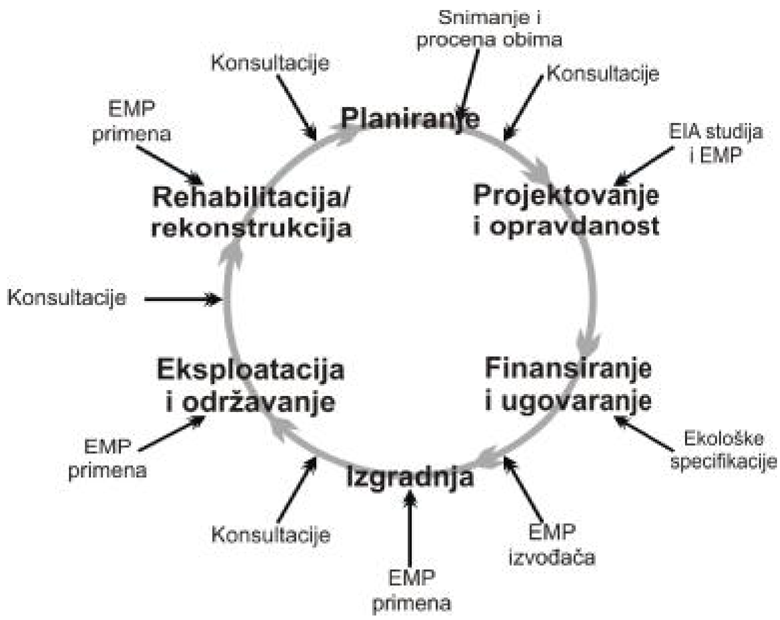
Slika 2. Faze životnog ciklusa puta
Fig. 2. Road life cycle phases

3 PROCENA UTICAJA NA ŽIVOTNU SREDINU U ŽIVOTNOM CIKLUSU PUTA

Proces procene uticaja na životnu sredinu (Environmental Impact Assessment-EIA) pomaže u utvrđivanju kako će projekat u budućnosti uticati na životnu sredinu, kako za vreme izgradnje, tako i tokom eksploatacije, itd. To treba da bude sistematski proces. Rezultat EIA studije pomaže donosiocu odluka i javnom mnjenju da odrede da li projekat treba provesti i u kom obliku. EIA ne donosi odluke, ali je važno pomoćno sredstvo za one koji ih donose [15, 16]. EIA ustvari predstavlja određenu vrstu sistema ranog upozoravanja, sa ciljem da uravnoteži interese zaštite životne sredine unutar šire slike problema razvoja. Primarni cilj EIA, uz prateći plan upravljanja aktivnostima (Environmental Management Plan-EMP), je da osigura da se predvide potencijalni problemi i da se na njih obrati pažnja u ranim fazama planiranja i razrade projekta. EIA treba da bude integralni deo životnog ciklusa od faze pokretanja projekta (Slika 3).

3 ENVIRONMENTAL IMPACT ASSESSMENT WITHIN THE ROAD LIFE CYCLE

The process of assessing the environmental impacts (EIA) helps in determining how a project will impact the environment in the future, both during construction and operation, etc. This should be a systematic process. The result of the EIA study helps decision makers and public opinion to determine whether the project should be carried out and in what form. The EIA does not make decisions, but it is an important resource of support for those who do make them [15, 16]. The EIA in fact represents a certain type of early warning system, with the aim of balancing the interests of environmental protection within the wider picture of the developmental problem. The primary objective of the EIA, along with the corresponding environmental management plan (EMP), is to ensure that potential problems are anticipated and that attention is given to them in the early phases of planning and drafting the project. The EIA should be an integral component of the life cycle from the phase of project initiation (Fig. 3).



Slika 3. Sinhronizacija procene uticaja na životnu sredinu i životnog ciklusa puta
Fig. 3. Synchronization of the environmental impact assessment and road life cycle

Dobro planiran EIA proces razlikuje dve ključne faze [2, 15]. Prva faza je u početnom periodu planiranja, kada se identifikuju opšti uticaji na životnu sredinu, od alternativnih rešenja do problema putnog transporta, nakon čega se oni porede, što dovodi do izbora projekta koji je prihvatljiv sa aspekta zaštite životne sredine. Druga faza je na nivou izrade projektne dokumentacije, kada se bira optimalan i željeni izgled projekta u smislu osovine, podužnog nagiba, tipa kolovoza, vrste odvodnjavanja, načina eksploatacije, itd. Upravo se ova druga faza vezuje za EIA. Snimanje i procena obima su dve ključne aktivnosti na početku dobro planiranog EIA procesa.

Faza ranog planiranja se često zanemaruje u procesu razvoja puta, jer je ona obično odgovornost ljudi

A well-planned EIA process differentiates between two key phases [2, 15]. The first phase is in the initial period of planning, when the general impacts on the environment are identified, starting from alternative solutions to the problems of road transportation and their comparison. This leads to the selection of a project which is acceptable from the aspect of environmental protection. The second phase is at the level of drafting project documentation when the optimum and desired design of the project is selected in the sense of axis, grade, pavement type, type of drainage, method of operation, etc. This second phase is actually connected to the EIA. Screening and scoping are two key activities at the beginning of a well-planned EIA process.

The early planning phase is often ignored within the koji ne provode EIA ili se smatra nebitnom na sveukupan EIA proces. Međutim, ovo je značajan faktor koji dovodi do najvećih problema u izvođenju projekta i do skupih kašnjenja u kasnijim fazama. U pravilno projektovanom EIA procesu, faza ranog planiranja je integrisana u procenu osnovnih uslova i karakteristika projekta

Faza snimanja se odnosi na rano utvrđivanje potencijalne veličine uticaja i, usled toga, obima studije koja treba da se provede. Ovo treba da bude prva faza u kojoj se uključuju razmatranja uticaja na životnu sredinu u novim projektima puteva. Procena obima studije je proces koji se koristi za definisanje šta se može, a šta se ne može postići za vreme konkretne procene uticaja na životnu sredinu.

Tek nakon završetka ovih planskih zadataka, upravljači putevima i planeri mogu opravdano da kažu da razumeju predložen projekat u kontekstu okruženja i u odnosu na druga inženjerska rešenja. Preskakanje navedenih ranih faza planiranja često vodi ka skupim komplikacijama i kašnjenjima koja se kasnije pojavljuju tokom projekta ili u toku razvoja programa.

Pretpostavljajući da su faze snimanja i procena obima završene i da je utvrđena potreba za izradom kompletne EIA studije, sledeći korak je da se pripremi i provede procena uticaja na životnu sredinu. Koraci koje je obično potrebno preduzeti da bi se dostigli ciljevi EIA su: sakupljanje i opis postojećeg stanja, identifikacija i analiza potencijalnih uticaja na životnu sredinu, razmatranje alternativnih rešenja, razvoj mera za ublažavanje i kompenzaciju uticaja, izrada planova ublaženja/sprečavanja i praćenja stanja (EMP) i rezimea studije (Environmental Impact Statement-EIS).

U slučaju da faze snimanja i procene obima ne utvrde potrebu za punom EIA studijom, dovoljno je nastaviti samo sa razvojem EMP.

EMP je verovatno najvažniji rezultat EIA procesa. EMP predstavlja sintezu svih predloženih mera ublažavanja/sprečavanja uticaja i praćenja stanja u određenom vremenskom roku, sa dodeljenim specifičnim odgovornostima i definisanim pratećim akcijama koje treba preduzeti nakon izvođenja projekta. Dobro osmišljen EMP rešava probleme koji se odnose na faze građenja i eksploatacije projekta.

EIS je najosetljiviji rezultat EIA procesa. Njegova funkcija je da donosiocima odluka obezbedi odgovarajuće informacije u vezi potencijalnih problema, uticaja i mogućnosti za njihovo sprečavanje i ublažavanje ili opcija za popravljanje šteta po životnu sredinu za konkretan putni projekat ili program. Ovaj dokument u kasnijim fazama mora biti dopunjen izveštajima iz perioda izvođenja radova i eksploatacije, koji opisuju kako se mere za ublažavanje uticaja na životnu sredinu primenjuju i koliko su efikasne.

Uobičajena situacija podrazumeva izradu kompletne EIA studije u slučajevima novih projekata saobraćajne infrastrukture i značajnih nadogradnji ili rekonstrukcija, dok je u slučajevima aktivnosti održavanja i rehabilitacije, pa čak u određenim slučajevima i rekonstrukcije, dovoljno pripremiti EMP [5, 15]. Tu se upravo ogleda i temeljna razlika u ova dva koraka životnog ciklusa. Prilikom planiranja i projektovanja novogradnje, akcenat je na analizi svih aspekata uticaja na životnu sredinu usled izgradnje puta i njegove eksploatacije, pa i uz mogućnost izbegavanja istih. U drugom slučaju, kod eksploatacije i održavanja

process of road development because it is usually the responsibility of those who do not conduct the EIA or it is considered insignificant to the comprehensive EIA process. However, this is a significant factor which leads to the greatest problems when carrying out the project, and also to expensive delays in subsequent phases. In a properly designed EIA process, the phase of early planning is integrated into the assessment of basic conditions and characteristics of the project.

The screening phase relates to the early recognition of the potential extent of impacts, and therefore, the scope of the study which must be carried out. This should be the first phase in which the environmental impacts should be taken into consideration within new road projects. The assessment of the scope of the study is a process which is used to define what can and cannot be achieved during the concrete environmental impact assessment.

Only after the completion of these planning tasks the road managers and planners can rationally state that they understand the proposed project in the context of the environment and in relation to other engineering solutions. Skipping the aforementioned early planning phases often leads to expensive complications and delays which emerge later during the project or during development of a program.

Assuming that the screening and scoping phases have been completed and that the need for carrying out a complete EIA study has been established, the next step is to prepare and conduct the environmental impact assessment. The steps which are normally necessary to take to achieve the objectives of the EIA are: collection and description of baseline condition, identification and analysis of potential environmental impacts, consideration of alternative solutions, development of measures for mitigating and compensating for environmental impacts, drafting plans for environmental mitigation/prevention and monitoring (EMP) and a summary of the study (Environmental Impact Statement-EIS).

In the event when the screening and scoping do not indicate the need for a full EIA study, it is sufficient to continue with the development of an EMP.

The EMP is likely the most important result of the EIA process. The EMP represents a synthesis of all proposed measures for mitigating/preventing environmental effects and monitoring during a specific time period, with assigned specific responsibilities and defined follow-up actions which should be taken after the project has been carried out. A well thought out EMP resolves the problems which relate to the phase of construction and operation of the project.

The EIS is the most tangible result of the EIA process. Its function is to provide decision makers with the appropriate information related to potential problems and effects, as well as possibilities for preventing or mitigating them, or options for repairing the damage to the environment for a particular road project or program. This document must be supplemented in the later phases with reports from the period of construction works and operation which describe how the measures for mitigating environments impacts are applied and how effective they are.

A standard situation entails the drafting of a complete EIA study in the case of new transportation infrastructure projects and significant upgrades or reconstruction postojeće putne mreže, fokus se pomera ka analizi postupaka održavanja sa ciljem da se umanje njihovi štetni uticaji, smanji potrošnja prirodnih resura i sl, pri čemu je veoma teško, skoro nemoguće, izbeći uticaje koji se pojavljuju od saobraćaja na putevima.

Tokom faza finansiranja i nabavke, u okviru životnog ciklusa puta, neophodno je pripremiti specifikacije, odnosno tehničke uslove, u skladu sa preporukama definisanim tokom razmatranja uticaja na životnu sredinu.

Kroz sve faze životnog ciklusa, korisno je učešće javnosti u prikupljanju podataka o životnoj sredini, u cilju identifikacije i razumevanja mogućih uticaja, utvrđivanja individualnih i interesa zajednice, na osnovu kojih se mogu izabrati projektne varijante i razviti isplativi i održivi planovi ublažavanja i kompenzacije tih uticaja [14, 15]. Nedovoljna uključenost javnosti može dovesti do nedostatka značajnih informacija i nepouzdanih zaključaka, što bi planere, koji provode EIA, odvelo u sasvim pogrešnom pravcu. Zanemarivanje procesa javnih konsultacija i komunikacija može proizvesti otpor pojedinaca, zajednice ili regije prema projektu izgradnje saobraćajnica. To, na kraju, može postati uzrok značajnih kašnjenja, povećanih troškova i nezadovoljavajućih kompromisnih rešenja, koja su mogla biti izbegnuta kroz ranije provedene javne konsultacije.

3.1 Problemi

Uobičajena je praksa da finansijske i regulatorne organizacije zahtevaju da se EIA provodi od strane konsultanata koji ne zavise od pokretača projekta ili regulatornog tela. Svrha toga je da se izbegne mogućnost pojave sukoba interesa između ekoloških i društveno-političkih aspekata, kao i ekonomskih aspekata projekta.

Međutim, ovo često dovodi do toga da se EIA provodi od strane nezavisnih timova koji rade u izolaciji od timova koji su zaduženi za planiranje i izradu projektne dokumentacije i za studije opravdanosti projekta. To može dovesti do činjenica da EIA postane ograničen, samostalan izveštaj.

Zakonodavci obično u svojim procedurama jasno navode pravne i administrativne zahteve EIA studija, ostavljajući mali prostor za kreativnost. To dovodi do realne činjenice da EIA postaje samo zakonska obaveza, koja se provodi kao aktivnost nezavisna od projektnog ciklusa. Ovo, opet, često dovodi do generisanja posebnog izveštaja za zakonodavce sa specifičnim formatom i sadržajem, koji se ne koristi od strane planera i projektanata uključenih u projekat.

Iz tog razloga se EIA od strane profesionalaca koji

works, while in the case of maintenance and rehabilitation, and even in certain cases of reconstruction, preparing an EMP is sufficient [5, 15]. This essentially reflects the fundamental difference between these two steps in the life cycle. During the planning and designing of new roads, the accent is on the analysis of all aspects of environmental impacts as a result of the construction of the road and its operation, and with the possibility of avoiding the same. In the second case, i.e. operation and maintenance of an existing road network, the focus is shifted to the analysis of maintenance procedures with the objective to reduce their harmful effects and decrease consumption of natural resources which is difficult, and almost impossible to avoid the effects which occur as a result of traffic.

During the phase of financing and procurement, within the framework of the road life cycle, it is necessary to prepare specifications, meaning technical conditions, in accordance with recommendations defined during consideration of environmental impacts.

Throughout all phases of the life cycle, it is beneficial to have the participation of public in collecting data on the environment for the purpose of identifying and understanding the possible impacts, determining individuals' interests and determining the interests of the community, on the basis of which a project variant can be selected and fiscally sound and sustainable plans can be developed for mitigating and compensating those impacts [14, 15]. Insufficient inclusion of public can lead to the lack of important information and unreliable conclusions, which would lead the planners who carry out the EIA in the completely wrong direction. Neglecting the process of public consultations and communication can produce resistance of individuals, the community or a region towards a project for constructing a traffic infrastructure. This, in the end, can become a cause for significant delays, increased expenses and unsatisfactory compromises which could have been avoided through previously conducted public consultations.

3.1 Problems

The standard practice of financial and regulatory organizations is to require the EIA to be conducted by a consultant that is independent from the project initiator or regulatory body. It is due to avoid possible conflicts of interest which can emerge between ecological and socio-political aspects, as well as the economic aspects of the project.

However, this often leads to the EIA being conducted by an independent team that works in isolation from the teams responsible for planning and drafting the project documentation and for the project feasibility study. This can lead to the situation when EIA has become a limited independent report.

Legislators normally state the legal and administrative requirements of the EIA study clearly within their procedures, leaving little room for creativity. This leads to the realistic fact that the EIA becomes only a legal obligation which is conducted as an activity independent from the project cycle. This, again, often leads to a special report being generated for legislators with a specific format and content, which is not used by the planners and designers included in the project.

Therefore, the EIA generally fails to be recognized as planiraju i razrađuju projekte, uopšteno, ne doživljava kao važno ili sredstvo koje doprinosi donošenju odluka prilikom razmatranja alternativa ili koje može uticati na važne odluke druge prirode.

Projekti se obično razvijaju u serijama iteracija, gde se sukcesivne ideje kontinualno testiraju/preispituju u odnosu na prednosti i nedostatke. Ovo se posebno odnosi na faze pre izgradnje. Planiranje i razrada projekta zahtevaju dosta fleksibilnosti. Iz tog razloga je zakonodavcima veoma teško da propišu standardnu formulu u kojim fazama EIA treba da bude u interakciji sa planiranjem i razradom projekta.

Dinamika faza planiranja i projektovanja takođe objašnjava zašto je tako važno integrisati EIA proces u ove faze. U tim fazama je moguće predložiti širok spektar opcija za prevenciju, smanjenje, poboljšanje ili kompenzaciju različitih negativnih uticaja. Ovo treba razjasniti EIA timu i profesionalcima koji rade na planiranju i projektovanju i tome treba dodeliti visok prioritet u ranim planerskim fazama projektnog ciklusa.

Jedan od zahteva EIA procesa je da bude otvoren svim zainteresovanim i „pogođenim“ stranama. Različite grupe koje su uključene u projekat imaju i različite interese i na različite načine doživljavaju značajna pitanja u vezi projekta. Usled toga je neophodna efikasna koordinacija i komunikacija između onih koji podržavaju projekat, vladinih institucija, privatnog sektora i lokalnih zajednica. Ovo može biti uzrok značajnih kašnjenja i frustracija projektanata i planera, npr. inženjera, arhitekata i dr.

Inženjeri koji rade na projektu obično imaju kratke rokove za realizaciju svojih zadataka. Kašnjenja mogu dovesti do toga da osnovni inženjerski radovi počinju pre završetka pripremne faze EIA studije. Usled toga, projektni tim rizikuje da specifični postupci koji se koriste za osnovne inženjerske radove, kao i kasnije za izgradnju, ne budu prihvatljivi za vladine institucije.

Jedan od izazova koji se nameće ispred planera i projektanata je ograničena količina informacija o društvenim aspektima i životnoj sredini koje su dostupne u regionu. To može dovesti do poteškoća u adekvatnoj integraciji EIA u planiranju i razvoju projekta, zbog kašnjenja u prikupljanju relevantnih informacija.

Druga bitna oblast koja izaziva određenu dozu zabrinutosti je činjenica da su regulatorna tela u regionu obično neefikasna i nedovoljno kvalifikovana da izvršavaju faze odobravanja EIA studija. Ovo često dovodi do kašnjenja celog EIA procesa. Profesionalci koji planiraju izvršenje projekta često rade u okviru kratkih rokova i rasporeda, te zbog gore navedenih razloga kašnjenja, rezultate EIA procesa uglavnom i ne doživljavaju kao značajne za realizaciju.

4 INSTITUCIONALIZACIJA UPRAVLJAČKOG OKVIRA

Upravljanje uticajima na životnu sredine predstavlja strategiju putem koje se ljudske aktivnosti koje utiču, ili mogu imati uticaja na životnu sredinu, organizuju u cilju maksimiziranja društvene dobiti, kao i radi sprečavanja

something important or a resource which contributes to decision-making when considering alternatives or which can influence important decisions of any other nature by the professionals who plan and develop the project.

Projects are normally developed in series of iterations where successive ideas are continuously tested/examined in relation to their advantages and disadvantages. This especially relates to the phases prior to construction. The planning and development of a project requires a great deal of flexibility. Therefore, it is very difficult for legislators to prescribe a standard formula and state the phases when EIA should interact with the planning and development of a project.

The dynamic of the planning and designing phases also explains why it is so important to integrate the EIA into the process. In these phases it is possible to propose a wide range of options for prevention, reduction, improvement or compensation of various adverse impacts. This should be explained to the EIA team and professionals who work on planning and design and a high priority should be given to this in the early planning phases of the project cycle.

One of the requirements of the EIA process is to be open to all stakeholders and affected parties. The various groups which are included into the project also have various interests and experience the significant issues related to the project in different ways. Therefore, it is necessary to have effective coordination and communication between those who support the project, government institutions, private sector and local communities. This can be a cause for significant delays and frustration for the designers and planners, e.g. engineers, architects, etc.

Engineers working on the project normally have tight deadlines for realization of their tasks. Delays can lead to the basic engineering works beginning before completion of the preparatory phase of the EIA study. As a result of this, the project team runs the risk of rejection of specific procedures which they use for basic engineering works, as well as later during construction by the government institutions.

One of the challenges which arise for planners and designers is a limited amount of information about social aspects and environment which is available within the region. This leads to difficulties in adequate integration of the EIA into the planning and development of the project due to delays in collecting relevant information.

Another important area which causes a certain amount of concern is the fact that the regulatory bodies in the region are often ineffective and insufficiently qualified to execute the approval phase of the EIA study. This often leads to delays in the entire EIA process. The professionals who plan the execution of the project often work within a framework of tight deadlines and schedules, and due to these delays, the results of the EIA process are mostly regarded as insignificant for realization.

4 INSTITUTIONALIZATION OF A MANAGEMENT FRAMEWORK

Environmental impact management is the strategy through which human activities which impact, or may impact, the environment are organized for the purpose of maximizing social benefits, as well as to prevent and/or i/ili ublažavanja potencijalnih problema delujući u osnovi uzroka.

Kako je potreba za kretanjem, odnosno saobraćajem, uslovila razvoj putne mreže, upravljanje putevima u velikoj mjeri zavisi od smernica, odnosno politike razvoja i upravljanja saobraćajem. Istraživanje saobraćajnih politika pojedinih razvijenih zemalja ukazuje da je, iako je u poslednjih četrdesetak godina postojala zabrinutost vezana za uticaje na životnu sredinu, tek poslednjih petnaestak godina uticaj saobraćaja na životnu sredinu adekvatno vrednovan kroz formulisanje saobraćajnih politika [9]. Međutim, to nije bio slučaj samo u sektoru saobraćaja, već i u drugim oblastima ljudskih aktivnosti. Značajna činjenica je da je na globalnoj osnovi postignuta saglasnost da su uticaji saobraćaja na životnu sredinu bitni, ali je daleko važnije da politike zaštite i unapređenja životne sredine ne budu u sukobu sa ekonomskom konkurentnošću, kako bi odgovarajuće formulisana regulativa mogla da dovede do pronalazaka i unapređenja, što bi rezultiralo dobitnom situacijom na obe strane, i kod javnosti i kod proizvođača, a naročito u porastu kredibiliteta nadležnih institucija i organizacija.

Postoje mnogi zakonski, finansijski i etički razlozi zbog kojih bi neka organizacija, strukturno ili formalno, uspostavila sistem upravljanja uticajima na životnu sredinu.

Zakonska regulativa, koja se odnosi na zaštitu životne sredine, bilo međunarodna, evropska ili domaća, se menja i proširuje zajedno sa razvojem svesti o uticaju ljudskih delatnosti na životnu sredinu. Iako domaća regulativa još uvek ne poseduje potpuno definisane odredbe koje se tiču usmeravanja razmatranja u vezi procene i kontrole uticaja na životnu sredinu, strani zakoni i propisi jasno definišu aktivnosti na putnoj mreži tokom kojih je potrebno obratiti pažnju na uticaje na životnu sredinu. Međutim, ova regulativa se u velikoj većini slučajeva odnosi na izgradnju novih objekata i poboljšanja, ali ne razmatra održavanje i manje intervencije na putnoj mreži.

Planeri i projektanti moraju da osiguraju ispunjavanje mnogobrojnih zakonskih odredbi u različitim fazama životnog ciklusa projekta, te je, s obzirom na stalno rastući nivo poznavanja materije i načina za rešavanje problema, potrebno da postoji određena vrsta sistema koja osigurava da organizacija bude u toku događaja i kontinualno ispunjava svoje zakonske obaveze. Neispunjavanje odredbi regulative u vezi zaštite životne sredine najčešće dovodi do optužbi, sudskih procesa i finansijskih kazni, ali, što je još lošije, i do dugotrajnog obeležja organizacije da nije delovala u skladu sa principima zaštite i unapređenja životne sredine. Ovakvo obeležje u velikoj meri ograničava mogućnosti poslovanja takve organizacije, što u vremenu tržišno orijentisanog privređivanja dovodi do neminovnog kolapsa. Osim toga, organizacije koje ne posluju po principima zaštite životne sredine imaju velikih problema u pristupu kapitalu kod banaka i osiguravajućih kuća, u odnosu na one koje demonstriraju svoj učinak i lakše ostvaruju prava na kredite i niže premije osiguranja.

Problemi uticaja na životnu sredinu su, sa marginalne aktivnosti pojedinih „ekstremnih" aktivista pre tridesetak godina, došli do nivoa kada su postali ključno pitanje industrijalizovanog sveta, odnosno njegovog informacijama bogatog i prestižnog dela. Aspekti

mitigate potential problems by addressing underlying causes.

As the need for movement, i.e. traffic, is the catalyst for development of a road network, the road management in large part depends on directives or policies for development and traffic management. Research on transportation policies of some developed nations indicates that, despite concerns related to environmental effects during the past forty years, the effect of traffic on the environment has been adequately appraised through the formulation of transportation policies only during the past fifteen years [9]. However, that was not the case just in the traffic sector, but also in other areas of human activity. It is significant to note that on a global level there is a consensus that the impacts of traffic on the environment are important, but it is far more important that environmental protection and improvement policies are not in conflict with economic competitiveness. An appropriately formulated set of regulations could lead to breakthroughs and advancements resulting in a beneficial situation for both sides, both the public and the producers, and would especially benefit the credibility of the responsible institutions and organizations.

There are many legal, financial and ethical reasons why an organization, structurally or formally, would establish an enviroenmental management system.

A legal set of regulations, which relate to the environment, whether international, European or domestic, is amended and expanded together with the expansion of the awareness for the effects of human activity on the environment. In spite of the fact that domestic regulations still do not have completely defined provisions related to directing consideration towards the evaluation and control of environmental impacts, foreign laws and regulations clearly define activities within a road network for which it is necessary to pay special attention to environmental impacts. However, a large majority of these regulations relate to construction of new structures and improvements, but do not deal with maintenance and smaller interventions within the road network.

Planners and designers must ensure compliance with numerous legal regulations in various phases of the project life cycle and, consider the ever growing level of knowledge within the field and the methods for resolving problems; it is necessary to have certain types of systems which ensure that an organization is up to date and continuously fulfilling its legal obligations. Failure to fulfill provisions of regulations related to environmental protection most often leads to lawsuits, court proceedings and monetary fines, but, what is even worse, the permanent labeling of an organization that failed to act in accordance with the principals of environmental protection and improvement. Such a label largely limits the business possibilities for such an organization, which in a time of a market-oriented economy leads to an unavoidable collapse. Aside from that, organizations which fail to operate according to the principles of environmental protection have significant problems accessing capital from banks and insurance companies when compared to those who demonstrate their output and easily realize their rights to credit and lower insurance premiums.

Starting from marginal activities of individual „extreme" activists thirty years ago, the problems of poslovanja povezani sa zaštitom životne sredine se moraju nadmetati sa ostalim upravljačkim problemima pošto, u veoma konkurentnim uslovima, poslovanje organizacija iz privatnog i javnog sektora mora imati komercijalan smisao. Usled toga je veoma bitno integrisati upravljanje uticajima na životnu sredinu sa ostalim aspektima poslovanja.

Etički argumenti za uvođenje sistema upravljanja uticajima na životnu sredinu su zasnovani na principima održivog razvoja, promovisanim na samitu Organizacije ujedinjenih nacija u Riju (Rio de Janeiro), 1992. godine. Održivost se mnogo više tiče ljudske vrste i njenih aktivnosti, nego životne sredine. Priroda „poznaje" sve moguće načine upravljanja sopstvenim sistemima na održiv način, i već nemerljiv niz godina stvara i razvija snažne, prefinjene ekološke sisteme i veoma kompleksne vrste. Održivi razvoj, zato, predstavlja putokaz za napredak čovečanstva po kome bi ljudska vrsta upravljala svojim sistemima na način koji odgovara upravljanju u prirodi, umjesto da te sisteme narušava kao što je to danas slučaj.

Sistem upravljanja putevima, preko planiranja i izgradnje putne mreže, planiranja eksploatacije, kao i njenog održavanja na zadovoljavajućem nivou kvaliteta, ima jedan od ključnih značaja za realizaciju koncepta održivog razvoja, budući da postoji zadatak zadovoljenja društvenih i ekonomskih potreba pojedinaca i zajednica za kretanjem roba i ljudi, uz obezbeđenje uslova za racionalno trošenje prirodnih resursa i zdrav život populacije.

