

NUMERIČKO-EKSPERIMENTALNA DIJAGNOSTIKA ČVRSTOĆE KONSTRUKCIJA NUMERICAL AND EXPERIMENTAL DIAGNOSTICS OF STRUCTURAL STRENGTH

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Ključne reči

- čvrstoća konstrukcija
- dijagnostika
- numeričke metode
- eksperimentalne metode
- modeliranje
- ekspertiza

Izvod

U radu je prikazan razvijeni postupak numeričko-eksperimentalne dijagnostike čvrstoće konstrukcija. Numerička dijagnostika primenjuje metodu konačnih elemenata, analizu rezultata proračuna i definisanje parametara ponašanja. Eksperimentalna analiza obuhvata merenje i definisanje ulaznih veličina za proračun i ocenu rezultata proračuna. Ciklusi merenje-proračun se mogu ponoviti, po potrebi.

UVOD

Razmatranje i ocena integriteta i veka konstrukcija su već u ranoj fazi primene zahtevali podatke dobijene dijagnostikom stanja i ponašanja u radu mašina i industrijske opreme. Razvoj ovog postupka dijagnostike je počeo modeliranjem i kompjuterskim proračunom konstrukcija. U proteklih 30 godina su razvijane i poboljšavane numeričke metode zasnovane na metodi konačnih elemenata unošenjem boljih pretpostavki čvrstoće konstrukcija, usavršavanjem kompjuterskog modeliranja i proračuna konstrukcija, do nivoa praktične primene. U tom periodu je razvijen i programski paket Kompjutersko modeliranje i proračun struktura – KOMIPS), /1, 2/, i primenjen za rešavanje problema čvrstoće konstrukcija, /3/. Sledeće proširenje postupka je bilo uvođenje eksperimentalnog ispitivanja za dijagnostiku.

Najmanje dva razloga su doprinela primeni postupka ocene integriteta i veka konstrukcija podržanog numeričkom i eksperimentalnom dijagnostikom. Prvi razlog je bila učestala pojava otkaza konstrukcija, ponekad sa katastrofalnim posledicama, /4, 5/. Ovi otkazi su zahtevali obimna ispitivanja i istraživanja, i na kraju, uvođenje dijagnostike. Drugi razlog je neslućeni razvoj kompjuterske tehnike i softvera, što je omogućilo usavršavanje numeričkih metoda, sa jedne strane, a sa druge strane projektovanje i proizvodnju sofisticiranih uređaja izuzetno velike osetljivosti i kapaciteta merenja, prikladnih za praktičnu upotrebu i sposobnih da zabeležu i sačuvaju ogromnu količinu podataka rezultata ispitivanja.

Keywords

- structural strength
- diagnostics
- numerical methods
- experimental methods
- modelling
- expertise

Abstract

The paper presents developed procedure of numerical and experimental diagnostics of structural strength. Numerical diagnostics uses finite elements method, calculated results analysis and behaviour parameters definition. Experimental analysis is based on measurement and definition of input calculation data and results evaluation. The measurement-calculation cycles can be repeated, if necessary.

INTRODUCTION

Structural integrity and life consideration and assessment required in very early phase of implementing data obtained by diagnostics of state and operational behaviour of the machine and industrial equipment. The development of these diagnostic procedures started by computer modelling and calculation of structures. During the past 30 years numerical methods based on finite element method have been developed and improved in optimising assumptions in structural strength, computer modelling and structural calculation to the level of practical use. In this period the programme package Computer Modelling and Structure Calculation – KOMIPS is developed, /1, 2/, and is used in solving structural strength problems, /3/. Diagnostics procedure is further updated with an experimental test application.

At least two reasons contributed to the application of a structural integrity and life assessment procedure, supported by numerical and experimental diagnostics. The first reason was frequent occurrence of structural failure, sometimes with catastrophic consequences, /4, 5/. These failures required extended investigation and research, and finally the introduction of diagnostics. The second reason was fast development of computer techniques and software, allowing, on one side, the improvement of numerical methods, and on the other, the design and production of sophisticated devices of extremely high sensibility and measuring capacity, user-friendly and capable to record and store enormous quantities of testing data.