Savremene strategije upravljanja uticajima na životnu sredinu prema konceptu održivog razvoja, polazeći od načela predostrožnosti i sprečavanja poremećaja životne sredine, se zasnivaju na proceni odnosa između uzroka i posledica ljudskih aktivnosti na životnu sredinu. Takav pristup predstavlja integrisanje kriterijuma zaštite životne sredine pri formulisanju strategija u svim bitnim područjima čovekovog delovanja, kao i kontrolu zagađivanja i degradacije životne sredine, počev od lokalnog, preko nacionalnog, pa do globalnog nivoa.

Savremena praksa agencija za puteve u regionu uglavnom pretpostavlja organizovanje aktivnosti na relativno niskom nivou. To podrazumeva činjenicu da se vodi računa samo o projektima novogradnje, odnosno zadovoljavanju osnovnih zahteva postavljenih kroz regulatorni okvir (zakoni i pravilnici). Sa druge strane, proaktivna uloga upravljača, kroz kompletan životnu ciklus jednog puta ili mreže u celini, se zapostavlja. Takođe, upravljački aspekt je sveden na angažovanje pojedinca ili veoma male grupe (2-3 stručna saradnika) koji samo vode poslove pripreme EIA, dok se o postojećim putevima, koji su u eksploataciji, kao i o novogradnjama koje se daju u eksploataciju, ne vodi računa. Pri tome su zapostavljene i upravljačke aktivnosti u odnosu na preduzeća angažovana na poslovima redovnog održavanja putne mreže i praćenju pokazatelja stanja životne sredine. Upravo u tom smislu se, u nastavku rada, definišu osnovne postavke sistema za upravljanje uticajima na životnu sredinu, i analizira mogućnost primene u putnom sektoru.

environmental impact have become key issues of the industrialized world, meaning the prestigious part of the world that is rich in information. The aspects of business related to environmental protection compete with other management problems because in exceedingly competitive conditions, the operations of organizations from the private and public sector have a commercial sense. Therefore, it is very important to integrate environmental impact management with the other aspects of business.

The ethical arguments for implementing an environmental management system are based on the principles of sustainable development, promoted at the Earth Summit of the United Nations held at Rio de Janeiro in 1992. Sustainability affects the human species and its activities much more than the environment. Nature recognizes every possible method for managing its own systems in a sustainable manner and has been creating and developing powerful, sophisticated ecological systems and very complex species for immeasurable number of years. Therefore, sustainable development represents a roadmap for the advancement of a mankind, and according to it the human species manages its systems in a manner which corresponds to the management of nature, instead of destroying those systems as it is the case today.

A road management system has a key significance for the realization of the concept of sustainable development through planning and construction of the road network, planning operations, as well as maintenance to a satisfactory level of quality, since its mission is to satisfy the social and economical needs of individuals and the community for transport of goods and people, while providing conditions for rational consumption of natural resources and a healthy life for population.

Starting from the principle of precaution and prevention of disturbance of the environment, modern strategies of environmental impact management according to the concept of sustainable development are based on the evaluation of relation between the causes and effects of human activities on the environment. Such an approach represents the integration of the criteria of environmental protection while formulating a strategy in all important areas of human activities, as well as control of pollution and degradation of the environment, starting from the local level, through the national level and finally up to the global level.

The modern practice of the road agencies in the region primarily entail organization of activities on a relatively low level. This implies that concern is given only to new roads construction projects, meaning the fulfillment of basic requirements instituted through a framework of regulations (laws and rulebooks). On the other hand, the proactive role played by the manager, through the complete life cycle of a road or entire network is neglected. Furthermore, the management aspect is reduced down to engaging an individual or very small group of experts (2-3 qualified specialists) who only conduct the preparation of the EIA, while the existing roads as well as newly built roads which are in function are completely neglected. At the same time, the management activities, in the sense of companies contracted to perform routine maintenance work on the road network and monitor environmental indicators, are also abandoned. Therefore, the subsequent sections of this paper define the basic fundamentals of an environmental management system and analyzes the possibility of its application in the road transportation sector.

5 UPRAVLJANJE UTICAJIMA NA ŽIVOTNU SREDINU

Upravljanje uticajima na životnu sredinu, kao upravljanje onim aktivnostima organizacije koje imaju ili mogu imati uticaj na životnu sredinu, nije nepoznat ili nov fenomen, ali je sistematski pristup upravljanju na ovaj način tek u skorije vrijeme dobio na značaju. Usvajanjem međunarodnih standarda upravljanja uticajima [8], 1996. godine, je stvorena dobra osnova za formulisanje upravljačkih aktivnosti i matrica delovanja, na isti način kao prilikom donošenja standarda za upravljanje kvalitetom.

Upravljanje uticajima na životnu sredinu predstavlja skup upravljačkih procesa i procedura koje organizaciji omogućavaju da analizira, kontroliše i umanji uticaj svojih aktivnosti na životnu sredinu. Sistem obezbeđuje organizacionu strukturu ustanove koja bi trebalo da dovede do efikasnog upravljanja uticajima poslovanja na sistematičan, aktivan i stalno unapređujući način, ali pod uslovom da se ispravno integriše u postojeće strukturne odnose organizacije i redovno primenjuje i ažurira. Sistem ne treba posmatrati izdvojeno, već u sklopu svih ostalih upravljačkih sistema koji se primjenjuju ili će se primenjivati, unutar neke organizacije u smislu ostvarenja odgovarajućeg učinka (Slika 4).

Svaka organizacija će, u određenom trenutku vremena, doći u poziciju da preispita svoje poslovanje i učinak i proveri da li na neki od načina doprinosi održivom razvoju. Upravo se uspostavljanjem ovog sistema ostvaruju mogućnosti za tu proveru i usklađivanje sa zakonskim okvirom, uz eventualna poboljšanja u procesu upravljanja [3].

Može se postaviti pitanje da li je za neku agenciju za puteve neophodno da uvodi sistem upravljanja uticajima ako provodi sve neophodne analize na nivou planiranja i projektovanja, putem procene uticaja na životnu sredinu i ako provodi planove upravljanja aktivnostima tokom izvođenja radova. Ako se analiziraju svi neohodni koraci analize i praćenja uticaja na životnu sredinu tokom životnog ciklusa puta i zakonske obaveze, sasvim je jasno da je agenciji za puteve potrebna neka vrsta sistema, putem koga bi se upravljalo aktivnostima vezanim za zaštitu i unapređenje životne sredine, a ne pristupalo problemima od projekta do projekta ili, što je daleko neprihvatljivije, nakon upozorenja od strane nadležnih službi ili ministarstva. U tom smislu, treba težiti uvođenju sistema sa ciljem [3, 7]:

- usklađenosti procesa rada sa odgovarajućom regulativom i propisima,
- smanjenja rizika po životnu sredinu,
- povećanja kontrole uticaja na životnu sredinu,
- ranog prepoznavanja problema vezanih za zaštitu životne sredine,
- upravljanja razvojem,
- povećanja poverenja u rukovodstvo,

5 ENVIRONMENTAL IMPACT MANAGEMENT

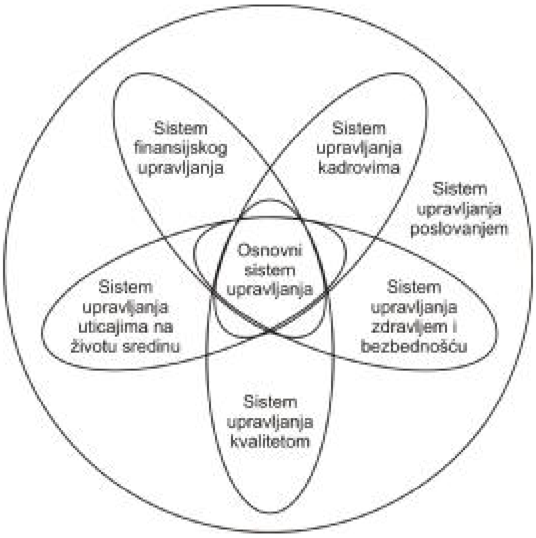
Environmental impact management, meaning the management of an organization's activities which have or could have an effect on the environment, is not an unknown or new phenomenon, but the systematic approach to management in this manner has just recently gained significance. With the adoption of international environmental management standards [8] in 1996, a good foundation was established for formulating management activities and activity matrices in the same manner as with passing standards for quality control.

Environmental impact management represents a collection of management processes and procedures which enable an organization to analyze, control and reduce the effect of its activities on the environment. The system provides an organizational structure for an institution which should result in the efficient management of the effects of operations in a systematic, active and constantly improving manner, but under the condition that it is properly integrated into the existing structural relations of the organization and is regularly applied and updated. The system should not be viewed separately, but rather within the structure of other management systems which are applied or will be applied within an organization in the sense of achieving proper output (Fig. 4).

Every organization, at one time or another, reaches the stage where it reevaluates its operations and output and verifies whether it is contributing to sustainable development in some manner. The establishment of this system facilitates the possibility for this type of verification and compliance with the legal framework, with potential improvements in the management process [3].

However, there is a question whether it is necessary for road agency to implement an environmental management system if it does all necessary analyses at the planning and design level through the environmental impact assessment and if it implements environmental management plans while works are carried out. If one performs all necessary steps of the analysis and monitoring of the impacts on the environment during the road life cycle and legal obligations, it is quite clear that the road agency needs some type of system by which it could manage the activities related to environmental protection and improvement instead of approaching problems from project to project or, even less acceptable, after warnings from the responsible service or ministry. In that sense, effort should be made to implement a system with the objective to [3, 7]:

- bring the working process into compliance with proper regulations and provisions,
- reduce the risk to the environment,
- increase control over the impacts on the environment,
- early recognize problems related to environmental protection,



Slika 4. Sistemi upravljanja [12]
Fig. 4. Management systems [12]

– povećanja efikasnosti i efektivnosti,
– kontrole rashoda i finansijskih ušteda,
– zadovoljavanja kriterijuma finansijskih i osiguravajućih institucija i donatora, i povećanja mogućnosti pristupa kapitalu,
– pravne sigurnosti,
– stvaranja ugleda u javnosti i kod državnog regulatornog i finansijskog sektora i
– želje da se predstavi kao predvodnik i inovator u svojoj oblasti.

Ciljeve, koristi i eventualne prepreke i iskušenja treba detaljno analizirati pre uvođenja sistema. Svaka organizacija mora jasno definisati šta očekuje od uvođenja sistema, kako ne bi došlo do gubitka samopouzdanja ili odustajanja tokom realizacije.

5.1 Osnovni principi upravljanja uticajima

Upravljanje uticajima na životnu sredinu, kako ga definišu ISO standardi, nije upravljanje životnom sredinom ili upravljanje okolinom, već upravljanje organizovanim ljudskim aktivnostima u organizacijama/preduzećima radi smanjenja, odnosno usmeravanja uticaja na životnu sredinu (management FOR environment, a ne management OF environment) [8].

Svaka organizacija može razviti i uspostaviti svoj sistem kako bi ispunila određene ciljeve, aktivnosti, budžet, uslove i zahteve zainteresovanih. Bez obzira na izabran način uspostavljanja sistema upravljanja uticajima na životnu sredinu, kada se radi o agenciji za puteve, sistem mora biti u skladu sa vizijom organizacije i integrisan sa nacionalnom ili državnom politikom zaštite i unapređenja životne sredine, kao i saobraćajnom politikom.

Sistem upravljanja uticajima predstavlja kontinualan ciklus procesa i aktivnosti koje organizacija preduzima da bi ispunila svoje obaveze u odnosu na životnu

– manage development,
– increase confidence in management,
– increase efficiency and effectiveness,
– control expenses and financial savings,
– satisfy the criteria of financial and insurance institutions and donors, and increase the possibilities for accessing capital,
– have legal security,
– establish reputation in public, as well as government regulation and financial sector and
– achieve the status of a leader and innovator in the field.

The goals, benefits and potential obstacles and difficulties should be analyzed in details before the system is implemented. Every organization should clearly define what it expects from the implementation of the system in order to avoid a loss of confidence or abandonment during realization.

5.1 Basic principles of impact management

Environmental management, as defined by the ISO standards, is not management of environment, but rather management of organized human activities within organizations/ companies for the purpose of decreasing or directing the effects towards the environment (management FOR environment and not management OF environment) [8].

Every organization may develop and establish its own system in order to fulfill certain goals, activities, a budget, conditions and requirements of the stakeholders. Regardless of the selected method for implementing the environmental management system, when dealing with road agency, the system must conform with the vision of the organization is integrated with the national or state policy for environmental protection and improvement, as well as with the traffic policy.

The environmental management system represents a continuous cycle of processes and activities which the organization takes in order to fulfill its obligations in sredinu. Sistem se sastoji od niza međusobno povezanih elemenata koji zajedno funkcionišu u postizanju postavljenih ciljeva. Kroz upravljanje, organizacija obraća pažnju ne samo na probleme koji se dešavaju, nego i zašto se oni dešavaju, te se tokom vremena, sistematskom identifikacijom i ispravljanjem nedostataka sistema dolazi do boljeg učinka. Dakle, može se reći da sistem omogućava organizaciji da odredi u kom pravcu želi da se kreće, odnosno usmerava svoje aktivnosti i utvrdi zašto ne dolazi do postavljenog cilja.

Upravljanjem uticajima na životnu sredinu unutar organizacije dominira sledeća filozofija:

- uskladiti (poštovanjem regulative);
- sprečiti/izbeći (istraživanjima, inovacijama);
- smanjiti (oblikovanjem životnog ciklusa);
- upotrebiti (recikliranjem);
- odbaciti (zamenom otpadnih materijala);
- unaprediti (kontrolom, usavršavanjem).

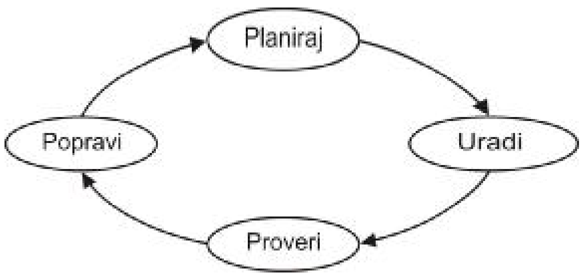
Osnovni koraci koji se pojavljuju u sistemu upravljanja uticajima na životnu sredinu su definisani Demingovim (Deming) ciklusom (Slika 5): planiraj-uradi-proveri-popravi. Ovi koraci se, nakon obavljenog kruga, ponavljaju, ali na višem kvalitetnijem nivou, čime se postiže trajno unapređenje, što je jedna od postavki sistema. Demingov krug se pojavljuje na svim nivoima sistema, od pojedinačnih elemenata, odnosno procedura, do kompletnog sistema.

relation to the environment. The system consists of a series of interconnected elements which function together to achieve the established objectives. Through this management, the organization gives attention not only to the problems which occur, but also to their cause and over time, through systematic identification and correction of shortcomings, leads to better output. Therefore, it can be said that the system enables the organization to determine the direction of its activities and identify the reasons for failing to achieve stated objectives.

Environmental management within an organization is dominated by the following philosophies:

- complying with (respecting regulations);
- preventing/avoiding (research, innovation);
- reducing (forming the life cycle);
- using (recycling);
- disposing (replacement of waste materials);
- improving (control, improvement).

The basic steps which appear within an environmental management system are defined by the Deming cycle (Fig. 5): plan-do-check-act. After completing of the circle, these steps are repeated, but at a higher quality level with permanent improvement, which is one of the fundamentals of the system. The Deming cycle appears at all levels of the system, from individual elements or procedures to the complete system.



Slika 5. Demingov ciklus [14]
Fig. 5. Deming cycle [14]

U osnovi svakog uspešnog sistema upravljanja, pa i sistema upravljanja uticajima na životnu sredinu stoje sledeći elementi:

- posvećenost i odlučnost rukovodstva,
- orijentacija na kontinualno unapređenje,
- jednostavnost i fleksibilnost,
- usklađenost sa kulturom poslovanja organizacije,
- svest i uključivanje zaposlenih i
- redovno informisanje i izveštavanje.

Treba imati u vidu da planiranje i uspostavljanje sistema ne predstavlja ogroman korak, odnosno promenu u načinu i kulturi poslovanja, nego usklađivanje sa regulatornim zahtevima, te u najvećoj mogućoj meri treba iskoristiti postojeće pojedinačne elemente sistema i praksu upravljanja u organizaciji, uz određena unapređenja da bi se zadovoljili zahtevi sistema [10, 11]. Većina organizacija koje upravljaju određenim infrastrukturnim objektima, po svojoj prirodi, već poseduje 80-85 % potrebnih elemenata i preduslova za formiranje sistema, tako da je potrebno odabrati pravu kombinaciju između promene kulture poslovanja, u skladu sa pristupom preko sistema za upravljanje

The foundation of every successful management system, even environmental management system, contains the following elements.

- dedication and decisiveness of management,
- orientation towards continuous improvement,
- simplicity and flexibility,
- compliance with the operational culture of the organization,
- awareness and inclusion of employees and
- regular notification and reporting.

It should be kept in mind that planning procedure and implementation of the system is a small step, i.e. change in the method and culture of operations, which means compliance with regulatory requirements, and thus, existing individual elements of the system and practice in organizational management should be used in the greatest possible extend with certain improvements to satisfy the requirements of the system [10, 11]. Due to their nature the majority of organizations that manage certain infrastructure already possess 80-85 % of necessary elements and prerequisites for establishing the system, so it is necessary to find proper uticajima, i prilagođavanja sistema kulturi poslovanja. Pri tome treba imati u vidu da promena organizacije i kulture poslovanja može biti vremenski, fizički i psihički veoma zahtevan proces.

Kao minimum, organizacije koje se orijentišu prema upravljanju uticajima na životnu sredinu prihvataju odgovornost izrade odgovarajuće politike, identifikacije svih aspekata i uticaja svog poslovanja na životnu sredinu i preduzimanja odgovarajućih postupaka ugrađenih u procedure za izvršenje aktivnosti [11]. Nakon uvođenja sistema, organizacija neće samo uskladiti svoje poslovanje sa zakonskim zahtevima, već može i nadmašiti standarde u vezi pojedinih aktivnosti i identifikovati mogućnosti za smanjenje neregulisanih uticaja koji se javljaju kao posledica njenih aktivnosti.

Značajan činilac svakog sistema upravljanja je i vreme, kako za razvoj i realizaciju, tako i za unapređenje. Prema tome, timu za realizaciju treba omogućiti dovoljan period vremena za sve aktivnosti na uspostavljanju sistema i ne uticati na ubrzavanje dinamike u značajnoj meri.

Definisanje, uspostavljanje i operacionalizacija sistema za upravljanje uticajima neće samo po sebi rezultirati neposrednim smanjenjem nepovoljnih posledica po životnu sredinu. Bitno je obezbediti merljive pokazatelje učinka sistema, preko kojih će se procenjivati učinak i ostvarivati unapređenja u funkcionisanju.

6 USPOSTAVLJANJE SISTEMA

Promene unutar neke organizacije, a naročito značajna transformacija poslovanja, kao što je usklađivanje sa principima poslovanja u skladu sa aspektima životne sredine, uvek donose mnoga pitanja, nedoumice i sumnje u ispravnost postupanja. Veoma je malo verovatno da bilo koja jedinka ili organizacija može tvrditi da delatnost koju obavlja ne prouzrokuje nikakvu štetu ili uticaj na životnu sredinu, bilo negativan ili pozitivan, te je stoga važno upravljati aktivnostima tako da se umanje negativni uticaji, a pozitivni pravilno usmere.

Imajući u vidu prirodu upravljanja uticajima na životnu sredinu, potreban je fleksibilan sistem koji će pratiti razvoj znanja u oblasti životne sredine i biti u mogućnosti da stalno unapređuje procedure i procese.

Standard ISO 14001 definiše model za razvoj i realizaciju sistema za upravljanje uticajima na životnu sredinu (Slika 6), na osnovu koga se može definisati i model sistema upravljanja uticajima na životnu sredinu u oblasti puteva.

Kada se osnovni model sistema prevede na Demingov ciklus jasno se uočava odnos bitnih elemenata koje je potrebno poštovati, odnosno definisati tokom uspostavljanja sistema u nekoj organizaciji (Slika 7).

combination between the change in operational culture, in accordance with an approach through the impact of management system, and to adapt the system to the operational culture. Therefore, changing an organization and operational culture can be a time consuming process which is also physically and psychologically demanding.

Thus, as a minimum, organizations oriented towards environmental management should accept responsibility for establishing proper policy, identify all the aspects and impacts of their operations towards the environment and take proper actions which are integrated into the procedures of their activities [11]. After implementing the system, the organization will not only bring its operations into compliance with the legal requirements, but it may also exceed the standards related to some activities and identify the possibilities of reducing unregulated effects which occur as a result of its activities.

The time is another important factor of each management system, both for development and realization, as well as improvement. Thus, the team for realization should have sufficient time for the accomplishment of all the activities related to the establishment of the system and should not be rushed as well.

Defining, implementing and operationalizing an environmental management system will not result in immediate reduction of adverse environmental impacts by itself. It is important to provide measurable indicators for the output of the system which will enable its evaluation and improvement in functions.

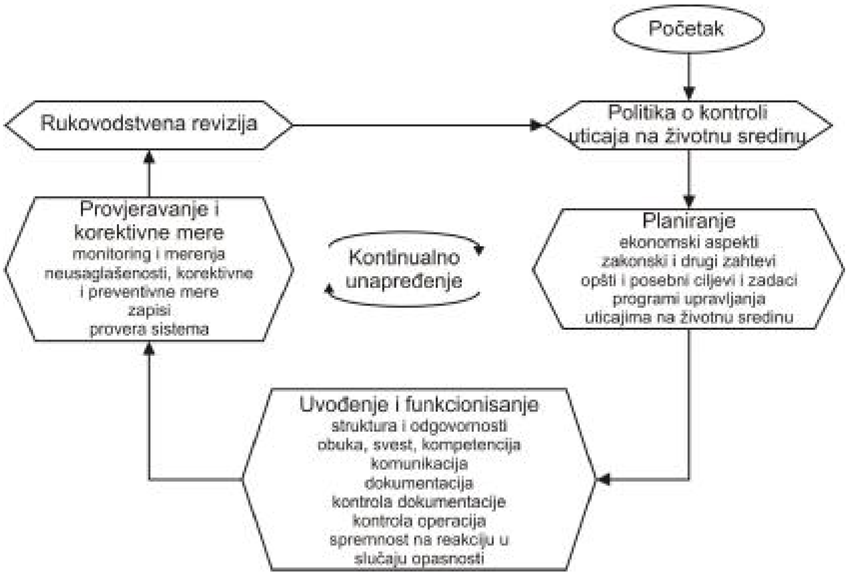
6 IMPLEMENTING THE SYSTEM

Changes within an organization, especially significant transformations of operations, such as complying with the principles of business in accordance with the environmental aspects, are always followed by many questions, confusion and doubts regarding whether the proper actions are being taken. It is unlikely that any individual or organization can maintain the activities that do not harm or have any impact on the environment, whether negative or positive, and therefore, it is important to manage it by reducing the adverse effects and properly direct positive ones.

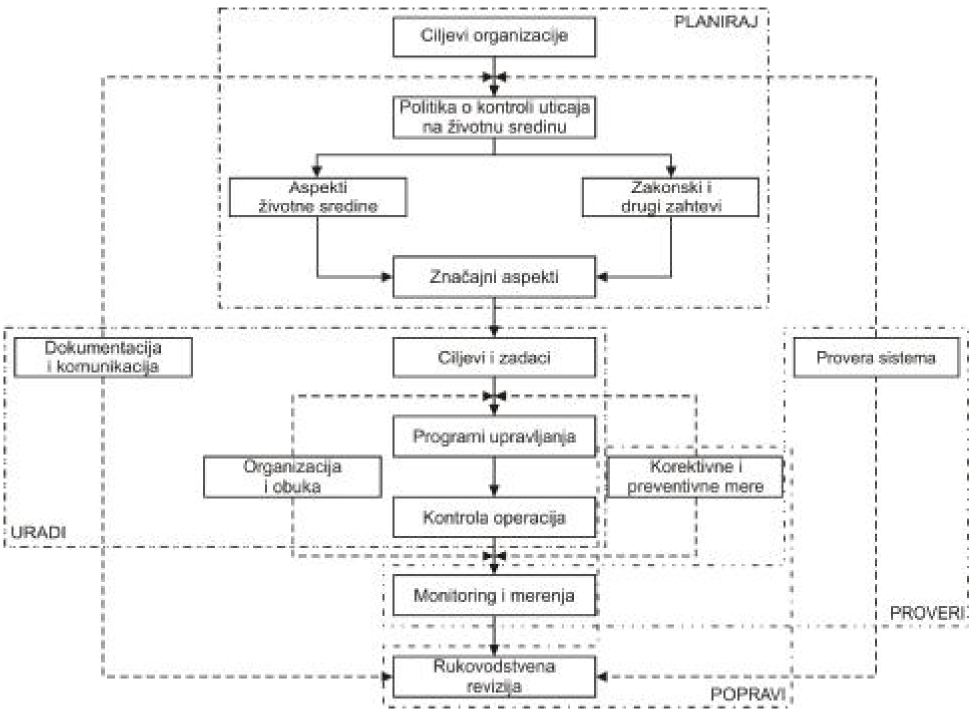
Keeping in mind the nature of environmental management, it is necessary to have a flexible system which monitors the development of knowledge in the field of environmental protection and be capable of improving procedures and processes constantly.

The standard ISO 14001 defines the model for development and realization of an environmental management system (Fig. 6), which enables defining a model for an environmental management system in the field of roads.

The relation between important elements which should be respected and defined during the implementation of the system within an organization can be clearly recognized when applying the Deming cycle to the basic model of the system (Fig. 7).



Slika 6. Opšti model sistema za upravljanje uticajima na životnu sredinu [14, 3]
Fig. 6. Generic model of an environmental management system [14, 3]



Slika 7. Odnos bitnih elemenata sistema
Fig. 7. Relation of important elements of the system

6.1 Primenljivost u oblasti puteva

Problemi ugrožavanja životne sredine su po svojoj prirodi međusektorski. Pošto životna sredina ne priznaje državne, administrativne i ostale granice, veoma je teško odgovornost zaštite i unapređenja životne sredine prepustiti nekoj od sektorskih agencija. U skladu sa tim, potrebno je više telo, u vidu ministarstva i/ili agencije za životnu sredinu, koje bi regulisalo prava i obaveze svih

6.1 Applicability in the field of roads

The problems of environmental damage include various sectors according to their nature. Due to the fact that environment fails to recognize national, administrative and other borders, it is very difficult to yield the responsibility for environmental protection and improvement to one of the sector agencies. Therefore, it is necessary to establish different institutions, i.e.

pravnih i fizičkih lica. Ovakav pristup ne eliminiše potrebu za specifičnom sektorskom analizom problema životne sredine. Naprotiv, na taj način se životna sredina postavlja kao sastavni dio sveukupnog planiranja razvoja, u kome odgovarajući sektori takođe imaju svoju ulogu preko relevantnih ministarstava, agencija i organizacija. Zbog toga je veoma važno i razjasniti institucionalne odgovornosti različitih agencija koje su uglavnom uključene u rešavanje problema ugrožavanja životne sredine [10, 11], kao što su agencije za puteve, vode, privredne komore, ministarstva industrije, saobraćaja, vodoprivrede, energetike i sl.

Od institucija javnog sektora, kakva je i agencija za puteve, se očekuje da upravljaju mnogobrojnim objektima i operacijama, odnosno aktivnostima i na taj način zadovolje brojne operativne, finansijske, pravne, društvene i ekološke potrebe stanovništva. Takođe, državne regulatorne institucije sve više nameću određene obaveze i rešenja u odnosu na javne institucije, koje su veoma često nespremne da učestvuju u rešavanju problema i usklađuju svoje poslovanje sa izazovima koji im se nameću. Time se javlja još jedna od realnih potreba za uspostavljanjem sistema radi konstantnog definisanja obima usluga koje obezbeđuje sa ograničenim budžetskim sredstvima, uz istovremeno održavanje usklađenosti sa regulativom. Osim toga, sistem omogućava da se korektno upravlja i problemima koji nisu definisani kroz regulativu.

Razvoj i primena sistema za upravljanje uticajima na životnu sredinu predstavlja realnost u agencijama za puteve koje se suočavaju sa sve većim zahtevima stručne, kao i opšte javnosti za zaštitom i očuvanjem životne sredine, prvenstveno u vidu zakonske i druge regulative. U svetlu odgovornosti za zaštitu i unapređenje životne sredine, treba naglasiti da agencije za puteve, u svakom slučaju, ne mogu uticati na globalne probleme zagađivanja i potrošnje resursa, međutim kroz adekvatno upravljanje aktivnostima tokom životnog ciklusa puta mogu značajno smanjiti opterećenje na životnu sredinu. Osim regulatornog konteksta, uvođenjem upravljanja uticajima na životnu sredinu je moguće povećati šanse za dodatnim dobitima životne sredine, u odnosu na javna ulaganja i programe.

6.2 Ograničenja i rizici

Uključivanjem zaposlenih u razvojni proces se povećava osećaj posedovanja podsistema i želja za prihvatanjem, s tim što nije potrebno uvoditi sistem u pojedine delove agencije za koje se utvrdi da bi to predstavljalo veliki problem i izazvalo određena protivljenja. U tom smislu se treba fokusirati na sektore/odeljenja čiji rad može imati najviše uticaja na životnu sredinu, a to su upravo tehnički sektori, uz postepeno ili povremeno uključivanje ostalih sektora, kao što su pravni ili finansijski.

Pod pretpostavkom da postoje obezbeđena finansijska sredstva, kako za razvoj i uvođenje sistema, tako i za redovne aktivnosti agencije za puteve, jedini rizik koji se može identifikovati kao moguća prepreka za primenu u oblasti puteva je nedovoljna posvećenost

ministries and/or agencies for environmental protection, which could regulate the rights and obligations of all legal entities and individuals. This kind of approach includes the need for a specific sector analysis of environmental problems. Thus, the environment is defined as an integral component of the overall planning of development in which the corresponding sectors also have their own role to play through the relevant ministries, agencies and organizations. Therefore, it is very important to explain the institutional responsibilities of various agencies which are mostly included in resolving the problems of environmental endangerment [10, 11], such as agencies for roads, water, chamber of commerce, ministries of industry, transport, water management, energy, etc.

Institutions from public sector, such as road agency, are expected to manage different structures and operations or activities and thus, satisfy numerous operational, financial, legal, social and ecological needs of the population. Furthermore, the state regulatory institutions continue to impose certain obligations and solutions in relation to public institutions which are very often incapable to participate in resolving problems or adjust their operations to the challenges which they face. This suggests further requirement to implement a system of constantly defining the scope of services provided with limited budget resources, and simultaneous maintenance of complying with regulations. Besides, the system enables proper dealing with problems which are not defined through regulations.

The development and application of environmental management system represents a realistic possibility within the road agencies, which are faced with increasing demands of professional and general public for environmental protection and maintenance, primarily in the form of legal and other regulations. Regarding the responsibility for environmental protection and improvement it should be noted that the road agencies cannot influence the global problem of pollution and consumption of resources; however, through adequate management of activities during the road life cycle, they can significantly decrease the burden on the environment. Besides regulations, it is possible to increase the opportunities for additional benefits to the environment in relation to public investments and programs by implementing an environmental management system.

6.2 Limitations and risks

The awareness about subsystem and willingness to accept it increases by including the employees into the developmental process although it is not necessary to implement the system into individual sectors of the agency for which it is determined to be a large problem and cause antagonism. Consequently, the focus should be placed on sectors/departments whose activities influence the environment substantially, and they are technical sectors, with gradual or periodical inclusion of the other sectors, such as legal or financial sectors.

Under the assumption that the financial resources have been provided, both for development and implementation of the system, as well as for the regular activities of the road agency, the only risk which can be identified as a possible obstacle for its application in the rukovodstva agencije za puteve. Sa nedostatkom posvećenosti rukovodstva, blisko je povezan i nedostatak entuzijazma među kadrovima. Ovo proizilazi iz činjenice da zaštita i unapređenje životne sredine ne predstavlja osnovnu delatnost agencije za puteve, te postoji sumnja u dobiti, uštede i pravilno trošenje sredstava, a može doći do pojave ubeđenja da dobrobiti od primene sistema mnogo sporije dolaze do izražaja u odnosu na troškove. Na taj način se agencija za puteve više ne može postaviti kao lider u svojoj oblasti i kao agencija koja bi zadobila poverenje javnosti i investitora u vremenu promocije održivog razvoja.

Kao posledica bi se pojavila nemogućnost obezbeđenja dovoljnih ulaganja u putnu infrastrukturu u smislu novih investicija i zaštite i unapređenja životne sredine, pošto bi se veoma teško obezbedila sredstva za neodržive projekte ili održive projekte kojima ne bi moglo da se rukovodi na održiv način, tako da bi veoma brzo postali neodrživi. Osim toga, agencija za puteve ne bi mogla ni da utiče na formiranje regulative i procedura za obavljanje radova koji su iz njene nadležnosti, odnosno dela koji se odnosi na probleme zaštite i unapređenja životne sredine.

Rizik koji nije direktno povezan sa agencijom za puteve, ali bi mogao uticati na odgovarajući učinak sistema u kontroli uticaja, je nedostatak volje i entuzijazma izvođača i konsultanata da svoju organizaciju usklade sa principima upravljanja uticajima na životnu sredinu i poštuju odgovarajuće zakone, propise i uputstva. Postojanje dodatnih obaveza, ovi saradnici uglavnom tumače kao veoma veliku prepreku koja usporava projekte putne infrastrukture i povećava koštanje građevinskih radova. Takav rizik bi agencija za puteve trebalo relativno lako da reši, pošto postoje odgovarajući zakonski instrumenti za postupanje u takvim slučajevima, a uz uspostavljen sistem upravljanja uticajima i svoj mandat agencija ima apsolutno pravo da ih provodi.

Osim navedenih ograničenja i rizika, moguće je identifikovati i generalne probleme koji bi se mogli pojaviti, a spadaju u domen:

- preklapanja nadležnosti institucija,
- nedostatak komunikacije između institucija,
- nedostatak stručnog kadra, što postaje izražajnije sa smanjenjem veličine organizacije i države,
- nedostatak obuke i
- potreba za stalnim ažuriranjem i unapređenjem sistema.

S druge strane, postoji i nekoliko mogućnosti i tehnika za prevazilaženje navedenih ograničenja. Najveća korist se ostvaruje interaktivnom obukom i komunikacijom sa zaposlenima, čime se povećava razumevanje i svest o problemu. Takođe, integracija sa postojećom praksom poslovanja i načinom vođenja dokumentacije pomaže u prevladavanju teškoća. Podelom odgovornosti između sektora, odnosno odeljenja agencije za puteve se ostvaruje smanjenje opterećenja na tim za realizaciju sistema i omogućava lakše prihvatanje istog.

field of roads is insufficient devotion of the road agency management. Insufficient devotion of the management is closely linked to the lack of enthusiasm among personnel. It is due to the fact that environmental protection and improvement is not the primary activity of the road agency and thus, there is a doubt in the benefits, savings and proper consumption of resources, and the belief that the advantages from applying the system appear much more slowly in comparison with the expenses. Thus, the road agency can no longer be considered a leader in the field or an agency which can earn confidence of the public and investors during the promotion of sustainable development.

The inability to secure sufficient investments in road infrastructure i.e. new investments and environmental protection and improvement, is a consequent result because it is very difficult to secure funds for unsustainable projects or sustainable projects which could not be managed in a sustainable manner, so they would quickly become unsustainable. Besides, the road agency would not be able influence imposing regulations and procedures for works which fall within its responsibilities, or relate to the problems of environmental protection and improvement.

A risk, which is not directly linked to the road agency but could affect the proper output of the system of impact control, is the lack of will and enthusiasm of the contractors and consultants to conform their organization to the principals of environmental management and comply with the corresponding laws, regulations and directives. The additional obligations are mostly considered a very large obstacle which slows down road infrastructure projects and increases the cost of construction works. Such a risk could be resolved relatively easily by the road agency because there are corresponding legal instruments for operating in these situations, and with the implemented environmental management system and its mandate, the agency has absolute right to implement them.

Aside from the aforementioned limitations and risks, it is also possible to identify general problems which could emerge, and fall into the domain of:

- overlapping authorities of institutions,
- lack of communication between institutions,
- lack of qualified staff, which becomes more common with the decrease in size of an organization and country,
- lack of training and
- need for constant updating and improvement of the system.

On the other hand, there are also several possibilities and techniques for overcoming the aforementioned limitations. The greatest benefit is achieved through interactive training and communication with employees whereby there is an increased understanding and awareness of the problem. Additionally, integration with the existing practice in business and the method for keeping documentation helps in overcoming difficulties. By dividing responsibility between sectors and departments, the road agency lightens the burden on the team for realization the system and facilitates acceptance of the same.

7 ZAKLJUČAK

Koncept održivog razvoja zahteva integrisanu i celovitu akciju, primenom serije ISO ili sličnih standarda, koji se odnose na upravljanje uticajima na životnu sredinu. Da bi se održivi razvoj mogao efikasno realizovati, on se mora na adekvatan način ugraditi u sve organizacione sisteme i u sve nivoe upravljanja u društvu, počev od međunarodne zajednice, preko nivoa državne administracije do preduzeća, a unutar preduzeća do radnog mesta. Na nižim nivoima upravljanja, ciljevi upravljanja uticajima na životnu sredinu se sve više konkretizuju, sve do radnih zadataka na radnom mestu.

Već spoznaja u kojoj fazi životnog ciklusa jednog puta se može pojaviti određena vrsta uticaja i izbor najboljeg vremena za primenu odgovarajućih mera ne samo da predstavlja osnovu u efikasnom ograničavanju ili sprečavanju negativnih uticaja, već pretpostavlja i postojanje niza aktivnosti kojima se ta pojava i evidentira, potom izbor alternativnih administrativnih i/ili tehničkih mera i izbor optimalne mere, sa stanovišta opšte društvene koristi. Ovaj problem se značajno uvećava kada se radi o putnom saobraćajnom sistemu-putnoj mreži, kada se ti problemi umnožavaju shodno veličini mreže, rastu obima saobraćaja, promeni transportnih sredstava, zatim različitoj osetljivosti životne sredine na uticaje puta i saobraćaja, istorijskom nasleđu koje se prvenstveno ogleda u prevaziđenim metodama projektovanja i građenja i, konačno, shodno budućim zahtevima koji se pred putnu mrežu postavljaju, a ogledaju se prvenstveno u novogradnji, rekonstrukciji, rehabilitaciji i održavanju. U tom slučaju, upravljačke odluke ne mogu biti zasnovane na intuitivnom procenjivanju. One, nužno, moraju biti zasnovane na rezultatima ključnih elemenata celovitog upravljačkog sistema, sposobnog da aspektu široke društvene zajednice dugoročno predoči sve posledice odlaganja ili preduzimanja odluka. To sve pretpostavlja optimizaciju koju je moguće ostvariti formiranjem odgovarajućeg modela upravljanja.

U okviru rada je prikazana najbolja praksa po pitanju analize uticaja na životnu sredinu, uz konkretno povezivanje sa pojedinim fazama životnog ciklusa puta. Takođe, preporuke za uspostavljanje sistema za upravljanje uticajima, uz analizu primeljivosti u sektoru puteva, mogu poslužiti kao vodilja za rad u okviru agencije za puteve.

EIA je relativno nov proces koji se još uvek razvija. Već sada postoji dosta pozitivnih iskustava, ali se još uvek dosta stvari može naučiti. Projektni ciklus je poznat već duži period vremena i primenjuje se bez preispitivanja. U akademskim, privrednim i ekonomskim krugovima EIA proces je već prisvojen. Takođe je dobro poznato da je čak i javnost generalno svesna šta obuhvata projektni ciklus. Nažalost, isto se ne može reći za EIA proces ili za upravljanje uticajima na životnu sredinu. Industrijski krugovi treba da prisvoje proces upravljanja uticajima na životnu sredinu, a ne da EIA proces doživljavaju kao zakonsku obavezu koju treba zaobići da bi se završio projekat.

EIA studije treba da budu sredstvo za planiranje i donošenje odluka koje će služiti regulatornim telima i pokretačima projekata da donose jasno utemeljene odluke koje eksplicitno i sistematski uzimaju u obzir

7 CONCLUSION

The concept of sustainable development requires an integrated and comprehensive action through the application of the series of ISO standards or similar standards which relate to the environmental management. Due to be efficiently realized, sustainable development should be adequately implemented into organizational systems and all the levels of management in the society starting with the international community, through various levels of government administration, to the company and in the company down to the individual worker. At lower levels of management, the objectives of environmental management should be explained more explicitly all the way down to the specific task of the individual worker.

The mere knowledge about a certain type of effect which emerges in certain phase of the road life cycle as well as a choice of the best time for application of corresponding measures, not only represents the basis of effective limitation or prevention of the adverse impacts, but also requires a series of activities through which that occurrence is also recorded, followed by the selection of alternative administrative and/or technical measures and selection of the optimal measure from the perspective of the general benefit of the society. This problem is significantly magnified when it involves a road transport system, i.e. road network; those problems are multiplied by the size of the network, increased volume of traffic, change in the means of transport, and then the varying sensitivity of the environment to the effects of the road and traffic, historical heritage which is primarily reflected in obsolete methods of design and construction and, finally, in accordance with future requirements which are placed on the transport network, and reflected primarily in construction of new roads, reconstruction, rehabilitation and maintenance. In that case, the management decisions cannot be based on an intuitive assessment. They should be based primarily on the results of key elements of an entire management system which is capable of foreseeing all the consequences of delaying or making decisions for the broader society. This all requires optimization which is possible to achieve by forming a corresponding management model.

This paper has presented the best practice with regards to the analysis of environmental impact with concrete connections to individual phases of the life cycle of the road. Furthermore, the recommendation for implementing an environmental management system, with the analysis of applicability in the sector for roads, can serve as a guide model for the activities within the framework of the road agency.

The EIA is a relatively new process which is still being developed. There have already been a lot of positive experience, but there is still much to learn. The project cycle has been known for a long time and applied without any further reassessment. In academic, business and economic circles, the EIA process has already been adopted. It is also well known that even the public is generally aware of what the project cycle entails. Unfortunately, the same cannot be said for the EIA process or environmental management. Industrial circles should adopt a process of environmental management and not consider the EIA process as a legal obligation which should be bypassed in order to razmatranja u vezi zaštite životne sredine u fazama planiranja i projektovanja. Iako teorija sugeriše da je najbolji put napretka integrisanje EIA u projektni ciklus, ovo se vrlo retko dešava u praksi. EIA tim zato treba aktivno da sarađuje sa profesionalcima koji planiraju i projektuju određena rešenja.

Za zemlje u tranziciji, koje se suočavaju sa mnogobrojnim problemima od kojih zavisi i njihov dalji razvoj, koncept održivog razvoja predstavlja veliki izazov. Mada shvatajući njegovu neophodnost, posebno u domenu saobraćaja, takva društva moraju da deluju postepeno, jer složeni činioci koncepta tipa „kako i na koji način" ustupaju mesto presudnom „kojim sredstvima". Specifičnosti pojedinih država nameću i dodatne teškoće za čije rešavanje se mora krenuti od regulatornog okvira, zakona i dokumenata kojima se usmerava dalji razvoj, ali i čuva životna sredina u skladu sa proklamovanim svetskim trendovima. Pri tome treba imati na umu da se u relativno nerazvijenim zemljama brže razvijala tehnička i tehnološka opremljenost stanovnika od razvoja njihove svesti i mudrosti države da izbegne zamke i negativne efekte takvog razvoja.

Put ka održivosti je složen i dugotrajan proces, jer zahteva promenu mišljenja i ponašanja svih društvenih aktera, odnosno shvatanja da je učinak razvoja na zaštiti životne sredine jednako važan kao i ekonomski, pri čemu odnos prema životnoj sredini treba postaviti tako da se ide ispred regulative, jer je to jedini način da se zadovolji buduća regulativa uz najmanje troškova.

complete the project.

EIA studies should be a resource for planning and decision making which helps the regulatory bodies and project initiators to make clearly founded decisions which explicitly and systematically take environmental protection into consideration in the phases of planning and design. Even though the theory suggests that the best way forward is the integration of the EIA into the project cycle, but it rarely occurs in practice. The EIA team therefore should actively cooperate with the professionals who plan and design certain solutions.

For countries in transition, which face numerous problems that affect their further development, the concept of sustainable development represents a great challenge. Although they understand its necessity, especially in the domain of traffic, the society must act gradually, due to the complexity of the concept of „how and in what way" give way to the crucial „by what means". Particularity of each country also imposes additional difficulties and their resolution starts from a regulatory framework, law and document which directs further development, but also protects the environment in accordance with the proclaimed global trends. At the same time, it should be kept in mind that in relatively undeveloped countries, the technical and technological capabilities of the population have developed faster than their awareness and the ability of the country to avoid the traps and adverse effects of such development.

The road towards sustainability is complex and lengthy process because it requires a change in the opinion and behavior of all the participants in society, meaning they should understand that the effect of environmental development is equally important as its economic benefits and thus, the attitudes towards the environment should be considered before introducing legislation because this is the only way to satisfy future regulations with the lowest expenses.

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REZIME

UTICAJ PUTNIH PROJEKATA NA ŽIVOTNU SREDINU TOKOM ŽIVOTNOG CIKLUSA I INSTITUCIONALIZACIJA UPRAVLJAČKOG OKVIRA

Igor JOKANOVIĆ

Saobraćajnice, kao specifični objekti u prostoru i vremenu, ograničavaju prostor za razvoj fizičkih struktura i aktivnosti, a istovremeno mogu doneti značajne koristi i negativne posledice. Integrisanjem procene uticaja na životnu sredinu u projektni ciklus saobraćajne infrastrukture se ostvaruju preduslovi za pravovremeno i sveobuhvatno razmatranje mogućih negativnih, ali i pozitivnih, efekata izgradnje i eksploatacije kroz čitav životni vek građevine. Razvoj i primena sistema za upravljanje uticajima na životnu sredinu predstavlja realnost u agencijama za puteve koje se suočavaju sa sve većim zahtevima stručne i opšte javnosti, prvenstveno u vidu zakonske i druge regulative. U svetlu odgovornosti za zaštitu i unapređenje životne sredine, treba naglasiti da agencije za puteve, ne mogu uticati na globalne probleme zagađivanja i potrošnje resursa, međutim, kroz adekvatno upravljanje aktivnostima tokom životnog ciklusa puta mogu značajno smanjiti opterećenje.

Ključne reči: putevi, životni ciklus, uticaji na životnu sredinu, procena uticaja, zaštita životne sredine, upravljanje uticajima

SUMMARY

IMPACT OF ROAD PROJECTS ON ENVIRONMENT DURING THE LIFE CYCLE AND INSTITUTIONALIZATION OF A MANAGEMENT FRAMEWORK

Igor JOKANOVIĆ

Transport infrastructure, as specific structures in space and time, limit space for development of physical structures and activities, and at the same time bring significant benefits and adverse effects. By integrating an environmental impact assessment into the project cycle for transport infrastructure, prerequisites would be achieved for timely and all-encompassing consideration of possible adverse and positive effects of construction and operation throughout the entire life cycle of the structure. Development and application of a system for managing environmental effects is the reality within the road agencies, which are faced with increasing demands of the professional and general public, primarily in the form of legislation and other regulations. Regarding the responsibility of environmental protection and improvement, it should be noted that the road agencies cannot influence the global problem of pollution and consumption of resources; however, through adequate management of activities during the road life cycle, they can significantly decrease the burden.

Keywords: roads, life cycle, environmental impacts, impact assessment, environmental protection, impact management

ISPITIVANJE DOZVOLJENE NOSIVOSTI VERTIKALNIH ŠIPOVA NA HORIZONTALNA STATIČKA OPETREĆENJA NA DOKOVIMA MARINE ZA MEGA JAHTE PORTO MONTENEGRO TIVAT, CRNA GORA

TESTING OF ALLOWABLE BEARING CAPACITY OF VERTICAL PILES UNDER LATERAL STATIC LOAD ON THE DOCKS OF THE MEGA-YACHT MARINA PORTO MONTENEGRO TIVAT, MONTENEGRO

Zvonko TOMANOVIĆ

ORIGINALNI NAUČNI RAD
UDK: 624.154.046:[656.616:629.525(497.16) = 861

1 UVOD

Marina za mega jahte Porto Montenegro se gradi na mjestu nekadašnjeg Vojno-remontnog zavoda "Sava Kovačević" u Tivtu. Najstariji dokovi koji su u upotrebi u ovoj luci postoje još od početka 19 vijeka i izgrađeni su kao masivne zidane konstrukcije (dok 1) za potrebe Austrougarske vojske-mornarice. Sedamdesetih godina prošlog vijeka luka je proširena izgradnjom još tri doka. Dograđeni dokovi su takođe izvedeni kao masivne nasute konstrukcije sa kamenim vertiklanim obložnim zidom ka unutrašnjosti luke.

Nakon što su dokovi manje ili više oštećeni u toku zemljotresa 15. aprila 1979. godine izvršena je sanacija i rekonstrukcija svih dokova do kraja 1984. godine. Pri ovoj sanaciji i rekonstrukciji postojeći dokovi su prošireni i sanirani tako što je izvedena armirano betonska polumontažna rasponska konstrukcija oslonjena na dva do tri reda šipova prečnika 60cm ili 100cm. Najveća oštećenja dokova, tridesetak godina nakon izgradnje (od 1984.), su zabilježena na rasponskoj konstrukciji. U toku radova na prenamjeni vojne luke u marinu za mega jahte izvedena je sanacija rasponske konstrukcije doka 1, dok su rasponske konstrukcije dokova 3 i 4 u potpunosti srušene i izgrađene nove. Mapa marine i dokova je prikazana na Slika 1.

Šipovi postojećih dokova su izvedeni uglavnom kao vertiklani. Pored nosivosti u vertikalnom pravcu, vertikalni šipovi moraju imati i dovoljnu nosivost u horizontalnom pravcu zbog prenošenja horizontalnih sila od brodova

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1 INTRODUCTION

Porto Montenegro Marina for mega yachts is being constructed on the site of the former Military Repair Facility Sava Kovacevic in Tivat. The oldest docks used in this port were built as massive embankment structures (Dock 1) for the purposes of the Austro-Hungarian Royal Navy in early 19th century. In the 70s of the last century the port was expanded by construction of three new docks. These additional docks were also built as massive embankment structures with a vertical stone facing towards the port interior.

After sustaining minor or major damages respectively during the earthquake on April 15 1979, all the docks were rehabilitated and reconstructed by the end of 1984. This rehabilitation and reconstruction project involved expansion and rehabilitation of the docks by construction of semi-precast reinforced concrete span structure supported by two or three rows of piles of 60cm or 100cm in diameter. Thirty years after the construction, major dock damages were identified in the span structure. During the works on conversion of a military marina into the mega-yacht marina, the span structure of Dock 1 underwent rehabilitation, while the span structures of Dock 3 and Dock 4 were completely demolished and replaced with new structures. Layout of the marina and docks is shown in Figure 1.

Pile support system of the existing docks mainly consists of vertical piles. In addition to the vertical bearing capacity, the piles must have adequate lateral

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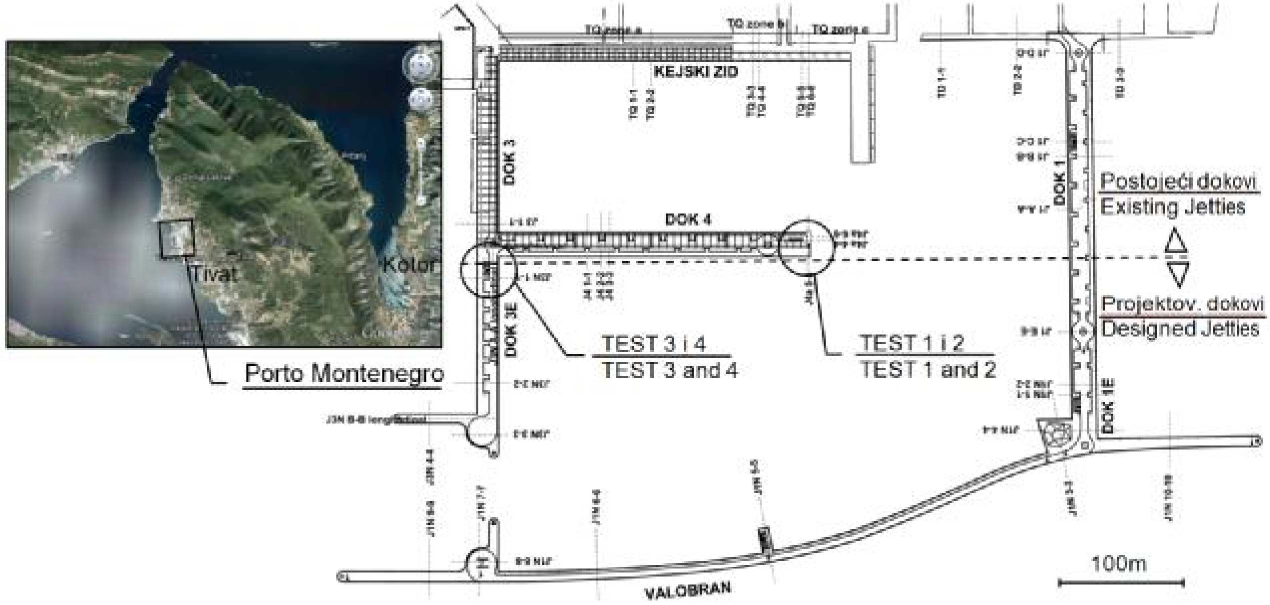
(sile vezivanja ili udar broda), vjetra, sila kočenja od vozila, i sl. U sklopu provjere ukupne nosivosti šipova izvedena su ispitivanja nosivosti vertikalnih šipova na horizontalna statička opterećenja, a povratnom analizom su definisani moduli rekacije pojedinih slojeva tla u kojima su izgrađeni šipovi. Povratna analiza je provedena korićenjem programskog paketa TOWER 6, na indentičnom modelu na kome je provedena analiza statičkih uticaja dokova 3 i 4 [3].

bearing capacity to accept lateral load transmitted by vessels (anchor force or ship collision force), wind load, vehicle break force etc. The estimate of total allowable pile bearing capacity involved testing of vertical piles under lateral static loads, while a reverse analysis was used to determine modulus of sub-grade reaction for individual soil layers. The reverse analysis was performed by applying TOWER-6 software package, employing the identical model as used for the static loading analysis of Dock 3 and Dock 4 [3].



Slika 1. Položaj marine Porto Montengero i raspored dokova
Figure 1. Layout of Porto Montenegro Marine and Dock Arrangement

2 OPIS POSTOJEĆEG STANJA DOKOVA I ŠIPOVA MARINE PORTO MONTENEGRO

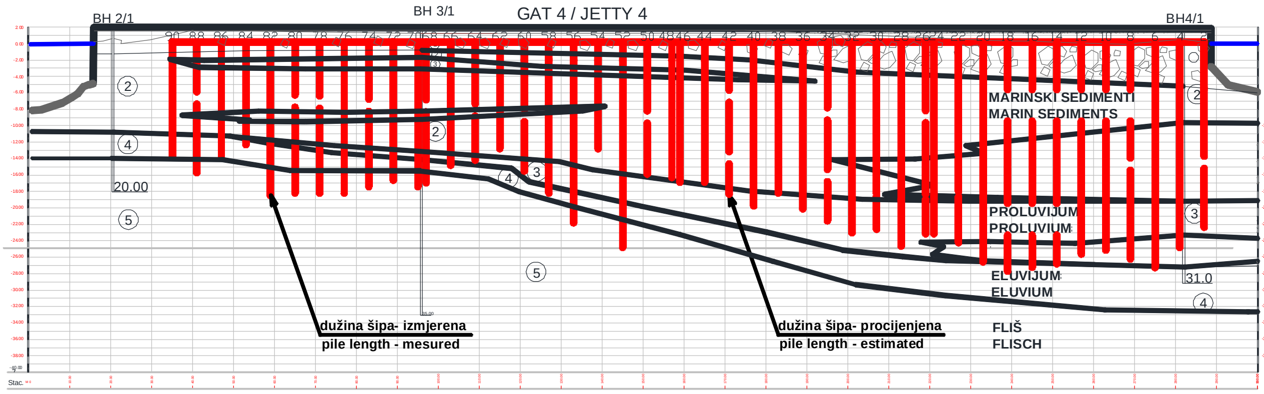
Šipovi na dokovima 3 i 4 su izvedeni 1984. godine, a u trenutku projektovanja rekonstrukcije 2010. godine nije postojala valjana dokumentacija o izvedenom stanju. Poseban problem pri procjeni nosivosti postojećih šipova predstavljala je činjenica da su ovi šipovi preko 30 godina bili u agresivnoj sredini i bilo je nepoznato u kavom su stanju sada. U cilju procjene stanja šipova na dokovima izvedena je serija testova i mjerenja koje su trebale da daju uvid u stepen oštećenosti šipova i njihovu nosivost za novoprojektovanu rasponsku konstrukciju i novu namjenu objekta. Izvedena su ispitivanja integriteta šipova prijenom ultrazvučne metode, ispitivanje kvaliteta betona šipova, provjera pojave korozije na armaturi šipova, ispitivanje debljine zaštitne čelične kolone šipa, ispitivanje nosivosti vertiklanih šipova u vertikalnom pravcu dinamičkom metodom i ispitivanje horizontalne nosivosti vertikalnih šipova.