OPIS RAZVIJENOG POSTUPKA

Razvijeni postupak numeričko-eksperimentalne dijagnostike čvrstoće konstrukcija podrazumeva primenu metode konačnih elemenata sa detaljnom analizom rezultata proračuna, definisanje parametara ponašanja, eksperimentalnu analizu merenja sa definisanjem ulaznih veličina za proračun i ocenom rezultata proračuna. U razvoj su uneta već dostupna saznanja, /1, 2, 6/. Treba napomenuti da se postupak neprekidno usavršava na bazi iskustva iz praktične primene i analize novih numeričkih i eksperimentalnih rešenja.

Ciklusi merenje-proračun mogu da se ponavljaju po potrebi. Osnovni izlazi razvijenog postupka su usmereni na rešavanje problema čvrstoće, rekonstrukcije, sanacije, popravke, revitalizacije, poboljšanja, promene režima rada, procenu radnog veka i naručivanje opreme.

Razvijeni postupak dijagnostike prikazan je na sl. 1.

Analiza opreme je početni korak u dijagnostici. Potrebno je pregledati i analizirati dostupnu dokumentaciju. Kontrola opreme je sledeći korak, započinje vizuelnim pregledom konstrukcije (geometrija, stanje), kao i zaštite protiv korozije (AKZ) i spojeva, i pratećim dodatnim kontrolama.

Funkcionalna merenja obuhvataju merenje struje i napona pogona (proračun opterećenja pogona), merenje temperature, termičko polje opterećene konstrukcije, merenje pritiska fluida, merenje dinamometrom opterećenja (pobudno, radno i posredno), trajno monitorsko praćenje opterećenja, vremensku i frekventnu analizu signala.

Numeričke i eksperimentalne metode predstavljaju suštinski deo postupka dijagnostike i posebno su prikazane.

Postupak se završava ekspertizom, u kojoj se sumiraju rezultati dijagnostike i preporučuju mere za rekonstrukciju, popravku, poboljšanje ili revitalizaciju, uz procenu preostalog veka, ili se predlaže nabavka nove opreme.

DESCRIPTION OF DEVELOPED PROCEDURE

Developed procedure for numerical and experimental diagnostics of structural strength uses finite element method and detailed analysis of calculated results, definition of behaviour parameters, experimental measurements analysis with defined input values for calculation and evaluation of calculated results. Already available achievements are involved in the procedure /1, 2, 6/. The procedure is under continuous improvement, based on experience gathered in practical use and in the analysis of new numerical and experimental solutions.

The cycles-measurement calculation can be repeated if necessary. Basic outputs of the developed procedure are aimed at strength problems solution, redesign, recovery, repair, retrofit, improvements, operating regime change, life assessment and equipment ordering.

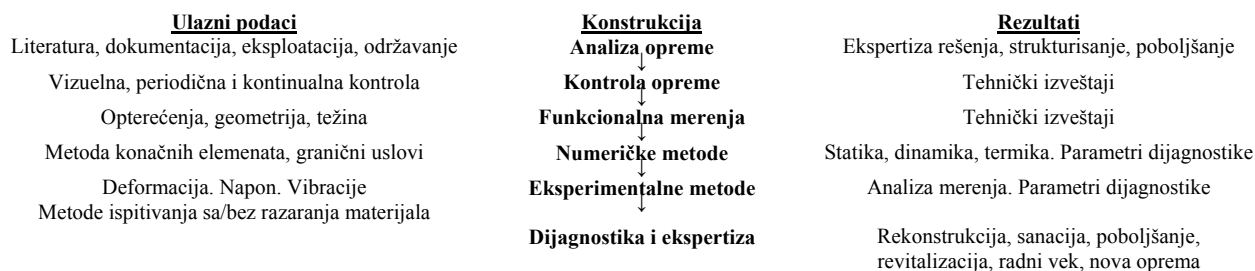
Developed diagnostics procedure is presented in Fig. 1.

Analysis of equipment is initial step in the diagnostics. It is necessary to examine and analyse available documents. Equipment inspection is the next step, with visual control of a structure (geometry, state), followed by anti-corrosion protection (AKZ) and joints, and additional inspections.