Nakon ispitivanja i prikupljanja raspoloživih podataka o šipovima na dokovima 3 i 4 ustanovljeno je da su postojeći šipovi izvedeni pobijanjem čelične cijevi (kolone), debljine zida 12mm i spoljašnjeg prečnika 610mm. Čelična cijev je pobijena u tlo kroz morsku vodu dubine 5m do 7m, a unutrašnjost cijevi je ispunjena betonom, nakon iskopa tla iz cijevi. Beton unutar čeličnih kolona je u

2 DESCRIPTION OF EXISTING CONDITIONS OF DOCKS AND PILES OF PORTO MONTENEGRO MARINA

Piles supporting Jetty 3 and Jetty 4 were constructed in 1984, while at the moment of the reconstruction planning in 2010 no valid as-built design documents were available. Estimation of the actual allowable piles bearing capacities was difficult due to the fact that these piles had been embedded in aggressive environment for more than 30 years and thus, their current condition was unspecified. In order to perform the estimate of condition of the piles supporting jetties and their actual bearing capacity, series of tests and measurements were conducted to obtain data on the extent of damage occurred to the piles and actual bearing capacity of the piles incorporated to the newly designed span upper structure and for a new purpose of the facility. The following tests were conducted: ultrasonic testing of pile integrity, testing of concrete quality of piles, inspection of piles reinforcement for occurrence of corrosion, testing of thickness of the pile steel casing tube, dynamic sonic testing of vertical bearing capacity on vertical piles and testing of allowable lateral bearing capacity on vertical piles.

Testing results and collected available data on piles of Docks 3 and 4 implied that the existing piles were



Slika 2. Produžni geološki profil kroz dok 4
Figure 2. Longitudinal geological profile through Jetty 4

dobrom stanju, klase betona MB40. Podužna armatura je postavljena samo u gornjih 10m šipa, dok je u ostalom dijelu šip nearmiran. Dužina šipova varira u rasponu od 15m do oko 35m. Čelične kolone su u toku čitavog perioda od izgradnje od korozije štićene katodnom zaštitom, tako da je nekorodirana debljina kolone sada između 9 i 12mm.

Geološki profil na mjestu izgradnje dokova 3 i 4 je tipičan za Tivatski zaliv [1]. Na Slika 2 je prikazan geološki profil doka 4. Marinski sedimenti su prestavljeni tamnosivim muljevima, pjeskovima sa šljunkom različitog petrografskog sastava i prašinastim glinama. Ispod marinskih sedimenata leži sloj proluvijuma koji čine: šljunak, pijesak, drobina, prašinasti i glinovit sediment, mjestimično sa proslojcima gline i više zaglinjenih ostalih partija. Osnovnu stijenu na lokalitetu prestvalja tektonski oštećen flišni kompleks, preko kog je u debljini od 1m do 5m eluvijum fliša predstavljen tvrdim i prašinastim glinama i glinovitim laporima.

3 PROGRAM I USLOVI TESTIRANJA

Cilj ispitivanja šipova na horizontalno statičko opterećenje je verifikacija dozvoljene horizontalne nosivosti vertikalnih šipova sračunate u idejnim projektima dokova 3 i 4 [3]. Na predmetnoj lokaciji nema podataka o ranijem ispitivanju šipova na horizontalna dejstva, postoji ograničeno iskustvo u prenošenju horizontalnih sila vertikalnim šipovima u predmentoj geološkoj sredini i geološka situacija je relativno nepovoljna (gornji slojevi tla su marinskog porijekla). Imajući u vidu navedeno, mogući rizik na predmetnoj lokaciji se može okarakterisati kao visok, pa se pristupilo ispitivanju dozvoljene nosivosti vertikalnih šipova na horizontalne sile testiranjem na licu mjesta, a u cilju verifikacije proračuna dozvoljene nosivosti vertikalnih šipova na horizontalna dejstva datih u idejnim projektima dokova [3].

Na lokaciji je postojao jedan broj slobodnih šipova, nakon uklanjanja oštećene rasponske konsrukcije, koji su mogli biti iskorišćeni za ispitivanje. Ispitivanje horizontalne nosivosti vertikalnih šipova bilo je najefikasnije izvesti istovremenim ispitivanjem po dva šipa u paru. Pored nosivosti šipova, povratnom analizom, na proračunskom modelu korišćenom u projektima konstrukcije, treba da se dođe do

constructed by driving steel casing tube with wall thickness of 12 mm and outer diameter of 610mm. The steel casing tube was lowered through seawater depths from 5m to 7m and then the casing tube was back-filled with concrete upon soil extraction from the tube. Longitudinal reinforcement was provided in the upper 10 meters of the pile only, while the remaining lower part of the pile has been made without reinforcement. The length of piles ranges from 15m to approximately 35m. The installed cathode protection system has prevented corrosion of the pile casing tubes throughout the whole period of construction; hence, the thickness of the non-corroded pipe now ranges between 9mm and 12mm

Geological profile at the construction site of Jetties 3 and 4 is typical for the Bay of Tivat [1]. The geological profile of Jetty 4 is illustrated in Figure 2. Marine sediments consist of dark gray mud, sand and gravel of different petrographic composition and silty clay. Beneath the marine sediments lies a proluvial layer which consist of gravel, sand, debris, silty and clayey sediment, occasionaly with inter-imposed layers of clay and other various clayey materials. Bed rock on the site is represented by a tectonically damaged flysch complex, overlaid by 1m to 5m thick flysch eluvimal layer that is represented by hard and dusty clays and clay-marls.

3 TESTING PROGRAM AND REQUIREMENTS

The main purpose of pile testing for lateral static load is to verify allowable lateral bearing capacity of vertical piles as calculated in the preliminary designs of jetties 3 and 4 [3]. For the site concerned there is no available data on any previous pile testing for lateral load. There is limited experience in transmission of lateral forces by vertical piles in the referred geological environment and geological situation is relatively unfavorable (upper soil layers are of marine origin). Considering the aforementioned circumstances, a risk level on the site concerned may be considered as high; hence the in-situ tests of the allowable bearing capacity of piles for lateral loads were conducted in order to verify computations of vertical piles under lateral loads as set out in the preliminary designs of jetties [3].

After removal of the damaged upper - span structure, a few piles remained on the site with free upper end suitable for testing purposes. The most efficient testing koeficijenata reakcije tla za različite geološke slojeve na predmetnoj lokaciji i verifikuju korišćenih modula - koeficijenata reakcije pri proračunu [3] i [5]. Da bi se došlo do traženih podataka, predvuđeno je da se na šipove, preko pomoćnog horizontalnog rama, nanosi sila hidrauličkom presom tako da se šipovi međusobno privlače – primiču u horizontalnom pravcu. Pri opterećivanju se mjeri sila i inicijalno pomjeranje šipova u inkrementima, a takođe i vremenska deformacija do dostizanja brzine deformacije koja se može smatrati završetkom deformisanja.

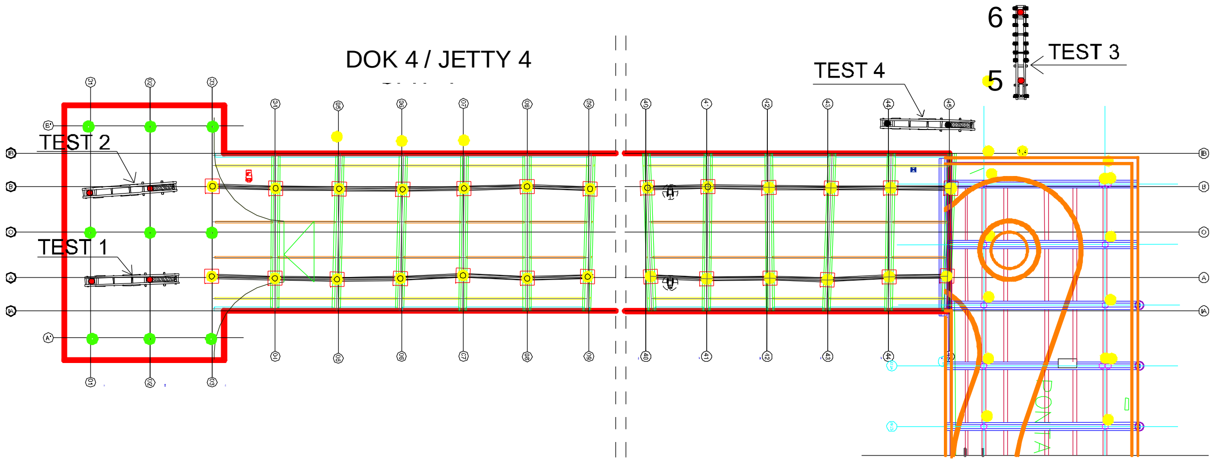
method of lateral bearing capacity of vertical piles assumed simultaneous testing of two piles in pair. Besides the determination of the allowable bearing capacity of the piles, the reverse analysis based on the computational model used in the structural designs should serve to derive actual coefficients of sub-grade reaction for different geological layers on the site concerned and to verify the coefficients of sub-grade reaction used for the design computations [3],[5]. In order to obtain the data required, it was envisaged to apply lateral force by using a hydraulic cylinder, through an auxiliary horizontal frame, and thus, made possible to develop the changes of the distance between tested pair of piles in the horizontal direction. During the testing the lateral force and initial and incremental displacements of piles were recorded, as well as the time-dependent displacements until their rates reach the state that may be considered as a completion of deformation.

3.1 Obim i uslovi ispitivanja

Programom ispitivanja je predviđeno da se ispitaju četiri para šipova [4]. Dva para na vrhu doka 3, a dva na vrhu doka 4. Položaj šipova koji su predviđeni za ispitivanje prikazani su na slici i 3. (Pozicije ispitivanja šipova su zbog značajnog smanjenja finansijskih sredstava odabrane na najpristupačnijim lokacijama dokova 3 i 4, slika 1.) Zbog tehničkih poteškoća u pristupačnosti nije ispitan jedan predviđeni par šipova na doku 3 (test 4).

3.1 Testing scope and requirements

Testing program specifies testing of four pairs of piles - two pairs on the top of Jetty 3 and two pairs on the top of Jetty 4 [4]. Position of piles subjected to testing is illustrated in Figure 3 (As a result of a significant fund size reduction, the positions for pile testing are selected on the most accessible locations of Jetties 3 and 4, Figure 1). Due to technical difficulties in accessibility, testing on one pile pair of Jetty 3 (Test 4) was not performed.



Slika 3. Položaj šipova predviđenih za testiranje
Figure 3. Position of piles to be tested

Pri definisanju programa istraživanja vodilo se računa da ispitivanje bude što jednostavnije, a uz korišćenje standardne opreme. Takođe, test je morao biti tako postavljen da se obezbjedi što je više moguće slični uslovi opterećivanja i granični uslovi na šipovima koji će kasnije biti ugrađeni u dokove i sa rasponskom konstrukcijom činiti jedinstvenu cjelinu. Posebnu specifičnost ovog ispitivanja prestavljalo je ispitivanje u otvorenoj morskoj vodi u kojoj su šipovi izgrađeni i u vrijeme oseke su iznad površine vode maksimalno oko 70cm, dok su u vrijeme plime šipovi praktično bili potopljeni u vodi.

Programom je takođe definisano da se u toku

At defining the Research Program, special attention was paid to the most simplified testing method and use of standard equipment. Further on, the underlying idea for the test was to provide the conditions most similar to the loading and boundary conditions for piles which are planned to be installed in jetties and to form integrated constituents to the upper-structure. A distinctive specificity of this testing is related to its performance in open seawater where the piles are constructed emerging above water surface to maximum 70 cm in times of high tide, while practically being submerged in the low tide period.

The testing program also specifies that, in addition to ispitivanja, pored instrumentalnog osmatranja i mjerenja, vrši permanentno vizuelno osmatranje svih pomoćnih ramova, presa i instrumenata. Cilj osmaranja je da se uoče eventualna pomjeranja, klizanja, krivljenja, uvijanja ili izvijanja ramova ili opreme koja bi mogla dovesti do gubitka stabilnosti rama za ispitivanje ili dijela opreme, a koji može dovesti u opasnost tim koji ispituje šipove. Nosači opreme i instrumenata za mjerenje pomjeranja moraju biti dovoljno kruti i fiksirani tako da u toku ispitivanja budu nepomjerljivi i bez vibracija koje mogu uticati na mjerenja. Oko šipova koji se ispituju potrebno je montirati adekvatne skele i platforme kako bi se obezbjedio nesmetan pristup [4].

Prije početka ispitivanja nosivosti šipova na horizontalno opterećenje proveden je test integriteta šipova ultrazvučnom metodom. Ovim testom je utvrđena dužina šipova i konstatovano je da li u šipovima ima eventualnih lokalna oštećenja u kontinuitetu betona. Mjerena je dubina – dužina šipa kroz slobodnu vodu.

3.2 Način testiranja

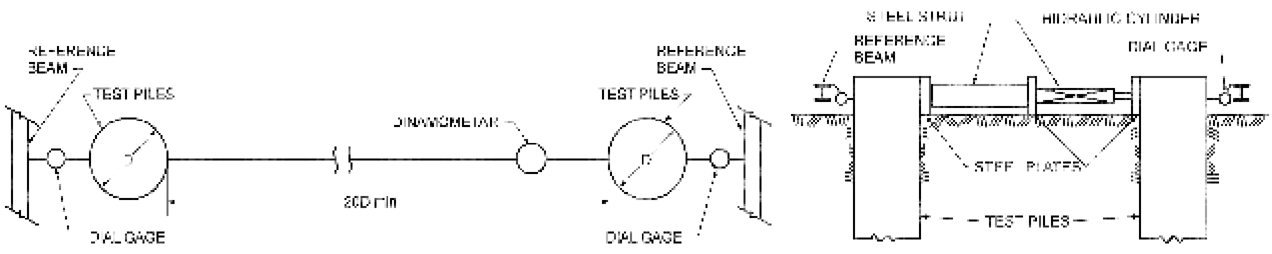
Ispitivanje je vršeno po standardu ASTM D3966-81, »Standard Method of Testing Piles Under Lateral Load«. Ovaj standard daje desetak tipičnih dispozicija testiranja. Na slici 3. prikazano je nekoliko načina ispitivanja šipova. Najjednostavniji način ispitivanja je da se dva šipa sa slobodnim krajem međusobno privlače užetom ili razmiču hidrauličkom presom, kako je prikazano na slici 4.a. Ovaj način ispitivanja je najeftiniji, ali na adekvatan način ne odražavaju granične uslove. Naime, prema projektu za dokove 3 i 4 jedan broj šipova je uklješten u gornju konstrukciju, kako je prikazano na karakterističnom poprečnom presjeku doka 4 na slici 5, [3].

instrumental observation and measurements, a continuous visual observation of all auxiliary frames, cylinders and instruments will be performed during the testing. The purpose of the observation is to identify any eventual displacement, sliding, bending, twisting or distortion of frames or equipment which could compromise stability of the frame or equipment constituents during the test procedure or pose a risk to the personnel carrying out pile testing. Support frames of the equipment and instruments for measurement of pile displacements will be sufficiently rigid and fixed in order to be immovable during the test procedure and exhibit no vibrations that may affect the measurement. Adequate scaffolding and platforms will be mounted around the piles which are subject to testing to allow unrestricted access [4].

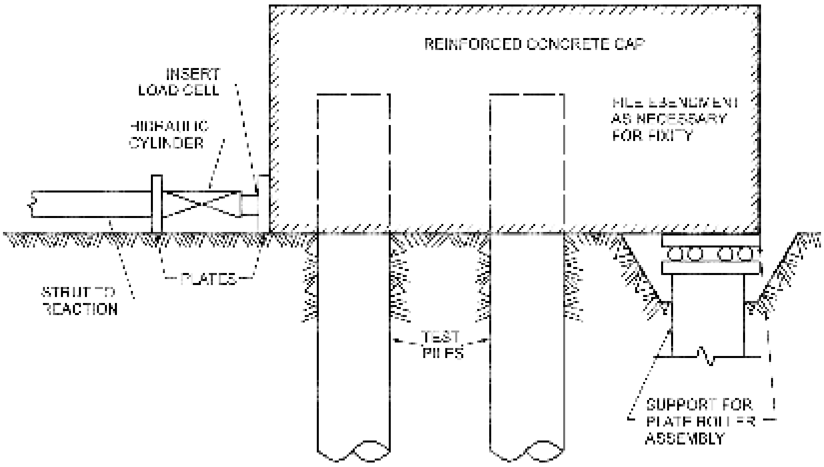
Prior to testing the pile bearing capacity for lateral load, the ultrasonic pile integrity test was conducted. This test was used to determine the length of the piles and identify any local damages to the concrete continuity. The pile depth i.e. pile length through free water was measured as well.

3.2 Testing method

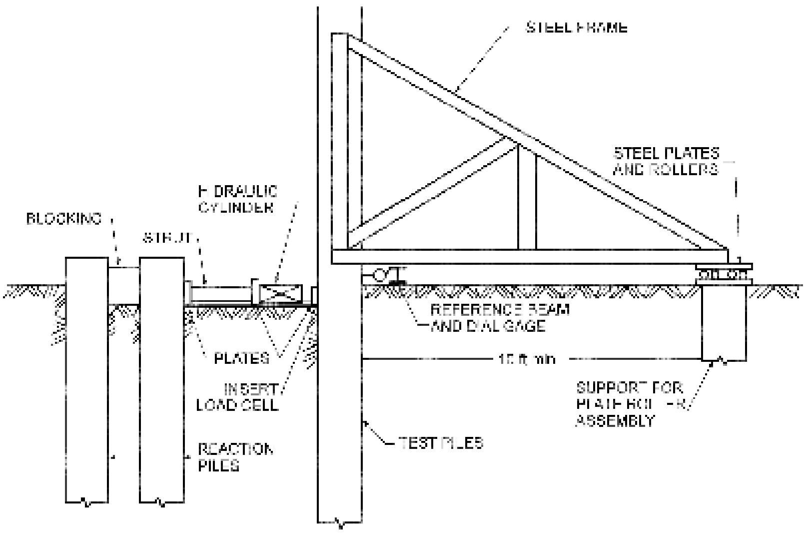
Testing is performed in compliance with ASTM D3966-81, »Standard Method of Testing Piles Under Lateral Load«. This standard provides for about ten typical disposition tests. Figure 3 illustrates several methods of pile testing. The most simplified testing method suggests that two piles with free ends are as illustrated in Figure 4.a. This testing method is the most cost-effective, yet does not indicate boundary conditions in a proper manner. The most simplified testing method is to reduce distance between two free-end piles by using a rope or increase distance by means of hydraulic cylinder, as illustrated in Figure 4.a. Though being the most cost-effective, this method fails to reflect boundary conditions in an adequate manner. Namely, the design of Jetties 3 and 4 specifies that certain number of piles has fixed ends to the upper structure, as illustrated in Figure 4 showing a typical cross section of Jetty 4 [3].



a) Sistem sa kojim se dva šipa koja se testriraju privlače užetom ili odmiču presom, respektivno
/ a) Two-pile testing system of reducing or increasing the distance between piles by rope or cylinder respectively



b)Sistem sa dva uklještena šipa koji se testriraju / b) Two fixed-end piles system testing



c)Sistem sa dva šipa od kojih je jedan uklješten u rešetku / c) Two-pile system testing, one having end fixed to the brace frame

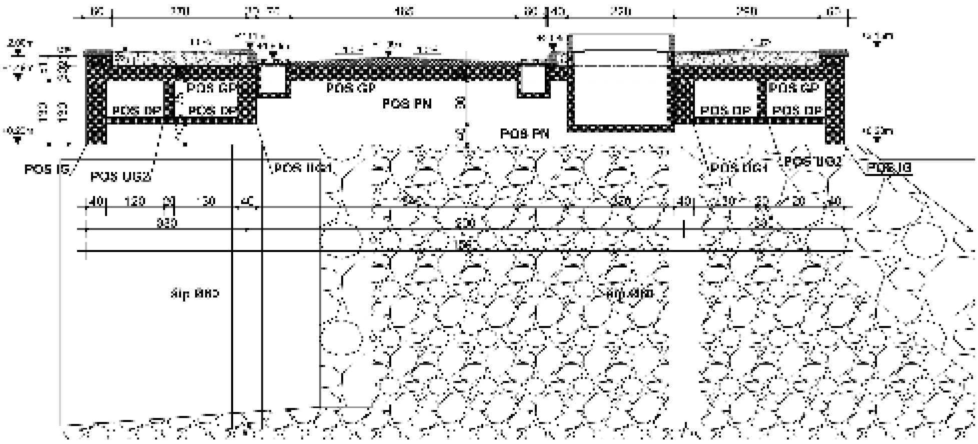
Slika 4. Moguće dispozicije testova za ispitivanje šipova po standardu ASTM D3966-81
Figure 4. Possible test dispositions for pile testing in compliance with ASTM D3966-81 standard

Najbolji način za ispitivanje šipova je da se zajedno ispitaju šipovi sa projekotvanom rasponskom konstrukcijom ili na način prikazan na slici 4.b. Ovaj način ispitivanja nije bilo moguće izvesti zbog dugog vremena za pripremu, cijene koštanja, a posebno zbog uticaja na dinamiku izvođenja radova. Kao najbolje izvodljivo rješenje prihvaćen je sistem prikazan na slici 4.c, stim što su izvršena prilagođavanja postojećem stanju na dokovima 3 i 4.

Šipovi su ispitivani u statičkim uslovima, nanošenjem sile pomoću hidraulične prese u zatvorenom čeličnom rešetkastom ramu. Za ispitivanje je projektovan rešetkasti ram prikazan na sl. 6. Čelični ram obezbjeđuje

The best available pile testing method implies that piles should be tested together with the designed span upper - structure or in the manner as illustrated in Figure 4.b. However, this testing method was not feasible due to the long lead-time preparations, cost price and particularly because of its impact on the schedule of works. The system illustrated in Figure 4.c. was accepted as the best possible option, though it required some adjustments according to the existing conditions of Jetties 3 and 4.

Tests on piles were conducted in static conditions, by using hydraulic cylinder to apply force in the enclosed steel brace frame. A brace frame illustrated in Figure 6



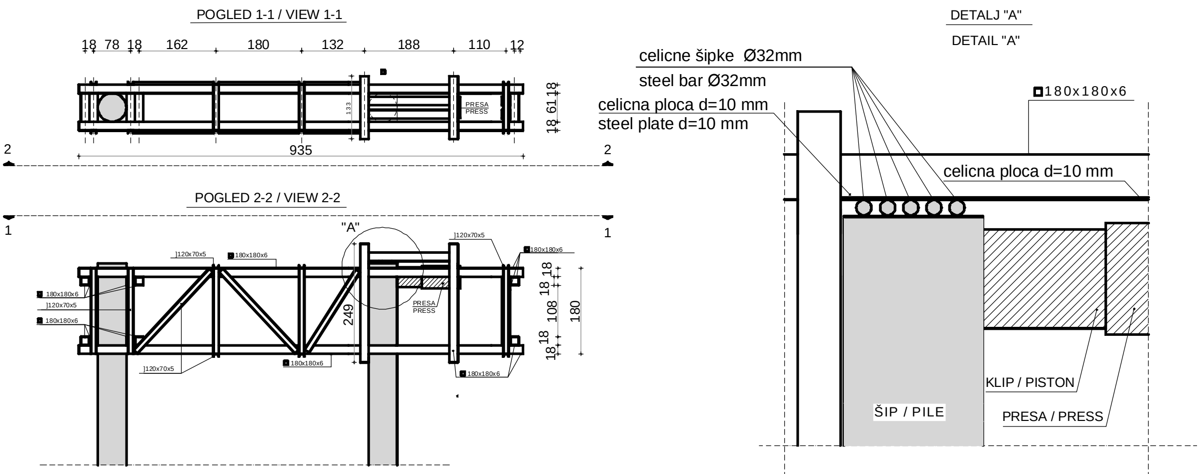
Slika 5. Karakteristični poprečni presjek doka 4
Figure 5. Typical cross section of Jetty 4

da je jedan šip (naspram prese) uklješten u ram, dok se drugi šip deformiše-pomjera kao slobodno oslonjen na vrhu. Međutim, zbog ušteda, izvođač radova je koristio ram, sastavljen od montažnih elemenata za „Bejli" most, ojačan i prepravljen za ispitivanje. Ovaj ram je prikazan na fotografijama na sl. 7.

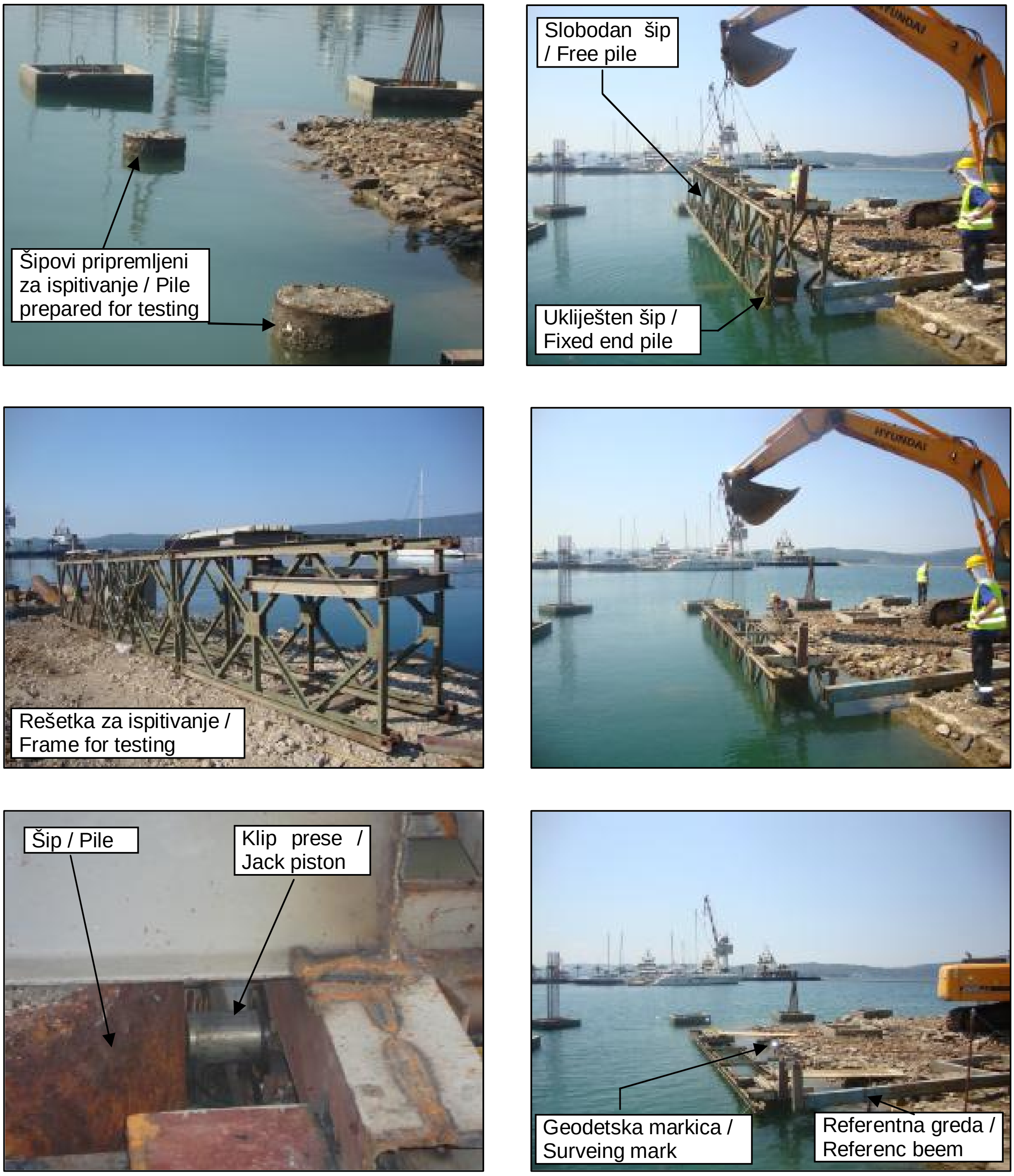
Prosječno računsko opterećenje vertikanih šipova u idejnom projektu dokova u horizontalnom pravcu iznosi 191,36kN, [3]. Programom ispitivanja je definisano da maksimalna horizontalna sila pri testiranju bude 1.5 puta veća od proračunske sile, dakle 287,04kN. Predviđeno je da se u toku testiranja opterećenje nanosi u četiri inkrementa, po četvrtina maksimalno predviđene sile testiranja. Opterećivanje i rasterećivanje šipa se vrši pri dostizanju eksploatacione sile. Pri nanošenju opterećenja mjere se pomjeranja vrha šipa. Kada se dostigne projektovana sila pojedinog inkrementa ona se nadalje održava konstatnom dok promjena pomjeranja ne padne ispod 0.25mm/sat. Pri mjerenju sile se mora obezbjediti min. tačnost od 3% od nanesene sile, a tačnost mjerenja pomjeranja min 0,1mm. [4].

was designed for the purpose of testing. The steel frame provides for one pile (opposite the jack) a fixed end to the frame, while allowing deformation i.e. displacement of the other as a free end pile. However, due to cost-savings, the contractor used a frame composed of the prefabricated elements for Bailey Bridge, reinforced and altered for the testing purposes. This frame is illustrated in Figure 7.