Functional measurements include operating current and voltage measurements (calculation of operating load), temperature measurement, thermal field of loaded structure, fluid pressure measurement, load measurement by dynamometer (exciting, operating and indirect loads), continuous load monitoring, time and frequency signal analysis.

Numerical and experimental methods present a substantial part of diagnostics procedure and are separately presented.

The procedure ends by an expertise in which diagnostics results are summarised and measures are recommended for redesign, repair, improvement or retrofit, followed by residual life assessment, or new equipment implementation.



Slika 1. Numeričko-eksperimentalna dijagnostika čvrstoće konstrukcija

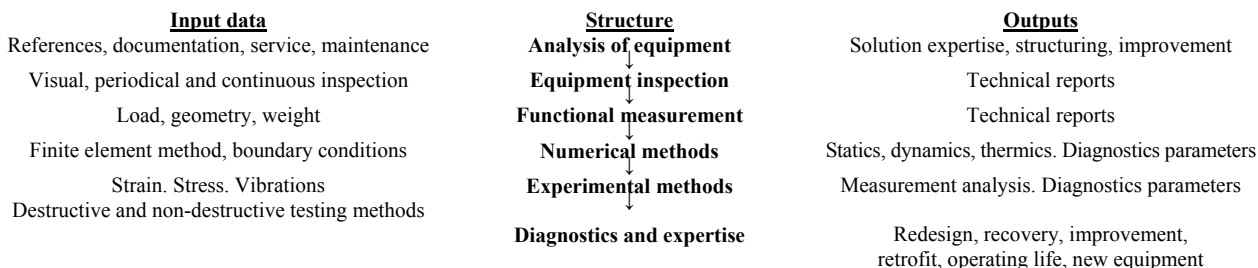


Figure 1. Numerical-experimental diagnostics of structural strength.

Numeričke metode

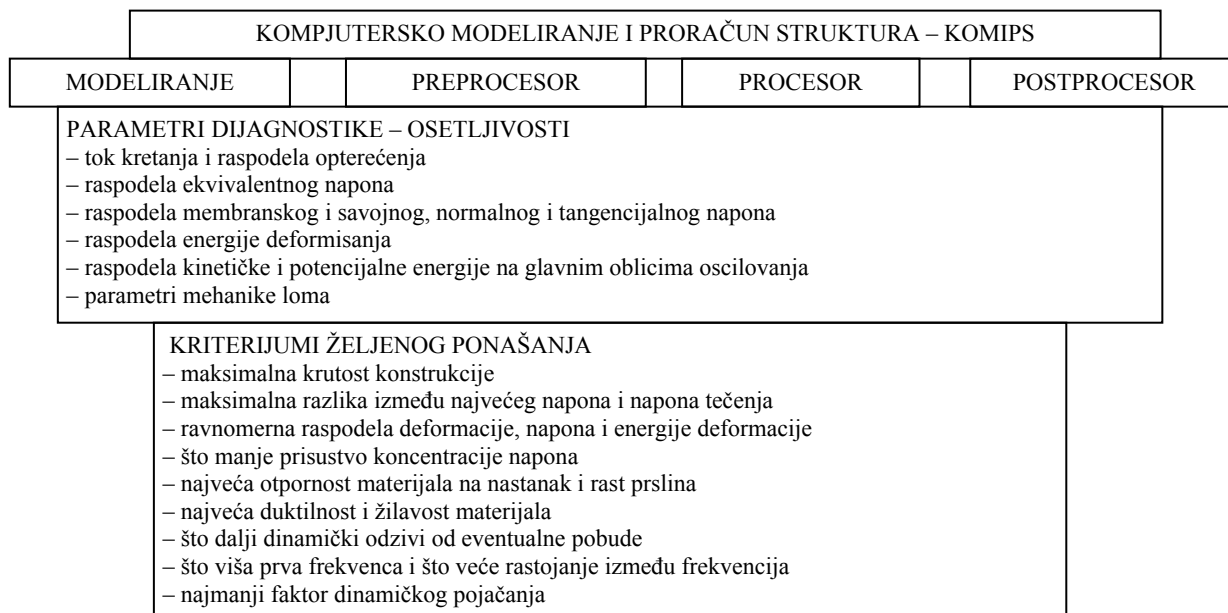
Numerička metoda na bazi metode konačnih elemenata je za potrebe dijagnostike proširena postavkom čvrstoće konstrukcija, kompjuterskim modeliranjem i proračunom struktura (programski paket KOMIPS), sl. 2, /1-3/, kao i rešenim problemima čvrstoće.