The average lateral load acting on vertical piles computed in the preliminary design of docks is 191.36kN [3]. The Research Program specifies that maximum lateral load during testing will be 1.5 times the computed load, meaning 287.04kN. It is anticipated that during testing the load should be applied in four increments each equal to one fourth the maximum test load. Pile loading and unloading was conducted at the level of the working load. When applying the loading increment, the displacements of pile head are measured. When each incremental load is reached, it is held constant until the rate of displacements is less than 0.25 mm per hour. During the load measurement, a minimum achievable accuracy should be 3% of the applied load with the measurement accuracy of displacements of minimum 0.1mm [4].



Slika 6. Projektovani ram za ispitivanje šipova
Figure 6. Frame designed for pile testing



Slika 7. Fotografije ispitivanja šipova na doku 4
Figure 7. Photos of tests on piles supporting Jetty 4

Svi pomoćni ramovi, prese, mjerači pomjeranja i druga sredstva moraju biti dovoljnog kapaciteta za ispitivanje. Pri tome prese moraju imati kapacitet min 1.5 x eksploataciona sila, a ostala oprema mora imati mogićnost da se test izvede pri pomjeranjima dvostruke veličine u odnosu na očekivano horizontalno pomjeranje. Kao osnov za definisanje očekivanih sila koje mogu da prenesu šipovi i pomjeranja koja se mogu očekivati poslužili su proračuni provedeni u idejnim projektima

All auxiliary frames, jacks, displacement measuring instruments and other devices should be of sufficient capacity to enable testing, where the capacity of jacks is not less than 1.5 times the working load, and thus, other devices enable testing conducted at the double values compared to the estimated lateral displacements. The calculations provided in the preliminary designs of Jetties 3 and 4 serve as basis for determining expected loads that can be transmitted by piles and expected dokova 3 i 4. Imajući u vidu navedeno, maksimalno planirano opterećenje šipa u horizontalno pravcu je 30t (300kN), pa je ram za opterećivanje, prese i druga sredstva morala biti dovoljnog kapaciteta za apliciranje navedene horizontalne sile. Maksimalno očekivano pomjeranje jednog šipa u horizontalno pravcu je oko 100mm.

Mjerenje pomjeranja su vršena elektronskim komparaterima i geodetskim opažanjem pomjeranja u horizontalnoj ravni. Očitavanja pomjeranja su vršena najmanje 5 puta u ravnomjernim intervalima u toku nanošenja sile u okviru jednog inkrementa opterećenja ili rasterećenja. Po dostizanju pojedine sile inkrementa očitavalo se pomjeranje sa komparatera nakon 1, 5, 15, 30 i 60 minuta, u preostalom vremenu na 1 sat do smirivanja pomjeranja, tj. dok promjena pomjeranja ne padne ispod 0.25mm/sat.

displacements. Considering the aforesaid, maximum pile design load in horizontal direction is 30t (300kN), hence the load frame, cylinders and other devices required sufficient capacity to accept applying the referred lateral load. Maximum expected displacement of a single pile in horizontal direction was about 100mm.

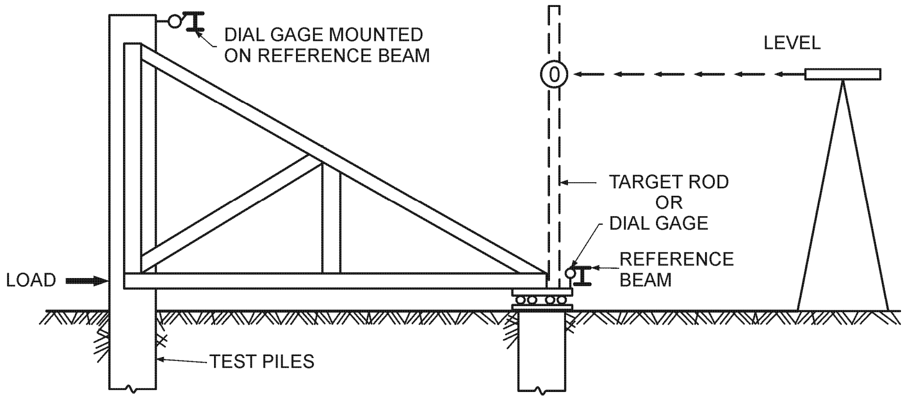
Measurements of displacements were conducted by means of electronic dial gauges and geodetic observations of displacements in the horizontal plain. Displacement readings were conducted not less than five times in equal time intervals during application of load within one loading or unloading increment. When final increment load is reached, the displacement readings were obtained from the dial gauges in time intervals of 1, 5, 15, 30 and 60 minutes and in the remaining period of 1 hour until the displacement remained constant, meaning the displacement rate was reduced to less than 0.25 mm per hour.

3.3 Oprema i instrumenti za ispitivanje

Za nanošenje opterećenja korišćena je presa kapacitata 300kN i hodom klipa 20cm. Za postizanje pritiska u presi je korišćena ručna uljna pumpa. Presa i pumpa za ulje su vidljive na fotografijama sl. 7. Sila koja se aplicira presom je mjerena preko baždarenog manometra ugrađenog u presu. Mjerenje pomjeranja šipa ukliještenog u ram vršeno je digitalnim elektronskim komparaterom i preciznim geodetskim instrumentom, dok je mjerenje slobodno oslonjenog šipa vršeno samo preciznim geodetskim instrumentom. Markice za geodetsko mjerenje pomjeranja šipova su vidljive na sl. 7. U svim inkermentima opeterećivanja vršena su nezavisna mjerenja jednim i drugim instrumentom. Šematski prikaz mjerenja prema standardu ASTM D3966-81 je prikazano na sl. 8.

3.3 Test equipment and instruments

A hydraulic jack of 300kN capacity and 20 cm long piston was used for applying the load. A manual oil pump is used to achieve pressure in the hydraulic jack. The jack and the pump are illustrated in Figure 7. The load applied by jack was measured by means of the integrated calibrated manometer. Displacement of the pile with end fixed to the frame was measured by means of a digital electronic dial gauges and precise geodetic instrument, while the free end pile displacement was measured by the precise geodetic instrument only. Geodetic referent points for the displacement of piles are illustrated in Figure 7. In all loading increments the independent measurements were conducted by either instrument. The scheme of measurements in compliance with ASTM D3966-81 standard is illustrated in Figure 8.



Slika 8. Šema mjerenja pomjeranja
Figure 8. Scheme of the displacement measurements

3.4 Vremenski i prostorni raspored ispitivanja

Ispitivanje šipova je vršeno u periodu od 9 do 17 jula 2010 godine. Ispitivanje šipova je izvedeno na lokacijama koje su predviđene programom ispitivanja, (vidi sliku 3.) U tabeli 1 prikazano je vrijeme ispitivanja i pozicija ispitanih šipova u odnosu na situaciju prikazanu u na sl.1 i 3.

3.4 Schedule and placement of tests

Pile testing was conducted from 9-17 June 2010. Pile testing was performed at the sites determined in the Testing Program (Figure 3). Table 1 shows test dates and position of tested piles compared to the site plan presented in Figures 1 and 3.

Tabela 1. Vrijeme ispitivanja i mjesto ispitivanih šipova
Table 1. Date and place of pile tests

Oznaka šipa u izvještaju / Pile designation in Report	Oznaka šipa u programu ispitivanja / Pile designation in Research Program		Datum ispitivanja šipa / Pile test date	Mjesto ispitivanja / Test site
	Uklješten / Fixed end	Slobodan / Free end		
TEST - 1	šip 1 / pile 1	šip 2 / pile 1	14. 07. 2010.	DOK 4
TEST - 2	šip 3 / pile 3	šip 4 / pile 4	16. 07. 2010.	DOK 4
TEST - 3	šip 5 / pile 5	šip 6 / pile 6	17. 07. 2010.	DOK 3

4 INTERPRETACIJA REZULTATA ISPITIVANJA VERTIKALNIH ŠIPOVA NA HORIZONTALNA OPTEREĆENJA

Ispitivanje šipova je izvršeno na dvije lokacije, i to: pri vrhu doka 4 i pri vrhu doka 3, kako je i bilo predviđeno programom ispitivanja (sl. 1). Moguće reprezentativnije lokacije za ispitivanje šipova (po sredini dokova) nisu bile slobodne zbog rasponskih konstrukcija koje su se nalazile na njima. Odabrane lokacije za ispitivanje šipova bile su na izvjestan način iznuđene slobodnim šipovima i pristupom, pa se zbog toga i rezultati ispitivanja na ove dvije lokacije značajno razlikuju.

4.1 Razmatrani parametri i procedure

Pri interpretaciji rezultata mjerenja neophodno je voditi računa o tipu i dužini ispitivanih šipova, vrstama tla i slojeva u kojim je šip izgrađen, modelu za povratnu analizu i sl. Radi toga u ovom dijelu se daje opis svih bitnih parametara koji su razmatrani i procedura koje su provedene u cilju definisanja dozvoljene nosivosti šipova u konstrukciji na horizontalna dejstva, a na bazi rezultata testova provedenih na pojedinačnim šipovima.

Tip i dužina šipa

Ispitivanje je provedeno na šipovima na kojima je izvršeno fundiranje rasponskih konstrukcija dokova 3 i 4. U ovom pogledu nije bilo potrebe vršiti bilo kakve korekcije ili skaliranja rezultata testiranja zbog razlike testiranih i šipova na kojim je fundirana konstrukcija.

Vrsta tla i slojeva u kojim je šip izgrađen

Ispitivani šipovi su izgrađeni u geološkoj sredini koja se u regularnom poretku slojeva prostire u čitavoj zoni dokova 3 i 4, pa su ispitivani šipovi u tom pogledu reprezentativni. Razlike koje se pojavljuju između doka 3 i 4 se prvenstveno odnose na debljinu pojedinih slojeva koja varira duž dokova.

Modul rekacije tla pojedinih slojeva tla u kojima su izgrađeni šipovi

Početne vrijednosti modula reakcije tla su sračunate primjenom formule Vesića,

4 INTERPRETATION OF THE RESULTS OF TESTING VERTICAL PILES UNDER LATERAL LOAD

Pile tests were conducted at two locations – near the top of Jetty 4 and Jetty 3 as it was determined in the Testing Program (Figures 1). Possibly more representative locations for pile testing (mid part of the docks) were not available due to the existing span upper structures. The selected locations were to some extent conditioned by the presence of free piles and available access; hence the test results at these two locations are significantly different.

4.1 Considered parameters and procedures

When interpreting measurement results, attention should be paid to the type and length of the tested piles, type of soil and presence of layers, in which the pile is embedded, reverse analysis model etc. Therefore, the description of all relevant parameters employed and procedures applied in order to define the allowable pile bearing capacity at the structure under lateral loads and based on the results of the tests conducted on each pile is provided here below.

Type and length of the pile

Tests were carried out on the piles forming piled foundation of the span upper- structures of Docks 3 and 4. In this regard no corrections or scaling of the test results due to the difference arising between the tested piles and the upper structure piled foundation was required.

Type of soil and layers in which pile is embedded

Tested piles are built in a geological environment extending over the total area of Jetties 3 and 4 in the regular sequence of layers, thus the tested piles are representative in this regard. Differences between Jetty 3 and Jetty 4 primarily refer to the thickness of single layers which varies along the jetties.

Modulus of sub-grade reaction to piles for single layers

Initial values of modulus of sub-grade reaction are calculated by Vesic's equation,

$$k_s = \frac{0.65}{d} \sqrt[12]{\frac{E_s \times d^4}{E_p I_p}} \times \frac{E_s}{1-n_s^{\;2}} \qquad (9a)$$

Gdje su E_s – modul elastičnosti tla

n_s – *Poasonov* koeficijent za tlo

E_pI_p – krutost šipa

d – prečnik šipa

Na osnovu podataka o karakteristikama tla datih u elaboratu o geotehničkim karakteristikama pojedinih slojeva tla sračunate su vrijednosti prikazane u tabeli br. 2, [1].

Where E_s – elastic modulus of soil

n_s – *Poisson's ratio* for soil

E_pI_p – rigidity of pile

d – pile diameter

Table 2 shows values that are calculated based on the soil properties provided in the Study on geotechnical properties of individual layers *[1].*

Tabela 2. Vrijednosti modula rekacije tla prema Vesiću
Table 2. Values of modulus of sub-grade reaction according to Vesic

Vrsta tla (sloj) / Type of sub-grade (layer)	Modul stišljivosti / Modulus of Compressibility [kPa]	Modula rekacije tla prema Vesiću / Modulus of sub-grade reaction after Vesic [kN/m^3]		Prosječan modul rekacije tla / Average modulus of sub-grade reaction [kN/m^3]
		donja granica / Lower limit	gornja granica/ Upper limit	
Nasip / Embankment	3000	2210		
Marinski sedimenti / Marine sediments	5674-16467	3000	14604	8785
Meke gline / Soft clays	5000	2587		
Proluvijum / Proluvium	4545-35714	2334	20844	11588
Fliš i eluvijum fliša / Flysch and eluvium flysch	10253-33330	8368	31348	19858

Model za povratnu analizu

Na osnovu izmjerenih pomjeranja vrha šipa povratnom analizom se došlo do modula reakcije tla pojedinih slojeva. Naime, šipovi i tlo su modelirani u programskom paketu TOWER na isti način kako je to urađeno i u projektu konstrukcije [3]. Šipovi su modelirani kao štapovi kojim su dodjeljene realne geometriske i materijalne karakteristike šipova, a tlo je modelirano oprugama sa konstantnim modulima reakcije tla za pojedine slojeve. Čelični ram za ispitivanje šipova je modeliran kao ravanski. U ospisanom numeričkom modelu su učinjena izvjesna pojednostavljenja, naročito u pogledu ponašanja tla. Međutim, tretiranjem "problema" na istom modelu tla, u proračunu konstrukcije i povratnoj analizi, uticaji pojednostavljenja su prigušeni i bez bitnog uticaja na krajnji rezultat za predmetni problem. Šema modela za analizu nosivosti šipova je prikazana na sl. 9.

Uklješteni šip je analiziran posebnim modelom zajedno sa ramom-rešetkom za nanošenje horizontalne sile (sl.9.a), dok je u posebnom modelu analiziran slobodno oslonjen šip opterećen istom horizontalnom silom i vertikalnom rekacijom rama na mjestu slobodno oslonjenog šipa, sl.9.b. Nakon iterativnog postupka iznalaženja vrijednosti modula reakcije tla, prema rezultatima testa 3, dobijene su računske vrijednosti iz povratne analize prikazane u tabeli 3.

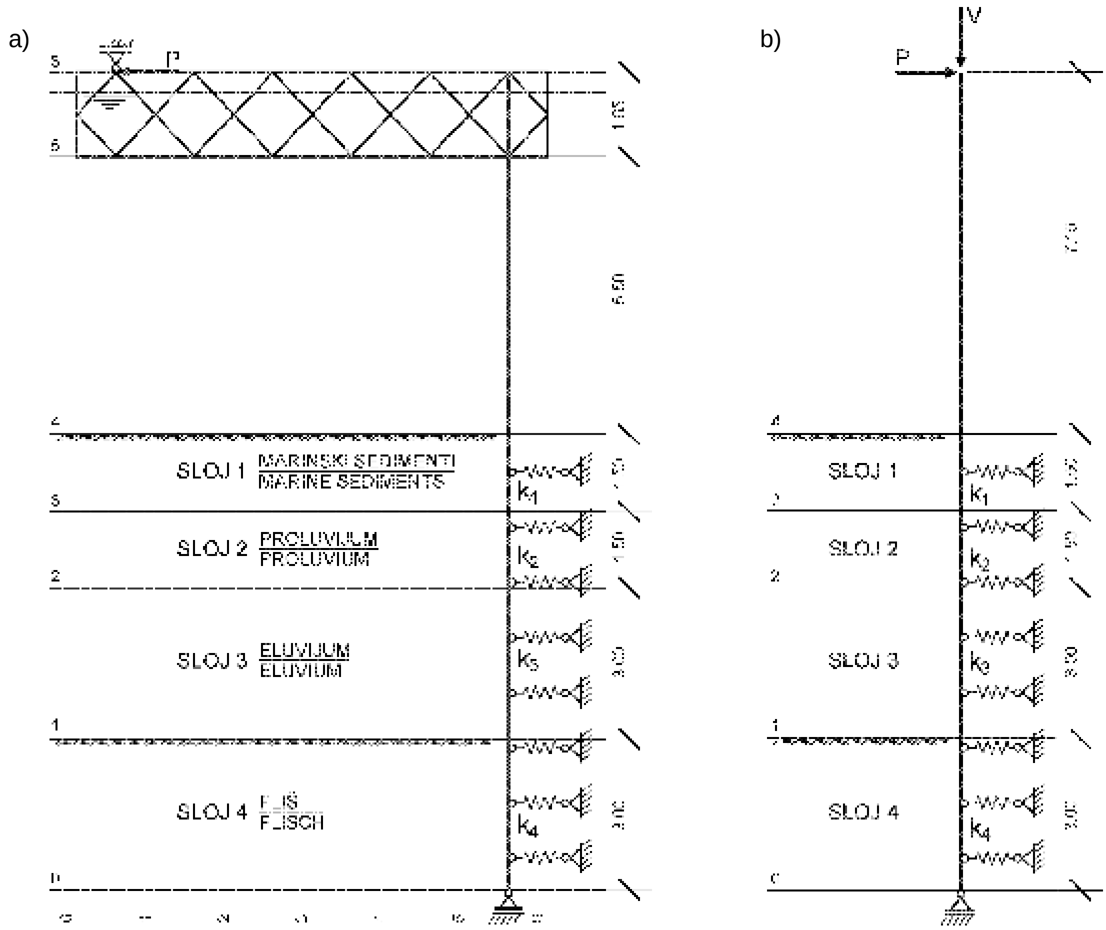
Reverse analysis model

Based on the measured pile head displacements, the modulus of sub-grade reaction of individual layers was derived from the reverse analysis. Namely, the piles embedded in soil were modeled using TOWER software package in the same manner as applied for the structural design [3]. The piles were defined as rods having the same geometric and material properties as the real pile, while the soil was modeled using springs with constant modulus of sub-grade reaction for individual layers. Steel frame for pile testing was modeled as a plane frame. The described numerical model involved some simplifications, particularly for the soil behavior. However, effects of such simplifications were mitigated and did not cause any relevant impact to the final result for the problem concerned by the treatment of "the problem" using the same soil model as in the structural computations and reverse analysis. The schematic model used for analysis of the pile bearing capacity is illustrated in Figure 9.

The fixed end pile was analyzed in one model case together with the frame-grid used for applying the lateral load (Figure 9.a), while another model case was used for the analysis of the free end pile being subject to the same lateral load and vertical reaction of the frame at the point of the free end of the pile (Figure 9.b). After iterative process of determining values of the modulus of sub-grade reaction, based on the Test 3 results, the computed values were obtained from the reverse analysis as shown in Table 3.

Tabela 3. Vrijednosti modula rekacije tla dobijene povratnom analizom
Table 3. Values of modulus of sub-grade reaction derived from the reverse analysis

Vrsta tla (sloj) / Type of sub-grade (layer)	Prosječan računski modul rekacije tla prema Vesiću / Average computed modulus of sub-grade reaction according to Vesic [kN/m^3]
Nasip / Embankment	3000
Marinski sedimenti / Marine sediments	14000
Meke gline / Soft clays	5000
Proluvijum / Proluvium	10000
Fliš i eluvijum fliša / Flysch and flysch eluvium	20000



Slika 9. Šematski prikaz modela šipa i rama za ispitivanje a) uklješten šip, b) slobodan šip
Figure 9. Schematic model of pile and frame for a) fixed end pile, b) free end pile

Rezultati prikazani u tabeli 3 su dalje analizirani u kontekstu dobijenih rezultata mjerenja na parovima šipova testiranih na doku 3 i 4.

4.2 Uporedna analiza rezultata mjerenja i proračuna

Test 3 proveden na paru šipova u produžetku doka 3 ukazuje na relativno malu dozvoljenu nosivost šipova na horizontalna opterećenja. Naime, ovi šipovi su izgubili nosivost već kod horizontalne sile od 75-80kN, dok je zahtjevana dozvoljena nosivost 190kN. Koristeći

The results shown in Table 3 were further analyzed in the context of the results obtained from measurements conducted on the pairs of piles tested at Jetties 3 and 4.

4.2 Comparative analysis of measuring and computation results

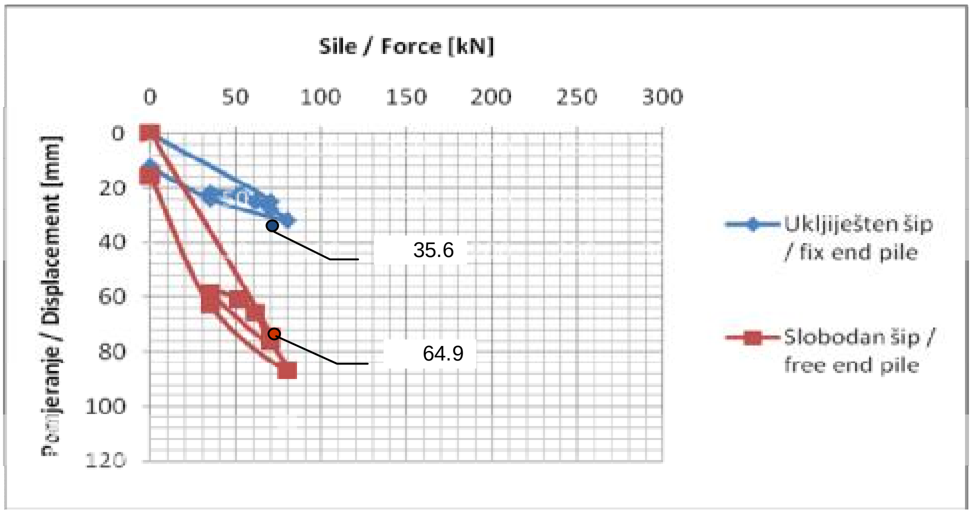
Test 3 conducted on the pair of piles located in continuation of Jetty 3 indicates a relatively low allowable bearing capacity of piles under lateral load.

pomjeranja vrha šipa dobijena pri horizontalnoj sili od 70kN povratnom analizom su dobijene vrijednosti modula reakcije tla prikazane u tabeli 3.

Sračunata pomjeranja vrha šipa pri horizontalnoj sili od 70 kN (vidi sl. 10), ralativno dobro se poklapaju sa izmjerenim vrijednostima. Tako za slobodno oslonjen šip sračunato pomjeranje iznosi 64.97mm, dok je izmjerena vrijednost oko 74mm. Za uklješteni šip sračunato pomjeranje iznosi 35.68mm, dok je izmjerena vrijednost oko 25mm. Na slici 10. je prikazan dijagam mjerenih i sračunatih horizontalnih pomjeranja vrha šipa.

Namely, these piles loose bearing capacity already under lateral load of 75-80kN, while the required allowable bearing capacity is 190kN. Using the pile head displacements, values of modulus of sub-grade reaction reached under lateral load of 70kN (Table 3) were derived from the reverse analysis.

Computed pile head displacements under lateral load of 70kN (Figure 10) relatively well coincide with the measured values. Consequently, the computed value for the free end pile is 64.97 mm and the measured value is 74 mm. In case of the fixed end pile, the computed value is 35.68 mm and the measure value is 25mm. Chart of measured and computed lateral displacements of pile head is illustrated in Figure 10.



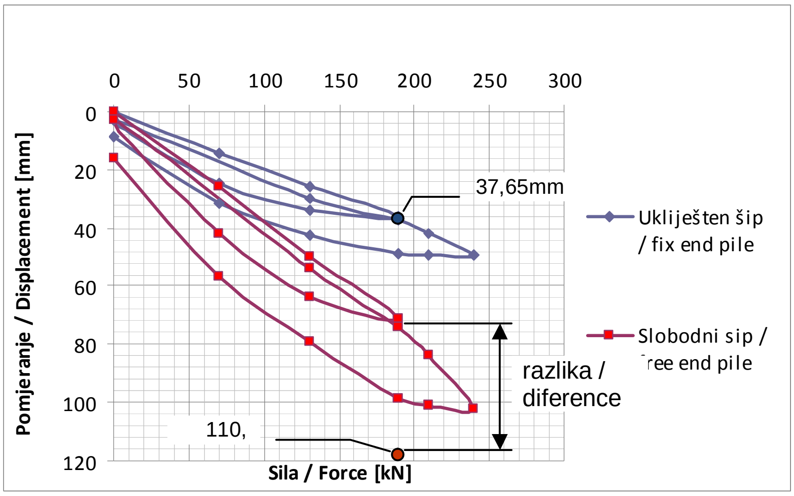
Slika 10. Dijagram mjerenih i sračunatih horizontalnih pomjeranja vrha šipa TEST 3
Figure10. Chart of measured and computed lateral displacements of pile head TEST 3

Testovi 1 i 2 su proveden na dva para šipova u produžetku doka 4 i prenjeli su značajno veće horizontalne sile (prije gubitka nosivosti) u odnosu na šipove ispitane u vrhu doka 3. Ovi šipovi su premašili zahtjevanu dozvoljenu nosivost od 190kN i izgubili nosivost kod horizontalne sile 240kN ili iznad 280kN. Koristeći rezultate povratne analize za module reakcije tla iz testa 3, pri horizontalnoj sili od 190kN (radno opterećenje) dobijene su računske vrijednosti pomjeranja vrha šipa, što je prikazano na dijagramima Slika 11 i 12.

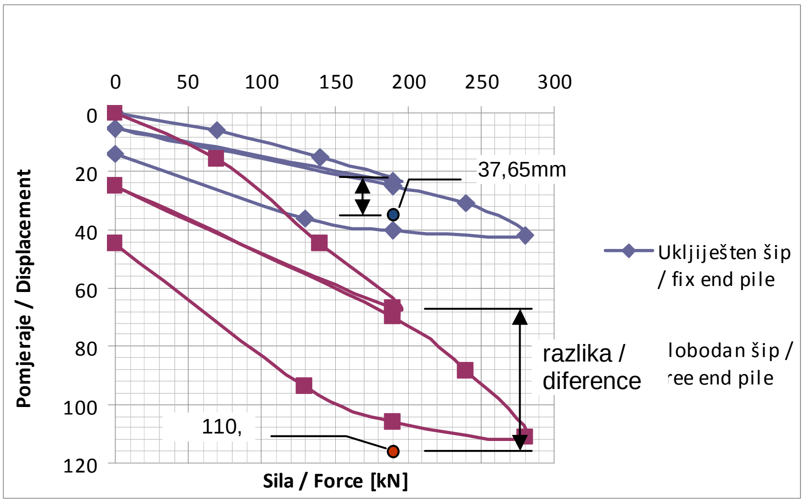
Sračunata pomjeranja vrha ukljiještenog šipa pri horizontalnoj sili od 190 kN (vidi sl. 11 i 12), relativno dobro se poklapaju sa izmjerenim vrijednostima. Za slobodan šip sračunata pomjeranja su značajno veća. U cilju iznalaženja modula reakcije pojedinih slojeva tla, koji će dati dobra poklapanja sračunatih i izmjerenih pomjeranja slobodno oslonjeg i uklještenog šipa, izrađeno je desetak modela i variran veliki broj kombinacija modula reakcija tla za različite slojeve tla u realnom geološkom presjeku. Međutim, ukoliko se zadaju moduli reakcije takvi da se računski rezultati pomjeranja vrha uklještenog šipa dobro poklapaju, onda rezultati za slobodni šip značajno odstupaju i obrnuto.

Test 1 and Test 2 were conducted on the two pairs of piles located in continuation of Jetty 4 and their recorded transmission was of significantly higher lateral load (before losing bearing capacity) compared to the piles at the top of Jetty 3. These piles have exceeded the allowable bearing capacity of 190kN and lost bearing capacity under lateral load of 240 to 280kN. Using the results of the reverse analysis for modulus of sub-grade reaction applied for Test 3, values of pile head displacements under lateral load of 190kN (work load) are obtained, as illustrated in Figure 11 and Figure 12.

Computed displacements of fixed end pile head under lateral load of 190kN (Figure 11 and Figure 12) relatively well coincide with the measured values. In the case of free end pile, computed displacements are significantly higher. In order to determine modulus of reaction of single soil layers that would ensure a close match of computed and measured displacement of free end and fixed end piles, about ten models was generated with different values used for modules of sub-grade reaction of individual layers in the real geological section. However, where used modules of sub-grade reaction are such that results of displacement of the fixed end pile head provide a close match, the results for the free end pile exhibit significant discrepancies and vice versa.



Slika 11 . Dijagram mjerenih i sračunatih horizontalnih pomjeranja vrha šipa TEST 1
Figure 11. Chart of measured and computed lateral displacements of pile head TEST 1



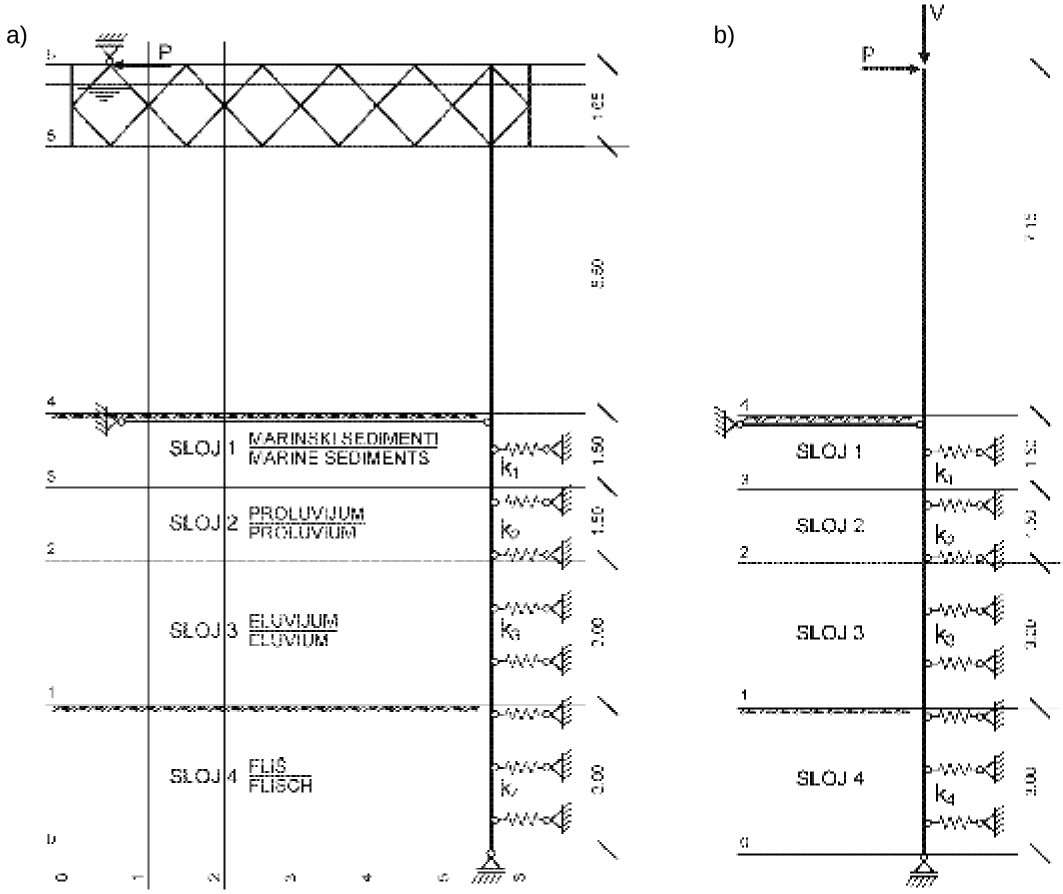
Slika 12. Dijagram mjerenih i sračunatih horizontalnih pomjeranja vrha šipa TEST 2
Figure 12. Chart of measured and computed lateral displacements of pile head TEST 2

Dalje analize su ukazale da se dolazi do prihvatljivih rezultata, ako se u visini dna mora (aktuelnog terena) postavi ojačanje tipa AB ploče, sloja vrlo nabijenog kamena, i sl. Ovo ojačanje bi se moglo povezati, ali ne i dokazati bez dodatnih radova, sa lokacijom ispitivanja na vrhu doka 4 gdje je, moguće, vršeno ojačanje "grudobrana" od talasa.

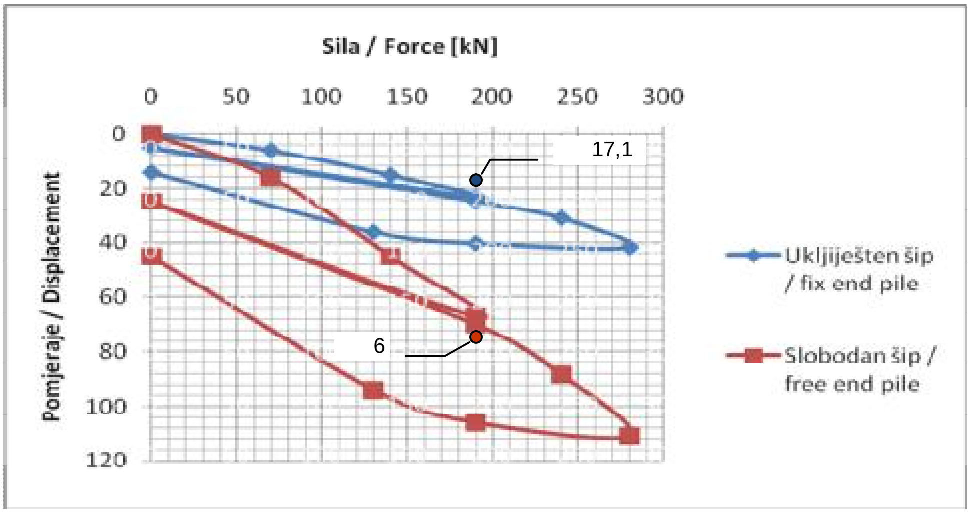
Jedan ovakav model sa ojačanjem u visini morskog dna je dao rezultate koji se najbolje uklapaju u izmjerena pomjeranja šipova u testu 2 kako je prikazano na slici 13. Pri računskoj analizi su korišćeni već ranije definisani moduli reakcije tla iz testa 3, prikazani u tabeli 3. Ojačanje u visini morskog dna nije bitno uticalo na sračunate vrijednosti pomjeranja vrha ukliještenog šipa, dok su vrijednosti pomjeranja vrha slobodnog šipa smanjene i približile su se mjerenim vrijednostima, sl 14. Uporedna analiza izmjerenih vrijednosti pomjeranja šipova i računskih modela ukazuju da su povratnom analizom dobijene realne vrijednosti modula rekacije pojedinih slojeva tla.

Further analysis indicated that acceptable results for pile behavior can be achieved if a concrete slab or similar reinforcement, as densely compacted stone layer etc. is installed at the sea floor level (actual ground surface). This kind of reinforcement could be joined but not verified without additional works at the location of testing place at the top end of Jetty 4, where, possibly, the reinforcement of breakwater against wave action was already carried out.

Previous model with reinforcement at the sea floor level showed the results which fit best to the computed displacements of piles subject to Test 2 as illustrated in Figure 13. Computational analysis employed modules of sub-grade reaction as previously defined in Test 3 and shown in Table 3. Reinforcement at the sea floor level displayed no relevant impact on the computed displacement values of the fixed end pile head, while displacement values of the free end pile head were reduced and approached the measured values, Figure 14. Comparative analysis of computed values of pile displacements and computational models from reverse



Slika 13. Šematski prikaz modela sa ojačanjem a) uklješten šip, b) slobodan šip
Figure 13. Schematic model with reinforcement for a) fixed end pile, b) free end pile



Slika 14 . Dijagram mjerenih i sračunatih horizontalnih pomjeranja vrha šipa za model sa ojačanim slojem u nivou morskog dna
Figure 14. Chart of measured and computed lateral displacements of pile head for model with reinforced layer at the sea floor level

Iz dijagrama sila – pomjeranje prezentovanih na slikama 11 i 12 može se vidjeti da se pri ciklusima opterećenja (do projektovane sile 190 kN) i rasterećenja akumuliraju plastične (nepovratne) deformacije koje progresivno rastu sa povećanjem broja ciklusa. Pri testiranju na statička opterećenja šipova nije izveden veliki broj ciklusa opterećenja i rasterećenja da bi se mogala ocijeniti deformacija posle velikog broja ciklusa (npr. pri dejstvu zemljotresa), ali je iz ponovljenog testa 1, sl.11, sasvim vidljivo da posle tri cikusa opterećivanja prirast plastične deformacije nije konačan. Ciklično opterećeivanje nije bilo predmet ispitivanja pa nije bilo moguće provesti detaljnije analize.

5 ZAKLJUČAK O PROCJENI DOZVOLJENE HORIZONTALNE NOSIVOSTI VERTIKALNIH ŠIPOVA

Ispitivanjem dozvoljene nosivosti šipova na horizontalno statičko opterećenje došlo se do realnih podataka o dozvoljenoj nosivosti šipova, koja je pokazala da su prosječne nosivosti šipova oko 196kN. Ova dozvoljena nosivost se može povezati sa slobodno oslonjenim šipom, dok je dozvoljena nosivost šipova uklještenih u konstrukciju veća. Uporednom analizom rezultata računskog modela i mjerenih vrijednosti pomjeranja vrha šipa došlo se do relativno pouzdane procjene o modulima reakcije tla u horizontalnom pravcu za pojedine slojeve tla na predmetnoj lokaciji i prosječne dozvoljene horizontalne nosivosti šipova.

Na osnovu rezultata mjerenja na terenu i dobijenih vrijednosti parametara iz povratne analize može se zaključiti da su moduli reakcije tla dobijeni povratnom analizom značajno veći od prosječnih modula koji su dobijeni primenom formule Vesića, a na osnovu procjenjenih vrijednosti modula stišljivosti pojedinih slojeva tla u geološkom elaboratu. Realne vrijednosti modula rekacije tla primjenom formule Vesića se dobijaju za gornje procjenjene vrijednosti modula stišljivosti tla, što su korisni podaci za buduće projekte koji su planirani u zoni marine.

Iz prezentovanih dijagrama sila – pomjeranje može se vidjeti da se pri ciklusima opterećenja i rasterećenja akumuliraju plastične (nepovratne) deformacije koje progresivno rastu sa povećanjem broja ciklusa i nivoa dostignute sile pri opterećivanju. Zaostale plastične deformacije zglobno vezanih šipova za konstrukciju su 2 do 2,5 puta veće od plastičnih deformacija šipova uklještenih u gornju konstrukciju.

analysis indicates that the reverse analysis provided actual values of modulus of sub-grade reaction for individual layers.

It is evident from the load-displacement chart illustrated in Figure 11 and Figure 12 that the irreversible plastic deformations increasing progressively as the number of cycles increases, and accumulate under loading (up to design load of 190kN) and unloading cycles. At testing piles for static loads, number of loading and unloading cycles applied was not high enough in order to enable estimation of accumulated deformation after much higher number of cycles (e.g. during earthquake impact). Therefore, from repeated loading in Test 1 (Figure 11), it is clearly visible that after three loading cycles, the increment of plastic deformation is not final. As the load-cycling versus displacements study was not envisaged for consideration during these tests, no further analysis could be conducted.

5 CONCLUSION ON ESTIMATION OF THE ALLOWABLE LATERAL BEARING CAPACITY OF VERTICAL PILES

By testing the allowable bearing capacity of piles under lateral static load the actual data on the allowable pile bearing capacity is derived indicating an average bearing capacity of piles of approximately 196kN. This allowable bearing capacity can be related to the free end piles, while it is higher in the case of the files having fixed ends to the upper structure. By comparative analysis of the computational model results and measured displacement values of pile head, a relatively reliable estimation was obtained for modulus of sub-grade reaction in horizontal direction for individual soil layers on the location concerned and also average allowable lateral bearing capacity of piles.

Based on the in-situ measuring results and the values of parameters obtained from the reverse analysis, it can be ascertained that the modules of sub-grade reaction derived from the reverse analysis are significantly higher than the average modules obtained by Vesic's equation based on the estimated elastic modules of individual soil layers in the Geological Study. Actual values of the modules of sub-grade reaction based on Vesic's equation are obtained using upper estimated values of the modules of soil compressibility; this is a useful information for further projects planned in the same marina zone.

It is evident from the presented load-displacement charts, that the irreversible plastic deformations increase progressively as the number of cycles and level of the achieved load raise, and accumulate under loading and unloading cycles. Residual plastic deformations of the piles with a hinged joint to the upper structure are from 2 to 2.5 times larger than the plastic deformations of the piles having ends fixed to the upper structure.

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REZIME

ISPITIVANJE DOZVOLJENE NOSIVOSTI VERTIKALNIH ŠIPOVA NA HORIZONTALNA STATIČKA OPTEREĆENJA NA DOKOVIMA MARINE ZA MEGA JAHTE PORTO MONTENEGRO TIVAT, CRNA GORA

Zvonko TOMANOVIĆ

Šipovi postojećih dokova marine za mega jahte „Porto Montenegro” su izvedeni uglavnom kao vertiklani. Pored nosivosti u vertikalnom pravcu, vertiklani šipovi moraju imati i dovoljnu nosivost u horizontalnom pravcu zbog prenošenja horizontalnih sila od brodova (sile vezivanja ili udar broda), vjetra, sila kočenja od vozila, i sl. Na predmetnoj lokaciji nema podataka o ranijem ispitivanju šipova na horizontalna dejstva, postoji ograničeno iskustvo u prenošenju horizontalnih sila vertikalnim šipovima u predmentoj geološkoj sredini (gornji slojevi tla su marinskog porijekla). Imajući u vidu navedeno, mogući rizik na predmetnoj lokaciji se može okarakterisati kao visok, pa se pristupilo ispitivanju dozvoljene nosivosti vertikalnih šipova na horizontalne sile testiranjem na licu mjesta, a u cilju verifikacije proračuna dozvoljene nosivosti vertikalnih šipova na horizontalna dejstva datih u idejnim projektima dokova. Povratnom analizom su definisani moduli reakcije pojedinih slojeva tla.

Ključne riječi: vertikalni šip, horizontalna dozvoljena nosivost, test, marina

SUMMARY

TESTING OF ALLOWABLE BEARING CAPACITY OF VERTICAL PILES UNDER LATERAL STATIC LOAD ON THE DOCKS OF THE MEGA-YACHT MARINA PORTO MONTENEGRO TIVAT, MONTENEGRO

Zvonko TOMANOVIĆ

Pile support system of the existing docks of marine for mega yachts “Porto Montenegro” is mainly consisted of vertical piles. In addition to the vertical bearing capacity, the piles must have adequate lateral bearing capacity to stand lateral load transmitted by vessels (anchor force or ship collision force), wind load, vehicle break force etc. There is a limited experience in transmission of lateral forces by vertical piles in the referred geological environment that is relatively unfavorable (upper soil layers are of marine origin). Considering the aforementioned circumstances, the risk level for the jetty structure on the site concerned may be designated as high; hence the in-situ tests of the allowable bearing capacity of piles for lateral loads were conducted in order to verify computation of the allowable bearing capacity of vertical piles for lateral loads as set out in the preliminary designs of jetties. Reverse analysis was used to determine modules of sub-grade reaction for individual layers.

Key words: vertical pile, lateral bearing capacity, test, marine jetty

NEKI PRIMERI PRIMENE TERMOGRAFIJE U DIJAGNOSTICI POSLEDICA ZEMLJOTRESA NA OBJEKTIMA ZAŠTITE KULTURNE BAŠTINE

SOME EXAMPLES OF THERMOGRAPHY APPLICATION IN DETECTING EARTHQUAKE DAMAGES TO BUILDINGS OF CULTURAL HERITAGE PROTECTION

Slavica RISTIĆ
Suzana POLIĆ-RADOVANOVIĆ
Mila POPOVIĆ-ŽIVANĆEVIĆ
Bore JEGDIĆ

PREGLEDNI RAD
UDK: 772.96:699.841 = 861

1 UVOD

Multidisciplinarni pristup istraživanju problema zaštite baštine polazi od dijagnostike stanja okruženja, uključuje i interdisciplinarno povezuje sve neophodne aktivnosti i mere zaštite objekata i artefakata, koji su valorizovani kao prirodne i kulturne vrednosti. Navedeni pristup na navedene probleme obuhvata različite oblasti kao što su: termoenergetika, procesna tehnika, tehnologija materijala, laserske tehnike, mehanika fluida, heritologija, meteorologija, ekologija, arheologija, informatika, istorija umetnosti i mnogo drugih disciplina [1-20].

Navedeni pristup zaštite od posebnog je značaja u akcidentnim situacijama, kao što je slučaj zemljotresa u Kraljevu. U zemljotresu koji se dogodio 3 novembra 2010. godine, kao i u potresima koji su usledili, oštećeno je više objekata ustanova zaštite. Za analizu uticaja zemljotresa na građevinske konstrukcije koriste se različite metode [3,4]. U cilju blagovremenog otkrivanja oštećenja usled zemljotresa na zgrade Narodnog muzeja i Istorijskog arhiva, kao i utvrđivanja delovanja klimatskih uslova i vlage na tim objektima, izvršena su ispitivanja primenom infracrvene termografije.

Termografija je samo jedna od metoda koje nalaze široku primenu u procesu preventivne i kurativne konzervacije. Ona je jedna od najefikasnijih tehnika beskontaktnog ispitivanja i monitoringa kompleksnih građevinskih objekata [1,2,5-108,14-20]. Neprocenjiva je

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1 INTRODUCTION

A multidisciplinary approach to research problems of cultural heritage protection is based on the diagnostics of the environmental surrounding, including interdisciplinary links all the necessary actions and measures to protect objects and artefacts, which are determined as natural and cultural values. A mentioned approach of these problems involves a variety of areas such as: thermal techniques, processing techniques, materials technology, laser technology, fluid mechanics, heritology, meteorology, ecology, archaeology, computer science, art history and many other disciplines [1-20].

This approach of protection is particularly important in accident situations, as it is earthquake in Kraljevo. During the earthquake, which occurred on the 3rd November 2010 year, and earthquakes, that followed, several buildings of heritage protection were damaged. These buildings need to be quickly restored, but first of all checked. For the analysis of the structures subjected to earthquake, the different methods are used [3,4]. For the purpose of early earthquake damage detection to the buildings of the National Museum and the Historical Archives, as well as determining the effects of climate and moisture conditions, tests were carried out using infrared thermography.

Thermography is one of the methods that are widely used in the process of preventive and curative conserva-

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u dijagnostici toplotnih gubitaka u građevinama, prisustvu vlage u građevinskim objektima, stanju betonskih konstrukcija, pregledu podnog grejanja i eventualnih curenja sistema vodovodnih i grejnih cevi, lociranja loše izolacije, proceni termičkih performansi, dihtunga i zaptivki, lociranju grejnih žica i cevi, detekciji delaminacije na fasadama, u betonskim mostovima i drugo. Termografija se koristi i za detekciju kapilarnog prodiranja vode u građevinskim objektima, kao i za otkrivanje zone potencijalne kondenzacije vlage iz vazduha.

U svetu se termografija koristi kao metoda za preventivno održavanje objekata i metoda ispitivanja njihove energetske efikasnosti. Kod nas je metoda koja beleži sve veću primenu, ali još uvek nije dostigla zadovoljavajući nivo primene.

2 OSNOVNI PRINCIPI INFRACRVENE TERMOGARFIJE

Termografija se može definisati kao tehnika pomoću koje se registruje infracrveno zračenje, karakteristično za svaki objekat, čija temperatura je iznad apsolutne nule. Ovo zračenje je posledica neprekidnog kretanja elementarnih naelektrisanih čestica unutar materije. Danas se koristi veoma sofisticirana opreme za termografiju, podržana složenim softverom za dijagnostiku stanja objekata na bazi njihovog infracrvenog zračenja [1,64,19,20].

Objekti u našem okruženju razmenjuju toplotu neprekidnim apsorbovanjem i emitovanjem infracrvenog zračenja. Emisija toplotnog zračenja je zavisna od raspodele temperature, a preko nje je zavisna od kompletnog stanja ispitivanog predmeta. IC termografija je beskontaktna metoda merenja temperature i njene raspodele na površini tela. Rezultat termografskog merenja je termogram, koji u sivim tonovima ili nekom kodu boja, daje sliku temperaturne raspodele na površini posmatranog objekta. Temperaturna raspodela posredno daje informaciju o stanju same površine ili je pak odraz strukture i unutrašnjeg stanja posmatranog objekta. U najjednostavnijoj verziji, termografski sistem se sastoji od termografske kamere i jedinice za obradu termograma (PC). U samoj kameri integrisana je IC optika visokog kvaliteta, senzor IC zračenja, jedinica za pretvaranje električnog u video signal, monitor i kartica za prikupljanje podataka. Računar služi za obradu termograma pomoću specijalnog softvera. Materijali koji se koriste za izradu sočiva termografskih kamera moraju biti propusni za IC zračenje, a to su; germanijum, cink sulfid, cink selenid, za dugotalasna IC zračenja, te silikon, safir, kvarc ili magnezijum, za kratka i srednjetalasna IC zračenja.

Sve podatke, vezane za svojstva površine objekta (emisivnost, transparentnost i absorptivnost), temperaturu okolnih objekata, udaljenost kamere od posmatranog objekta, temperaturu i relativnu vlažnost vazduha, potrebno je prethodno podesiti kao ulazne parametre u softveru kamere. Takođe je veoma bitno termografska ispitivanja raditi pri temperaturnim i metrološkim uslovima pogodnim za primenu ove metode. Danas se infracrvena termografija koristi u skoro svim sferama ljudske delatnosti. Pored spomenute primene u tehnici i građevinarstvu, posebno

tion. It is one of the most effective techniques for contactless testing and monitoring of complex buildings [1,2,5-108,14-20]. The thermography is invaluable tool in the diagnosis of heat losses and the presence of moisture in buildings, the state of concrete structures, review of floor heating systems, leakage of water or heating pipes, locating the poor insulation, estimation the thermal performance, seals and gaskets, location of wires and heating pipes, delamination detecting on the façades, in concrete bridges and so on. Thermography is used for detection the capillary water penetration in buildings, and to detect potential areas of moisture condensation from the air.

Thermography is used throughout the world as a method for preventive maintenance of buildings and method of their energy efficiency testing. In our country thermography records the increasing use, but has not yet reached a satisfactory level of implementation.

2 THE BASIC PRINCIPALS OF THERMOGRAPHY

Thermography can be defined as a technique by which the infrared radiation can be recorded, characteristic for each object whose temperature is above absolute zero. This radiation is the result of continuous motion of elementary charged particles inside matter. Today, a very sophisticated equipment for thermography is in use, and it is supported by complex software for diagnostic the state of objects, based on their infrared radiation [1,64,19,20].

Objects in our environment continuously exchange heat by absorbing and emitting the infrared radiation. Emission of thermal radiation depends on temperature distribution, and through it is dependent on the entire state of the investigated objects. IR thermography is a contactless method of temperature measurements and its distribution on the object surface. The result of thermographic measurements is a thermogram, which in a gray scale or colour code shows the temperature distribution on the surface of the observed object. Temperature distribution provides indirectly information about the state of the object surface, internal structure and the internal state of the observed object. In the simplest version, the thermographic system is consisted of a thermal imager and thermogram processing unit (PC). The infrared, high performance optics, infrared radiation sensor, the unit for converting the electrical in a video signal, viewfinder and the card for data acquisition and primary reduction are integrated in the IC camera. The computer for IR images processing uses special software. The materials used for making thermal imagers lenses must be permeable to infrared radiation, and they are made of: germanium, zinc sulphide, zinc selenite for the long wave infrared radiation, and silicon, sapphire, quartz or magnesium, for medium and shortwave infrared radiations.

All data related to the properties of the object surface (emissivity, transparency and reflectivity), the temperature of surrounding objects, camera distance to the observed object, temperature and relative humidity of air are needed to set up previously as input parameters in the camera software. The temperature and metrological conditions must be also suitable for the application of thermographic testing. Today, infrared thermography is used in almost all spheres of human visokogradnji, treba spomenuti i njenu primenu u medicini, kriminalistici, biologiji, svakodnevnom životu itd.

Infracrveno zračenje (IC) je deo elektromagnetnog spektra, čije su talasne dužine λ u opsegu 0,7-1000 μm i predstavlja toplotno zračenje koje proizvode sva tela zagrejana iznad temperature apsolutne nule. Sa povećanjem temperature objekta raste i intenzitet emitovanog IR zračenja. Raspodela energije po pojedinim talasnim dužinama zavisi od temperature objekta i fizičkih kaarkteristika njegove površine. U termografiji se koriste dve vrste detektora:

– kratkotalasni, otkriva talasne dužine u opsegu 3-4 μm;

– dugotalasni, u opsegu 8-14 μm.

Ova dva opsega nisu slučajno izabrana. Oni su takozvani atmosferski prozori u kojima je veća propustljivost atmosfere za IR zrake [19].

Termografija može biti “pasivna“ i “aktivna“. Pasivna termografija detektuje zračenje tela koja su na višoj temperaturi od okoline, a aktivna detektuje zračenje tela, koje je rezultat širenja toplote unete na različite načine u ispitivani objekat.

activities. In addition to mentioned applications of thermography in engineering and construction, particularly construction, it is important to point out its use in medicine, criminalistics, biology, everyday life and so on.

Infrared radiation (IR) is a part of electromagnetic spectrum, whose wavelength λ in the range of 0.7 to 1000 microns and represents thermal radiation, produced by the entire object with the temperature above absolute zero. With temperature increasing, the intensity of emitted IR radiation increases, too. The energy distribution at particular wavelengths depends on the temperature and physical properties of the emitting surface. The two types of detectors are used in thermography:

– Shortwave, detects wavelengths in the range of 3-4 microns;

– Long wave, in the range of 8-14 microns.

These two bands are not randomly selected. They are called atmospheric “windows” in which the greater permeability of the atmosphere for the IR beam exists [17].

Thermography can be "passive" and "active" one. Passive thermography detects radiation of bodies on higher temperature than ambient, and active thermography detects radiation, as the result of the added heat spread in tested object.

2.1 Osnovi infracrvene tehnologije

Osnovni postulat klasične elektromagnetne teorije je da ubrzane naelektrisane čestice zrače energiju [4]. Toplotno kretanje elektrona i protona povećavaju se sa temperaturom, zbog čega sledi da energija zračenja određenog uzorka, mora da se povećava sa temperaturom.

Intenzitet infracrvenog zračenja zavisi prvenstveno od temperature objekta kao i od spektralne emisivnosti materijala. Objekat sa visokom emisivnošću ima i visoku apsorpciju.

Crno telo je idealan apsorber celokupnog zračenja, koje pogađa telo sa bilo kojom talasnom dužinom, pod bilo kojim uglom. Ako je crno telo u fizičkoj ravnoteži, ono mora da emituje zračenjem tačno onoliko energije koliko apsorbuje. Otuda sledi da crno telo nije samo savršen apsorber, nego i savršen emiter. Za opisivanje pojava vezanih za pojam crnog tela koriste se Plankov, Winov i Štefan/Bolcmanov zakon.

Karakteristike zračenja stvarnih necrnih (sivih) površina, razlikuju se od idealno crnog tela na nekoliko načina. Zračenje stvarnih površina zavisi od mnogobrojnih faktora kao što su sastav, završna obrada površine, temperatura, talasna dužina zračenja, ugao pod kojim se zračenje emituje, spektralna raspodela upadnog zračenja i od toga da li je telo neprozirno [4].

Za opisivanje zračenja realnih tela u odnosu na zračenje crnog tela, koriste se različita svojstva IC zračenja, koja karakterišu emisivnost, apsorpciju i odbijanje odnosno refleksiju. Sposobnost zračenja, ili emisivnost označava osobine realnog tela koje su vezane za zračenje u poređenju sa crnim telom. Emisivnost je funkcija temperatura tela, talasne dužine i ugla detekcije. Apsorbovana količina upadnog zračenja je teško merljiva vrednost. Eksperimentalno je često

2.1 The basis of infrared technology

The basic postulate of classical electromagnetic theory is that accelerated charged particles radiate energy [4]. Thermal motion of electrons and protons increases with temperature, so the radiation energy must increase with temperature, too.

The intensity of infrared radiation depends primarily on the temperature of the object and the spectral emissivity of the material. The object with the high emissivity, has the high absorption, too.

Black body is a perfect absorber of the entire incoming radiation, regardless to wavelength and incidence angle. If the black body is in a thermal balance, it must emits the energy exactly as much as it absorbed. The black body is not only a perfect absorber, but it is also a perfect emitter. To describe phenomena related to the black-body, Plank, Win and Stefan / Boltzmann law are used.

The radiation characteristics of real (grey) bodies are different from an ideal black body radiation in several ways. Radiation from real body depends on many factors, such as composition, surface finish, temperature, wavelength of radiation, the angle of the transmitted radiation, spectral distribution of incident radiation and whether the body is opaque or not [4].

To describe the radiation of real bodies in relation to the radiation of the black body, the different properties of infrared radiation, such as emissivity, absorption and reflection are used. The emissivity properties of the real body are compared with black body properties. Emissivity is a function of body temperature, wavelength and angle of detection. Amount of incident radiation absorbed is hard measured value. Experimentally, it is often easier to determine the emissivity, and determine the coefficient of emissivity. Therefore it is desirable to lakše odrediti emisivnost, odnosno odrediti koeficijent emisivnosti. Zato je poželjno znati odnos između ovih veličina, tako da vrednosti izmerenih svojstava jedne površine omoguće izračunavanje drugih.

Kirhofov zakon je vezan za odnos između emitujućih i apsorbujućih svojstava tela. Ovaj zakon može da obuhvati različite uslove, u zavisnosti od toga da li se razmatraju spektralne, ukupne, usmerene ili osobine u poluprostoru. Primenom Kirhofovog zakona i uzimajući u obzir da je materijal potpuno neproziran, mogu se utvrditi odnosi između sposobnosti apsorpcije, zračenja i refleksije tela.

U opštem slučaju, sredina koja okružuje objekat razmatra se kao prozračna, neemitujuća neapsorbujuća sredina, što nije uvek slučaj. Zbog toga je bitno poznavati zakone poremećaja IC zračenja u apsorbujućoj, emitujućoj i rasejavajućoj sredini.

IC zračenje koje telo emituje kroz sredinu, može da se poremeti emisijom zračenja sredine i apsorpcijom zračenja u sredinu. Emisija zračenja u sredini identifikuje se sa oslobađanjem energije u obliku fotona, dok se apsorpcija identifikuje sa apsorpcijom fotona. Takođe, tokom prolaska kroz sredinu prisutan je i efekat rasejanja, koje može da bude: elastično, neelastično, izotropno i anizotropno rasejanje. Kako zračenje prolazi kroz dati sloj sredine, tako se njegov intenzitet smanjuje usled apsorpcije i rasejanja. Eksperimentalno je utvrđeno da promene u intenzitetu zavise od koeficijenta ekstinkcije, rasejanja i koeficijenta apsorpcije sredine.

Toplotno zračenje koje prima infracrveni objektiv, sastoji se od zračenja koje emituje ne samo objekat, već i njegova okolina. Kada signali prvobitnog zračenja dospeju u IC detektor, signali su modifikovani zbog zračenja koje emituje sočivo, skenirajući sistem i detektor. Imajući u vidu kompleksnost detektovanja IC zračenja vrši se filtracija svih uticaja na zračenje emitovano od ispitivanog objekta.

Materijali koji su transparentni za infracrvene talasne dužine nisu nužno transparentni za talasne dužine vidljive oblasti spektra zračenja. Na primer, dok su silicijum i germanijum neprozirni u vidljivim talasnim dužinama, oni su transparentni u delovima infracrvenog spektra. Za germanijum, koji se obično koristi kao materijal za izradu infracrvenih sočiva, indeks prelamanja n=4, a transparentnost ovog materijala postaje t=0,47. Veliki gubici u transparentnosti obično se minimiziraju primenom anti-refleksionih premaza na površini sočiva. Time se koeficijent transmisije povećava na oko 94% - 99% za dati interval talasnih dužina. Interval talasnih dužina određuje naneti materijal i debljina antirefleksnog sloja.

Infracrveni detektori su veoma značajna komponenta u termografskim sistemima. To su konvertori koji apsorbuju IR-energiju i konvertuju je u signal, obično električni napon ili struju. Infracrveni detektori mogu se podeliti u dve grupe: termičke i fotonske detektore [1,3,17].

2.2 Termografske metode

Klasifikacija termografije se može vršiti prema različitim kriterijumima. Termografija se može podeliti na pasivnu i aktivnu. Pasivna termografija se zasniva na prirodnom temperaturnom distribucijom na površini

know the relationship between these values, so that values measured on one surface enable the calculation of the other body properties.

The Kirhoff`s law relates the relationship between emission and absorbtion properties of the body. This low may includes variety of conditions, depending on whether it consider the spectral, total, or directed features in half space. Applying the Kirhoff`s law, and taking into account that the material is completely opaque, the relationship between the ability of absorption, radiation and reflection can be determined.

In general, the environment surrounding the object is considered as a transparent, no emissive and no absorptive medium, which is not always the case. It is therefore important to know the laws of medium influence on the infrared radiation in absorbing, radiated and scattering environment.

The body IR radiation transmitted through the atmosphere, may be disrupt by he emission, radiation and absorption of the environment. The radiation in the environment is identified with the emission of energy in the form of photons, while the absorption is identified with the absorption of photons. Also, when the IR radiation is passing through the atmosphere, there is a scattering effect, which may be: elastic, inelastic, isotropic and anisotropic scattering. As radiation passes through atmosphere, or some outer medium, so the intensity is reducing due to absorption and scattering occurred. It is confirmed experimentally that the changes in intensity depend of the extinction coefficient, scattering and absorption coefficient of the medium.

Thermal infrared radiation received by the lens, is consisted of the radiation emitted from not only tested body, but by its surroundings also. When the initial radiation signals reach the infrared detector, the signals have been modified due to radiation emitted by the lens, scanning system and detector. Having in mind the complexity of detecting infrared radiation, the filtration of the body radiation must be done.

Materials that are transparent for infrared wavelengths are not necessarily transparent for the wavelength of the visible part of spectrum. For example, while silicon and germanium are opaque in visible wavelengths, they are transparent in the infrared parts of the spectrum. For germanium, which is commonly used as material for making infrared lenses, refractive index n = 4, and transparency of this material becomes t = 0.47. Large losses in transparency are usually minimized by applying anti-reflection coating on the surface of the lens. This increases the transmission coefficient from 94% to 99% for a selected wavelength interval. The material and thickness of antireflection layer, determine the wavelength interval.

Infrared detectors are very important components in the thermographic systems. These are the converters that absorb IR energy and convert IC signal, usually to voltage or current. Infrared detectors can be divided into the two groups: thermal and photon detectors [1,3,17].

2.2 Thermographic methods

The classification of thermography can be made by different criteria. Thermography can be divided into passive and active. Passive thermography is based on the natural temperature distribution on the surface of the objekta i spontanim IC zračenjem istih. Ona se koristi u ispitivanjima strukture objekata ili njihovih delova. Pasivna termografija u najvećem broju ispitivanja je povezana sa kvalitativnim određivanjem anomalija u konstrukcijama, a u nekim specijalnim slučajevima može biti korišćena i za kvantitativna ispitivanja.

Aktivna termografija je metoda koja koristi spoljne izvore, kao što su lampe, laseri itd., da uniformno zagreje ili ohladi predmet koji se ispituje. Termalni gradijent koji se u tom slučaju uspostavlja na površini ispitivanog objekta, snima se pomoću termografskog uređaja.

Prsline, uključci, delaminacije, prisustvo vlage ili vazdušnih džepova i sl. su elementi koji unose temperaturni gradijent zbog toga što imaju različit koeficijent prenosa toplote [7,13,18]. Uslov za pravilnu vizuelizaciju strukture pomoću termografije je da se vrši strogo ravnomerno zagrevanje ispitivanog objekta. Postoji više načina kako se unosi spoljna temperatura. Prema tom kriterijumu termografija se može podeliti na:

- impulsnu,
- sa stepenastim zagrevanjem,
- Lock-in (sinhronu) termografiju i
- Vibrotermografiju.

Impulsna termografija je jedna od najčešće korišćenih metoda za nedestruktivna testiranja (NDT). Toplotna stimulacija objekta se vrši sa izvorima toplote koji zrače energiju u kratkim vremenskim intervalima od nekoliko *ns* do stotina *ms*. Kao izvori toplote služe impulsne lampe, laseri itd. U kratkom vremenskom intervalu dolazi do narušavanja toplotne ravnoteže ispitivanog objekta. Nakon prestanka delovanja izvora toplote, dolazi do brzog hlađenja zbog difuzije, konvekcije, kondukcije i zračenjem sa površine tela. Na osnovu snimljenog temperaturnog kontrasta, može se vršiti kvantitativna analiza i postaviti zavisnost između vremena prenosa toplote i dubine defekta u odnosu na površinu objekta.

Prisustvo defekata ispod površine objekta smanjuje brzinu difuzije, tako da kada se posmatra površinska temperatura, registruju se različite temperature kod defekata u odnosu na okolinu. Prema drugoj klasifikaciji, postoji transmisiona i refleksiona impulsna termografija. U transmisionoj, uzorak se greje sa jedne strane, dok infracrvena kamera snima sa druge strane, dok u drugom tipu termografije, i izvor zračenja i kamera se nalaze na istoj strani. Suprotno od impulsne, gde se prati hlađenje (nakon greanja), ispitivanja termografijom sa stepenastim grejanjem se odvija u toku grejanja, vrši se posmatranje tokom procesa zagrevanja. Promene površinske temperature sa vremenom su direktno povezane sa karakteristikama objekta. Ova tehnika se često naziva i infracrvena radiometrija sa vremenskom rezolucijom (time-resolved infrared radiometry-TRIR). Koristi se najčešće za ispitivanje višeslojnih struktura, kompozita, keramike itd.

Lock-in (sinhrona) termografija je dinamički metod analiza toplotnih talasa, generisani u objektu. U ovoj metodi se uzorak je izložen sinusnom, moduliranom signalu sa frekvencijom koja proizvodi termalne talase u materijalu sa različitom frekvencijom I atenuacijom. Toplotni izvori mogu biti halogene lampe, laseri ili toplotni pištolji. Za vreme ispitivanja, istovremeno se registruju signali pobude i signali odgovora ispitivanog predmeta. U ovoj metodi je neophodno da se vrši

object and the spontaneous IC radiation. It is used to examine the structure of objects or their parts. Passive thermography in most studies has been associated with the determination of qualitative abnormalities in structures and in some special cases can be used for quantitative testing.

Active thermography is a method that uses external sources such as flashlights, lasers, etc.., for uniformly heating the tested object. Thermal gradient established in this case on the surface of the test object, can be recorded using thermographic devices. Cracks, inclusions, delaminations, the presence of moisture or air pockets inside object, are the elements that cause the temperature gradient because they have different coefficients of heat transfer [7,13,18]. The requirement for correct visualization of the structure using thermography is strictly depend of the uniform test object heating. There are several ways to generate temperature into test object. According to this criterion thermography can be divided into:

- Pulse,
- Step-heating,
- Lock-in (synchronous) thermography,
- Vibrothermografphy

Pulsed thermography is one of the most commonly used methods for non-destructive testing (NDT). Thermal stimulation of the object is done with the heat source which radiates energy at short time intervals, several hundreds of ns to ms. Pulse lamps, lasers and so on, serve as sources of heat. In a short time, there is a violation of thermal equilibrium of the investigated object. After the cessation of operation of heat sources, leads to rapid cooling due to diffusion, convection, conduction and radiation from the surface of the body. Based on the recorded temperature contrasts can be made quantitative analysis and set between the time dependence of heat transfer and the depth of the defect to the surface objects.

The presence of defects below the surface of the object reduces the speed of thermal diffusion, so that when the surface temperature is measured, different temperatures are recorded for defects locations in relation to the environment. According to another classification, there is a transmissive and reflective pulse thermography. In transmisive thermography, the sample is heated on the one side, while an infrared camera captures the temperature changes on the outer side, while in the second type of thermal imaging, the radiation source and the camera are on the same side of tested object. Contrary to pulse, for which the temperature decay is of interest (after the heat pulse), thermography tests with stepped heating occur during heating, the increase of surface temperature is monitored during the application of a step heating. Changes in surface temperature in the time are directly related to the characteristics of the object structure. This technique is often referred to as infrared radiometry with time resolution (time-resolved infrared radiometry - TRIR). It is used mostly for testing of multilayer structures, composites, ceramics and so on..

Lock-in (synchronous) thermography is a dynamic method of heat waves, generated inside the object, analysis. In this method using, the specimen is submitted to a sine-modulation heating at a frequency which introduces highly attenuated and dispersive precizni monitoring vremenske zavisnosti snimljenih signala. Može se dobiti amplitudna raspodela IC zračenja sa površine, ali isto tako i fazna raspodela. Prva zavisi od više karakteristika površine objekta, dok druga ne zavisi od stanja površine objekta, nego od vremena kašnjenja, odnosno od fazne razlike između pobudnog i dobijenog signala, povezana je sa vremenom širenja i termalnom difuzijom.

Vibrotermografija je aktivna metoda, u kojoj se vrši direktna konverzija mehaničke energije unetih vibracija u toplotnu energiju. Toplotna energija je posledica trenja molekula na mestima gde postoje defekti, kao što su prsline ili raslojavanje, odnosno delaminacija. Metoda je pogodna za ispitivanje objekata sa visokom temperaturnom provodnošću.

Postoji više proizvođača termografske opreme [1,3,17]. Najjednostavnije kamere daju samo kvalitativnu sliku raspodele temperature na površini objekta sa skromnom rezolucijom. Najnovije kamere su veoma kompleksni sistemi sa vrhunskim elektronskim i optičkim komponentama i sa softverom koji omogućava kontrolisanje režima snimanja, automatsku kompenzaciju ambijentalnih uslova, emisivnosti površine, obradu termograma u toku snimanja i naknadnu obradu po zadatim kriterijumima i za više promenjivih.

3 PRIMENA TERMOGARFIJE U GRAĐEVINARSTVU

Termografija je metoda koja ima široku primenu u građevinarstvu. Ona je metoda izbora pri određivanju energetske efikasnosti građevinskih objekata, beskontaktnom i daljinsko otkrivanju i vizuelizaciji složenih struktura, kao i detekciji strukturnih oštećenja,. Uspešna primena termografije u ovoj oblasti podrazumeva da su stvoreni optimalni uslovi za njeno korišćenje, da su eliminisani faktori koji dovode do nepoželjnih uticaja na ukupnu termografsku sliku objekta, zatim da je izvršena kompenzacija atmosferskih uticaja, da je pravilno izabrana emisivnost ispitivanih površina i da ispitivanje radi termografer sa iskustvom.

Termogarfsko ispitivanje strukture građevinskih objekata i postojanje defekata u njima je bazirano na razlikama u termalnim karakteristikama materijala. Posebno značajna je uloga termografije u otkrivanju struktura ispod maltera. Otkrivanje toplotnih greda, pukotina i loših spojeva je u direktnoj funkciji određivanja energetske efikasnosti objekata, a veoma često i bezbednog korišćenja istih.

Detekciju vlage i prodiranje vode u građevinskim objektima, korišćenjem infracrvenih kamera, bazira se na različitim svojstvima termalne provodljivosti i termalnog kapaciteta vode i materijala od kojeg je izgrađen objekat. Mnogo faktora utiče na to kako će se vlaga pojaviti u infracrvenoj slici, odnosno na termogarmu. Na primer, grejanje i hlađenje vlažnih zona će se drugačije prikazati u zavisnosti od materijala, doba dana itd. Iz tog razloga je važno da se za sprovođenje sanacionih radova koriste i druge metode za proveru vlage u zidovima i krovnim konstrukcijama.

Utvrđivanje prisustva vlage i nedostaci termoizolacije objekata zaštite kulturne baštine je veoma bitno pri

thermal waves of different frequency inside the material. Heat sources can be halogen lamps, heat guns or lasers. The excitation signals and response signals of the tested object are recorded at the same time. In this method it is necessary to perform precise monitoring of the exact time dependence between the recorded temperature signal and the reference signal. It can be obtained amplitude distribution of infrared radiation from the surface, but also the phase distribution. The first depends on several characteristics of the object surface, while the other does not depend on the state of object structure, but the time delay or the phase difference between the excitation and received signals is related to the propagation time and a thermal diffusivity.

Vibrothermography is the active technique, where a direct conversion of mechanical energy of vibration entered into object to thermal energy occurs. Thermal energy is the result of molecular friction in areas where defects such as cracks, disintegration or delamination exist. The method is suitable for testing objects with the high temperature conductivity.

There are several manufacturers of thermographic equipment [1,3,17]. The simplest cameras provide only a qualitative monitoring and recording of the temperature distribution on the surface of the object, with a low resolution. The latest cameras are very complex systems with superior electronic, high performance optical components and software that lets control shooting modes, automatic compensation of ambient conditions, surface emissivity, processing IR images during recording and post processing with the specified criteria for multiple variables.

3 THERMOGARAPHIC APPLICATION IN CIVIL ENGINEERING

Thermography is a method widely used in civil engineering. It is the method of choice in determining the energy efficiency of buildings, distance and contactless detection and visualization of complex structures, as well as structural damages detection. Successful application of thermography in this area means that there were optimal conditions for its use; adverse impact factors on the IC camera image of an object were eliminated, the atmospheric influences compensation was carried out, the properly surface emissivity is chosen and testing is performed by termografer with experience.

Thermographic test of the building structure and the existence of defects in them are based on differences in thermal properties of materials. Especially important is the role of thermography in the detection of structures under the plaster. Detection of thermal beams, cracks and poor joints is in a direct function of determining the energy efficiency of buildings, and very often the safe use of them.

Detection of moisture and water penetration in buildings, using infrared cameras, is based on different thermal conductivity and thermal capacity of water and the material built in building. Many factors affect the way the moisture will appear in the infrared image, i.e. thermogram. For example, heating and cooling of moist zone will be displayed differently depending on the material, time of day, etc. For this reason it is important to simultaneous used the other methods to check the moisture in the walls and roof structures.

obezbeđivanju optimalnih temperaturnih uslova i vlage u depoima i galerijama muzeja. Ovaj problem je posebno značajan za metalne i papirnate eksponate. Nedovoljna izolacija može da se pojavi zbog gubitka izolacione mase s vremenom, mehaničkih oštećenja, ili nestručnom intervencijom prilikom različitih sanacionih radova, što stvara nepotpuno ispunjene zidne strukture. Termografska kamera omogućava da se vide delovi sa nedovoljnom izolacijom zato što ona ili imaju drugačija svojstva toplotne provodljivosti u odnosu na područja sa dobrom izolacijom, odnosno na termogramu mogu da se vide zone pothlađivanja.

U svetu se realizuje značajan broj istraživanja u čijoj osnovi je primena termografije u dijagnostikovanju stanja objekata zaštite kulturne baštine. [2,6,8,11-16]

Termografaijom se mogu uspešno detektovati i mesta gde dolazi do strujanja vazduha zbog slabe zaptivenosti, loše izvedene izolacije ili oštećenja na objektima delovanjem spoljnih ili unutrašnjih sila. Prodiranje hladnog i vlažnog vazduha je takođe važna komponenta pri obezbeđivanju stabilnih temperaturnih uslova za čuvanje i izlaganje eksponata izrađenih od papira, tekstila ili metala.

Sledeći uslovi treba da se obezbede kada se ispituje energetska efikasnost građevinskih objekata. Termografsko ispitivanja unutrašnjosti objekata zahteva konstantnu temperaturnu razliku vazduha u ispitivanim delovima objekta u odnosu na spoljnu sredinu. Ona mora biti najmanje 10°C i to nekoliko sati pre snimanja, kao i za vreme snimanja. Za period od nekoliko sati, spoljna temperatura ne sme da varira više od 30 %, od trenutka kada počne snimanje. Za vreme termografskog snimanja, unutrašnja, ambijentalna temperatura ne sme da se menja više od ± 2°C. Nekoliko sati pre početka snimanja i dok ono traje, ne sme biti uticaja sunca na posmatrane delove objekta. Negativni pritisak unutar objekta 10-50 Pa je poželjan ako se ispituje zaptivanje prozora i vrata.

4 REZULTATI TERMOGRAFSKIH ISPITIVANJA

Zaštita kulturne baštine predstavlja jedan od društvenih prioriteta u savremenom svetu [11]. To potvrduju brojni medunarodni dokumenti i konvencije, koje su donete u cilju uspostavljanja standarda zaštite kulturne i istorijske baštine. U dokumentima se posebno ističe da je preventivna zaštita kao strategija izuzetno važna za zaštitu celokupnog nasleda. Menadžment zaštite kulturne baštine u smislu sistemskog planiranja preventivne i kurativne konzervacije, obuhvata ne samo zaštitu kulturnog dobra, već i intervencije u objektima zaštite i degradiranom prostoru koji okružuje kulturno dobro. Naučni rezultati u menadžmentu rizika unose nove metodologije u procese upravljanja kulturnom baštinom.

Imajuci u vidu ovakva gledišta, logičan zaključak nameće potrebu za primenu najsavremenijih tehnologija u ispitivanju zagađenja okoline, degradacije materijala predmeta i objekata baštine, uticaja globalnih metereoloških promena, ispitivanju posledica katastrofalnih zemljotresa na objekte kulturne baštine i drugo.

Determining the presence of moisture and thermal insulation defects of cultural heritage protection buildings is very important in providing optimal temperature and moisture conditions in the museum depot and galleries. This problem is particularly significant for the metal and paper artefacts. Insufficient insulation can occur due to loss of insulation mass over time, mechanical damage, or improper intervention in the various repair works, which creates incompletely filled wall structure. Thermal Imager allows seeing places with insufficient insulation because they have different properties and thermal conductivity compared to areas with good insulation, thermogram shows the over-cooling zones.

The considerable researches which are based on the application of thermography in diagnosing the condition in the buildings of cultural heritage protection are carried out in the world, last few years [2,6,8,11-16].

Thermography can be successfully applied in detection of air circulation due to poor tightness, badly made insulation, or damage to the structure because of external or internal forces. Penetration of the cold and humid air is also an important component in ensuring stable temperature conditions for storage and show exhibits made of paper, textile or metal.

The following conditions must be fulfilled when the energy efficiency of buildings is investigated. Thermographic tests inside buildings require the constant air temperature difference in the investigated parts of the object relative to the external environment. It must be at least 10°C a few hours before the test and during test. For a period of several hours, the ambient temperature must not vary more than 30%, from the moment of test starting. During the thermographic recording, ambient temperature must not change more than ± 2 ° C. Several hours before the thermographic test and while it lasts, it has to eliminate effects of the sun on the building. The negative pressure inside the building 10-50 Pa is desirable if the windows and doors sealing is tested.

4 RESULTS OF THERMOGRAPHIC TESTS

Protection of cultural heritage is one of social priorities in the modern world [11]. This is confirmed by numerous international documents and conventions, which have been made to establish standards for the protection of cultural and historical heritage. The document specifically states that preventive care is extremely important as a strategy for the protection of whole heritage. The management of cultural heritage in terms of systematic planning of preventive and curative conservation includes not only the protection of cultural property, but also interventions in care facilities and degraded space that surrounds the monuments. Scientific results in risk management entered a new methodology in cultural heritage management processes.

Having in mind this aspect, a logical conclusion leads to the implementation of the modern technology in environmental pollution research, degradation of artefacts and objects material, the impact of global meteorological changes, the impact of the catastrophic earthquake in objects of cultural heritage and so on.

4.1 Termografsko ispitivanje zgrade Narodnog muzeja u Kraljevu

U zemljotersu koji se dogodio 3. novembra 2010. godine, kao i u potresima koji su usledili, oštećeno je više objekata zaštite kulturne baštine. Ovaj momenat je prepoznat kao veoma rizičan za očuvanje kulturne baštine u zoni pogođenoj zemljotresom. Sproveden je obiman program istraživanja [16]. U ovom radu će biti prikazani rezultati istraživanja posledica razaranja na zgrade Narodnog muzeja u Kraljevu i zgrade Istorijskog arhiva.

Snimanje termograma vršeno je infracrvenom kamerom Therma CAM T-335, FLIR Systems, čije tehničke karakteristike su:

- Detektor: nehlađeni mikrobolometar, rezolucije 320x240 piksela
- Temperaturni opseg: od – 20 °C do + 650 °C
- Temperaturna osetljivost: 0.05 °C
- Spektralni opseg: od 7,5 do 13 µm
- Objektivi: 45°x 33.8° i 25°x 19°

Snimanja su vršena u sledećim temperaturnim uslovima: spoljna temperatura 12°C, unutrašnja temperatura 18°C, vremenski uslovi, sunčano, bez vetra.

Na slici 1. je prikazan video snimak i termogram dela plafona i zida u hodniku muzeja, gde su se pojavile pukotine i gde je vidljiv prodor vlage. Prisustvo vlage je posebno štetno za eksponat izložen u ovom prostoru.

Vidljiva pukotina na spoljnjem zidu istorijskog depoa, sl.2, je uzrokovala odlepljivanje maltera na gornjem delu

4.1 Thermographic investigation of the National Museum building in Kraljevo

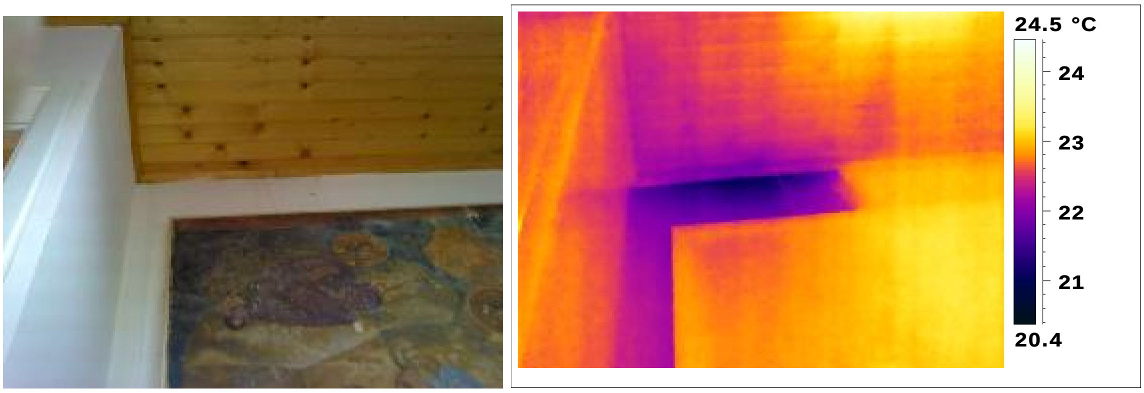
The earthquakes which occurred on 3rd November 2010, as well as earthquakes that followed, several buildings of cultural heritage protection were damaged. This is recognized as a very risky for the preservation of cultural heritage in the area affected by the earthquake. A comprehensive program of thermogarphic research is performed [16]. This paper presents the results of the destructive consequences of National Museum building in Kraljevo and the building of the Historical Archives.

Thermogram recording was done with an infrared camera Therma CAM T-335, FLIR Systems, whose technical characteristics are:

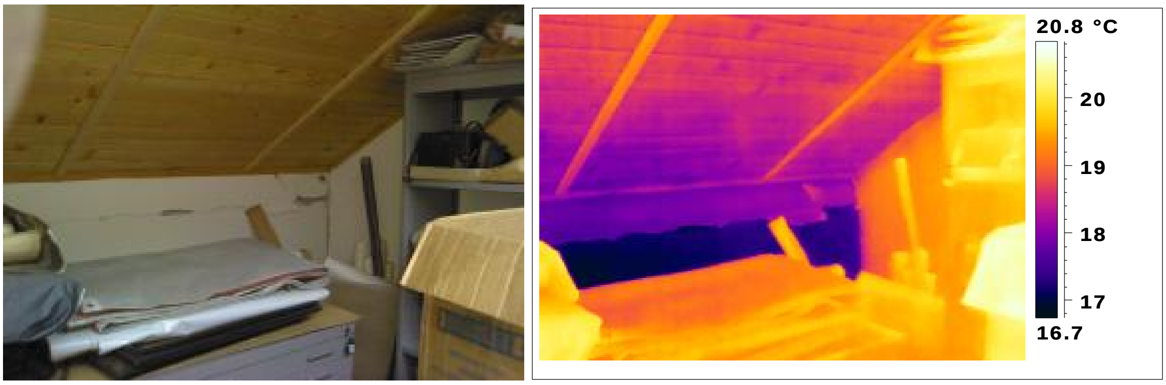
- Detector: uncooled micro bolometer with a resolution of 320x240 pixels
- Temperature range: from - 20 ° C to + 650 ° C
- Thermal sensitivity 0.05 ° C
- Spectral range: 7.5 to 13 microns
- Lenses: 45 ° x 33.8 ° and 25 ° x 19 °.

Recordings were performed in the following temperature conditions: ambient temperature 12°C, the internal temperature of 18°C, weather conditions, sunny, no wind.

Figure 1 shows the thermogram and a video photo of ceiling and wall in the hallway of the museum, where the cracks and moisture are visible. The presence of moisture is especially detrimental to the paint exhibited in this area.



Slika 1. Video snimak i termogram dela hodnika
Figure 1. Digital photo and thermogarm of the museum hallway



Slika 2. Istorijski depo sa Vidljiva pukotina spoljneg zida
Figure 2. Visible cracks in the outer wall of the Historical depot

zida. Zbog toga je odlepljeni sloj maltera na višoj temperaturi u odnosu na kompaktni deo zida. Razlika u temperaturi je oko 2°C. Temperatura vazduha u ovom depou je u trenutku snimanja bila 21°C. Spoljni betonski zid je slabo termički izolovan i predstavlja potencijalno mesto za kondenzaciju vlage iz vazduha tokom zimskih, niskih temperatura.

Slična situacija po pitanju termičke izolacije je dijagnostikovana u najvećem delu zgrade Narodnog muzeja u Kraljevu. U hodniku, na spratu, termografska ispitivanja su pokazala da deo spoljnog zida, prema ulici, ima hladne zone koje su indikacija za postojanje vlage (sl. 3).

Visible cracks in the outer wall of the historic depot, Figure 2, caused the plaster peeling on the upper part of the wall. Because of that plaster peeling layer was at a higher temperature compared to the compact part of the wall. The difference in temperature is about 2°C. The air temperature in the depot at the time of recording was 21°C. This concrete wall is poorly insulated and is a potential place for the air moisture condensation during the winter, when low temperatures were in surrounding.

A similar situation, in terms of thermal insulation, is diagnosed in most parts of the National Museum building in Kraljevo. In the first floor hallway, thermography records have shown that the outer wall facing the street, has cold

Slika 3. Digitalni snimak il termogram zida u hodniku, deo prema ulici savidljivime hladnijim zonama
Figure 3. Digital photo and thermogram of the outer wall facing the street, cold zones are visible

Detaljnija ispitivanja dela zida u hodniku su izvedena primenom aktivne termografije. Zid je sa spoljašnje strane zagrejan suncem, a sa unutrašnje strane postavljene su u hodniku, dve grejalice ukupne snage 6KW. Unošenje dodatne toplote uslovilo je termičku neravnotežu i pojavu temperaturnog gradijenta. Diskontinuiteti u strukturi zida predstavljaju barijere za širenje toplote i kao takvi unose dodatni gradijent. Na slikama 4a do 4d prikazani su video snimci i termogrami donjeg dela zida oko vitrine, snimljeni tokom grejanja i nakon isključivanja grejalica.

Ispitivanja ovom metodom su pokazala da u zidu postoje nehomogenosti (možda pukotine ili odlepljeni slojevi) u zidu ili malteru, koji se golim okom ne mogu videti. Razlika u temperaturi u trenutku isključenja (u uokvirenoj zoni, sl 4d) je preko 2°C, što je indikator da tamniji delovi na termogramu mogu biti hladnija mesta na zidu povezana sa postojećim pukotinama koje propuštaju hladan vazduh spolja.

Slična fenomenologija je registrovana i na delu zida sa druge strane vitrine (sl. 5a-5c). Termogrami pokazuju da tu postoje nehomogeni delovi zida, diskontinuiteti u zidu ili malteru.

Termografska ispitivanja su pokazala da postoji kapilarna vlaga u zidovima naa prilazu i u arheološkom depou (sl.6). Hladne zone sa izraženom vlagom su okružene izotermama na termogramu na slici 6d. Svi bočni zidovi depoa, su sa manjim ili većim površinama pod vlagom. U depou je izmerena vlažnost 67%, a temperatura vazduha je bila 18°C. Pri promenjivim temperaturama, osim kapilarne vlage, ovde je moguća i pojava vlage zbog kondenzacije iz vazduha.

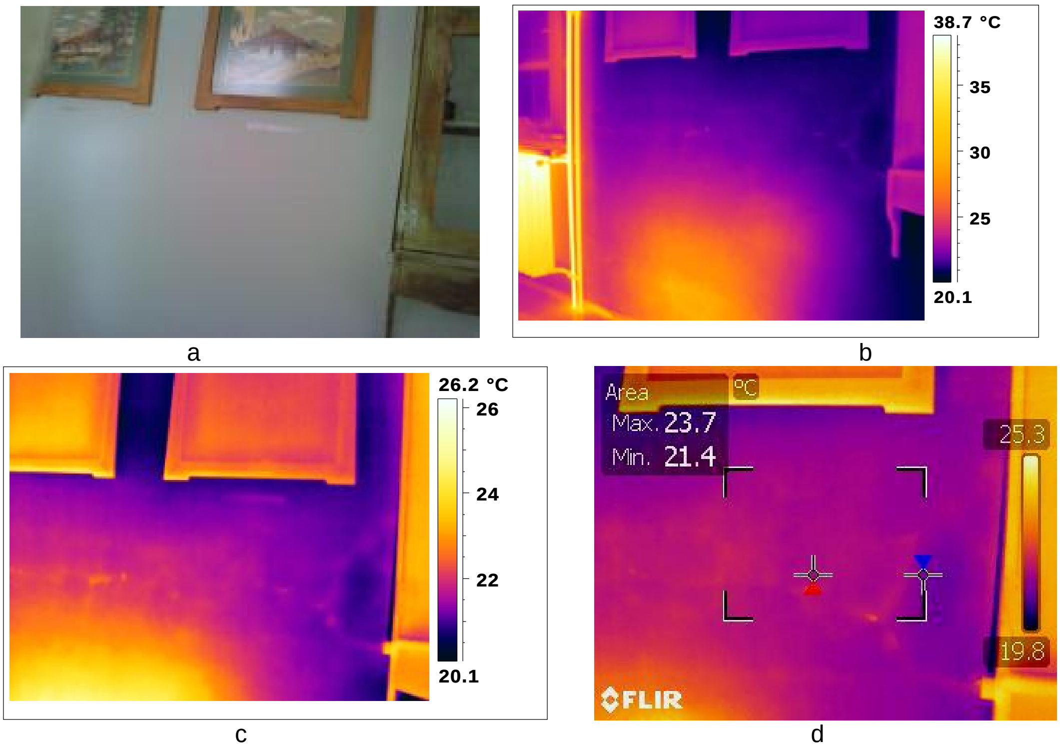
zones that are an indication of the existence of moisture (Fig.3).

More detailed tests of the wall in the hallway were performed using active thermography. The wall is the outside sun warmed and the set of two heaters, total power 6KW, were positioning inside, in the hallway. The additional heat caused the appearance of thermal unbalance and temperature gradient. Discontinuities in the structure of the wall are the barriers to the heat spread making additional temperature gradient. The digital photo and thermograms around the bottom of the wall cabinets, recorded during heating and after switching off the heater, are shown in figures 4a to 4d.

Tests performed by this method have shown that there are unhomogeneities, (possible cracks or detached layers) in the wall or in the plaster that can not be seen by the naked eye. The difference in temperature at the time of disconnection (the framed area, fig. 4d) was more than 2°C, which is an indicator that the dark colder parts in the thermogram, may be wall places related with the cracks leaking cold air from outside.

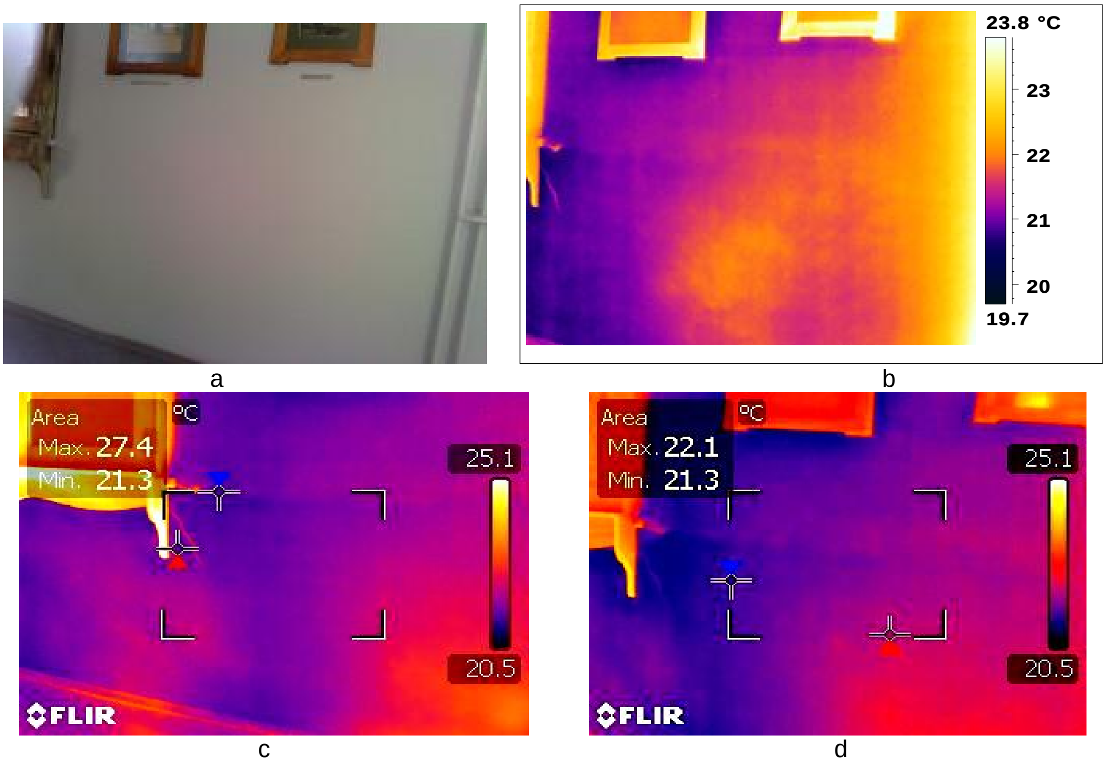
The similar phenomenology is registered on the other side of the wall cabinet (figs. 5a-5c). Thermograms show that there are unhomogeneous parts of the wall, discontinuities in the wall or plaster.

Thermal tests have shown that there is rising moisture in the walls of the entrance to the archaeological depot (Fig.6). Cold zone are surrounded by isotherms on the thermogram and marked moisture zones (fig.6d). All depot side walls have smaller or larger moisture areas. The humidity measured in the depot was 67% and air temperature was 18°C. At varying temperatures, except capillary moisture, here is possible the occurrence of air moisture condensation.



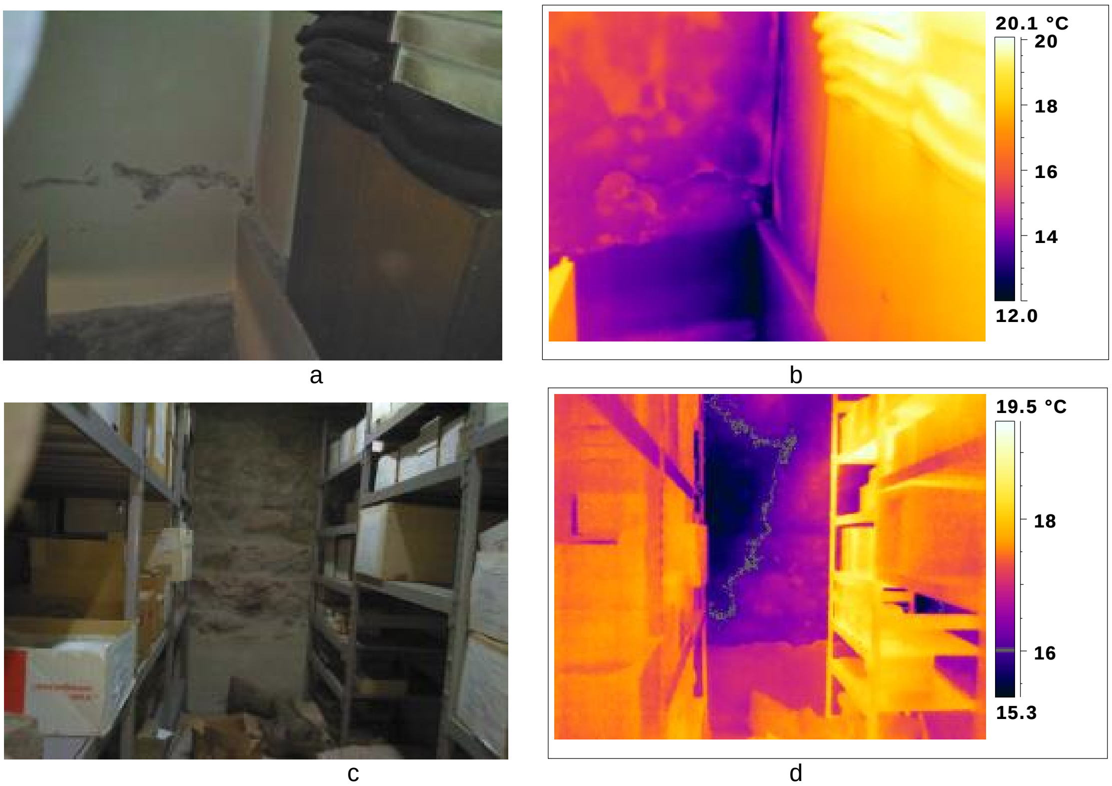
Slika 4. Donji deo zida, a- video snimak, b-termogram u toku zagrevanja, c- u trenutku isključenja grejnih tela, d-termogram sa mernim alatom za određivanje temperature izabrane površine

Figure 4 The bottom of the wall, a-digital photo-, b-thermogram during heating, c-at the time of disconnection heaters, d-thermogram with a measuring tool for determining the temperature of the selected area



Slika 5. Donji deo zida, a- video snimak, b-termogram u toku zagrevanja, c- u trenutku isključenja grejnih tela, d-30 s nakon isključenja

Figure 5 The bottom of the wall, a-digital photo, b-thermogram during heating, c-at the time of disconnection heaters, d-30 s after disconnection



Slika 6. a, b-Stepenište za arheološki depo, vidljiva vlaga u uglu, c i d- srednja prostorija arheološkog depoa sa vlažnim zonama obeleženi izotermima
Figure 6 a, b-The stairs of the archaeological depot, visible moisture in the corner, c, d-the mean archaeological depot, the part with wet zones marked by isotherms

4.2 Termografsko ispitivanje zgrade Istorijskog arhiva u Kraljevu

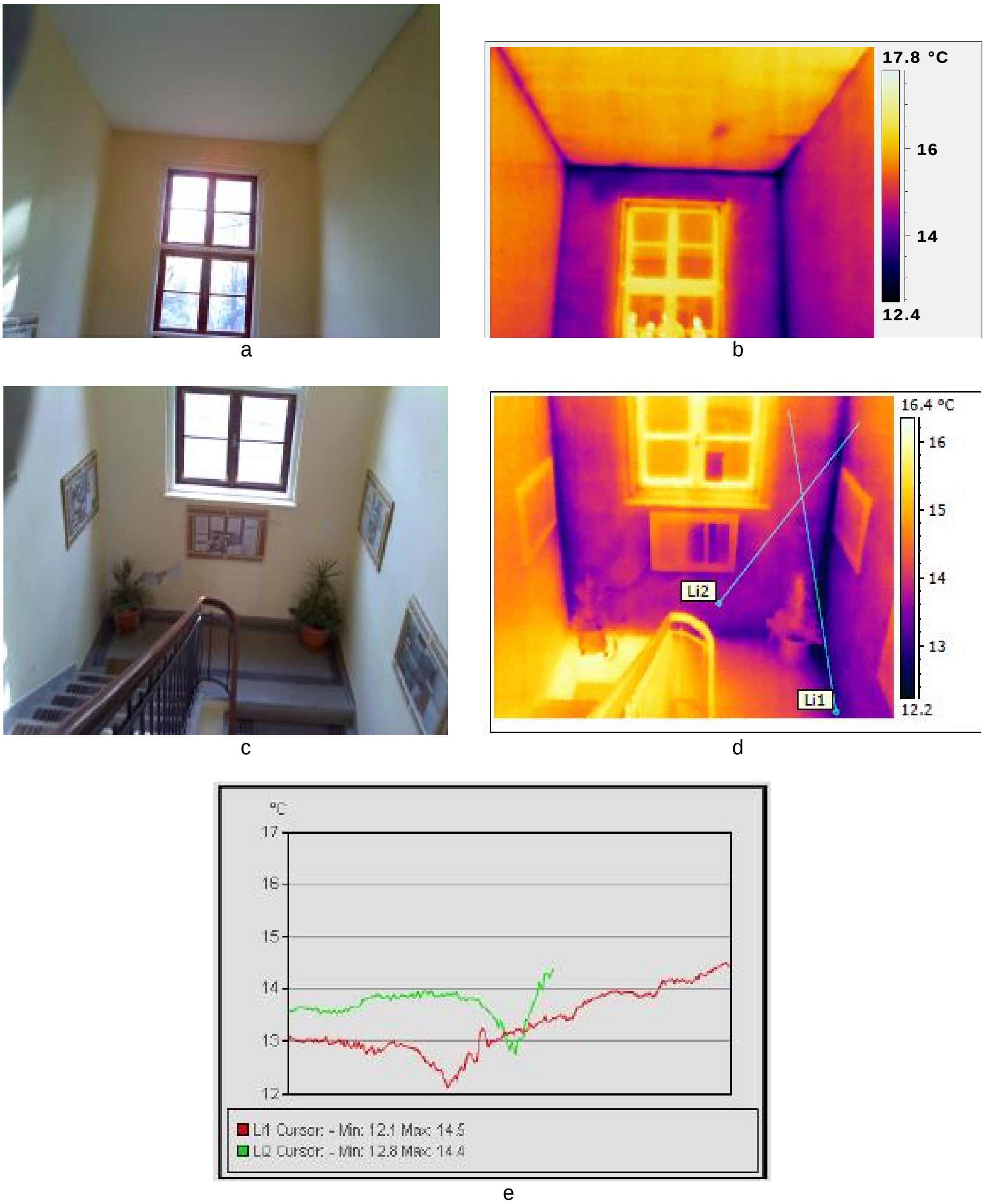
Zgrada Istorijskog arhiva Kraljeva je pretrpela znatna oštećenja tokom zemljotresa. Na slici 7 a - 7e su prikazani termogrami dela zgrade. Postoje ozbiljna oštećenja, koja je neophodno brzo sanitati. Ulazni deo i stepenište koje vodi ka prvom spratu su znatno oštećeni. Pukotine su vidljive golim okom. Termografija je omogućila preciznije definisanje pozicije, dužinu i širinu pukotine.

Gornji i donji deo zidova na prvom odmaralištu je sa vidljivim pukotinama kroz koje prodire hladniji vazduh i vlaga. Razlika u temperaturi na pojedinim delovima zida je i do 2,5°C. Merne linije su postavljene na zidu preko delova koji su sa vlagom i bez vlage. Termografija je potvrdila da su nastale pukotine po celoj širini zida. Ispitivanja su pokazala da na mnogim mestima postoje zone gde se malter odlepio i da je loša termalna izolacija. Termogram fasade zgrade Istoriskog arhiva u Kraljevo (sl.8) potvrđuje da je veoma loša termalna izolacija zgrada arhiva.

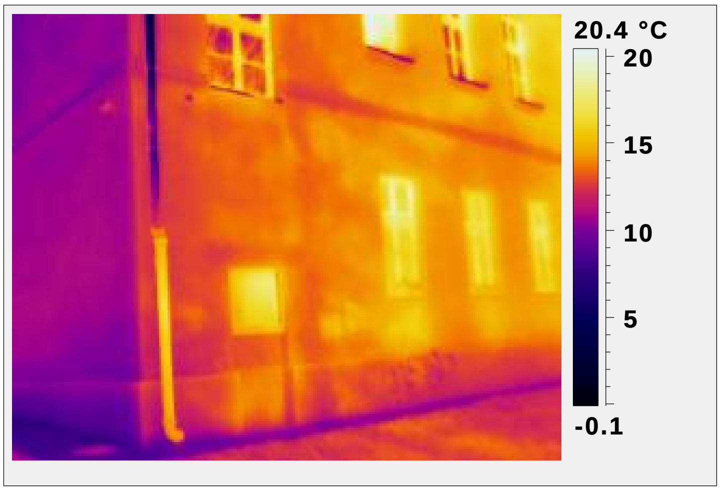
4.2 Thermographic test of the Historical Archive building in Kraljevo

The building of the Historical Archives in Kraljevo suffered considerable damage during the earthquake. Figures 7a-7e shows the digital photos and thermograms of this building. There are serious defects, which have to be quickly repaired. Entryway and staircase, leading to first floor, were badly damaged. The cracks are visible by the naked eye. Thermography has enabled a more precise definition of the position, length and width of cracks.

In the first stair gap between the floors, the upper and lower wall was with visible cracks with colder air and moisture penetration through its wall. The difference in temperature on these parts of the wall is up to 2.5°C. The measurement lines are placed on the wall over the parts where are moisture and without moisture. Thermography confirmed that the cracks formed across the whole width of the wall. Tests have shown that in many places there are areas where the plaster layer is detached from the wall and the poor thermal insulation exists. Thermogram of the Historical Archives building façade in Kraljevo (fig.8) confirms the poor thermal insulation of the building.



Slika 7.a- Digitalni video snimak gornjeg dela zida iznad stajališta, b-termogram. c-donji deo zidova, stajališta, d - termogram donjeg dela zida, e- temperaturna raspodela po izabranim mernim linijama
Figure 7a-Digital video photo of the upper wall above the first stair gap between the floors, b-thermogram of the same place. c-lower part of the walls, , d – thermogram of lower wall, e-temperature distribution at selected measuring lines



Slika 8. Termogram fasade zgrade Istoriskog arhiva u Kraljevo
Figure 8. Thermogram of the Historical Archives building façade in Kraljevo

5 ZAKLJUČAK

Primena novih tehnika u zaštiti kulturne baštine predstavlja međunarodno prihvaćen savremeni standard. Termografska ispitivanja zgrada Narodnog muzeja i Istorijskog arhiva u Kraljevu pokazala su prednosti termografije kao beskontaktne, nedestruktivne metode istraživanja u dijagnostikovanju oštećenja nastalih u zemljotresu. Nalazi potvrđuju da postoje pukotine, mesta prodora vlage kroz pukotine i oštećenja krova, kao i da je prisutna kapilarna vlaga. Obe zgrade imaju veoma lošu termičku izolaciju. Posebno treba naglasiti da su ispitivanja uz primenu aktivne termografije omogućila detaljniju analizu i otkrivanje nevidljivih oštećenja. Sprovedene mere u okviru ovog projekta pripadaju postupcima preventivne konzervacije objekata u kojima se štite kulturna dobra nacionalne baštine.

5 CONCLUSION

Application of new techniques in the preservation of cultural heritage is an internationally accepted modern standard. Thermographic tests of National Museum and Historical Archives buildings in Kraljevo have shown the benefits of thermography as non-contact, non-destructive method in the diagnosis of the damage caused by the earthquake. The results confirm that there are cracks, penetration of moisture through the cracks, roof damages and that there is rising moisture. Both buildings have very poor thermal insulation. It should be point out that the tests with the use of active thermography provide detailed analysis and detection of invisible damages. Implemented activities under this project belong to the preventive conservation procedures of buildings concerning to protect the artefacts of national cultural heritage.

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REZIME

NEKI PRIMERI PRIMENE TERMOGRAFIJE U DIJAGNOSTICI POSLEDICA ZEMLJOTRESA NA OBJEKTIMA ZAŠTITE KULTURNE BAŠTINE

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U radu su prikazani prvi rezultati primene termografije na dijagnostikovanju stanja objekata Narodnog muzeja i Istorijskog arhiva u Kraljevu, posle zemljotresa. Analize su rađene u cilju ispitivanja mogućnosti primene infracrvene termografije na specifičnom zadatku utvrđivanja optimalnog okruženja za muzejske metalne eksponate. Potvrđene su prednosti termografija kao nove metode u dijagnostikovanju vlage u zidovima i krovovima, analizi kvaliteta termičke izolacije i oštećenja u konstrukcijama. Dobijeni rezulatti omogućavaju izradu studija rizika, kao i formulisanje uslova preventivne konzervacije za muzejske eksponate i objekte zaštite kulturne baštine.

Ključne reči: termografija, kulturna baština, dijagnostika vlage, oštećenja konstrukcije, zemljotres

SUMMARY

SOME EXAMPLES OF THERMOGRAPHY APPLICATION IN DETECTING EARTHQUAKE DAMAGES TO BUILDINGS OF CULTURAL HERITAGE PROTECTION

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This paper represents the results of first thermographic application in buildings diagnosis of the National Museum and the Historical Archives in Kraljevo, after the earthquake. Analyses were performed to investigate the possibilities of infrared thermography to the specific task of determining the optimal environment for the metal museum artefacts. The advantages of thermography as a new method in the diagnosis of moisture in walls and roofs, the analysis of thermal insulation and damage to building structures are confirmed. Obtained results enable the preparation of risk studies and formulation of conditions for preventive artefacts conservation, as well as the objects of cultural heritage protection.

Key words: thermography, cultural heritage, diagnosis of moisture, structural damage, earthquake

UPUTSTVO AUTORIMA*

Prihvatanje radova i vrste priloga

U časopisu Građevinski materijli i konstrukcije štampaće se neobjavljeni radovi ili članci i konferencijska saopštenja sa određenim dopunama ili bez dopuna, prema odluci Redakcionog odbora, a samo izuzetno uz dozvolu prethodnog izdavača prihvatiće se i objavljeni rad. Vrste priloga autora i saradnika koji će se štampati su: originalni naučni radovi, prethodna saopštenja, pregledni radovi, stručni radovi, konferencijska saopštenja (radovi sa naučno-stručnih skupova), kao i ostali prilozi kao što su: prikazi objekata i iskustava - primeri, diskusije povodom objavljenih radova i pisma uredništvu, prikazi knjiga i zbornika radova, kao i obaveštenja o naučno-stručnim skupovima.

Originalni naučni rad je primarni izvor naučnih informacija i novih ideja i saznanja kao rezultat izvornih istraživanja uz primenu adekvatnih naučnih metoda. Dobijeni rezultati se izlažu kratko, jasno i objektivno, ali tako da poznavalac problema može proceniti rezultate eksperimentalnih ili teorijsko numeričkih analiza i tok razmišljanja, tako da se istraživanje može ponoviti i pri tome dobiti iste ili rezultate u okvirima dopuštenih odstupanja, kako se to u radu navodi.

Prethodno saopštenje sadrži prva kratka obaveštenja o rezultatima istraživanja ali bez podrobnih objašnjenja, tj. kraće je od originalnog naučnog rada. U ovu kategoriju spadaju i diskusije o objavljenim radovima ako one sadrže naučne doprinose.

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Stručni rad predstavlja koristan prilog u kome se iznose poznate spoznaje koje doprinose širenju znanja i prilagođavanja rezultata izvornih istraživanja potrebama teorije i prakse. On sadrži i rezultate razvojnih istraživanja.

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Ostali prilozi su prikazi objekata, tj. njihove konstrukcije i iskustava-primeri u građenju i primeni različitih materijala, diskusije povodom objavljenih radova i pisma uredništvu, prikazi knjiga i zbornika radova, kao i obaveštenja o naučno-stručnim skupovima.

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