Numerical methods

Numerical method based on finite element method is for the diagnostics purpose extended by postulating structural strength, computer modelling and structure calculation (programme package KOMIPS), Fig. 2, /1-3/, and also in the addition of solved strength problems.

Od značaja su parametri dijagnostike, pre svega osetljivost, koji se odnose na osobenosti opterećenja i napona, posebno na energiju deformacije i raspodelu kinetičke i potencijalne energije na glavnim oblicima oscilovanja, i na parametre mehanike loma i zamora materijala. Njima se na pogodan način definišu zahtevi u pogledu ponašanja konstrukcije, što je istaknuto kriterijumima navedenim na sl. 2.

The importance is given to diagnostics parameters, first of all the sensitivity, relating to loading and stress performances, especially on strain energy and distribution of kinetic and potential energies of main oscillation forms, as well as fracture mechanics and fatigue parameters. They can be used to define requirements regarding structural behaviour, as emphasized by the criteria cited in Fig. 2.



Slika 2. Kompjutersko modeliranje i proračun struktura – KOMIPS

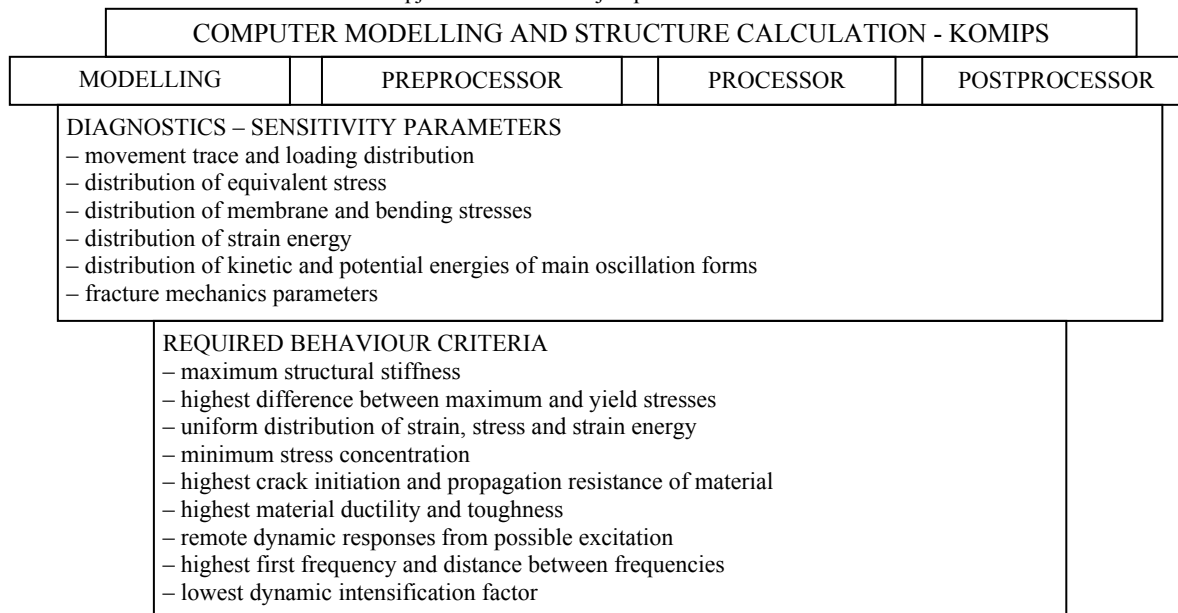


Figure 2. Computer modelling and structure calculation – KOMIPS.

Eksperimentalne metode i metode ispitivanja

Za konstrukcije u radu, čije stanje treba dijagnostikovati potrebno je poznavati opšte karakteristike materijala (hemijski sastav, mehaničke osobine, tvrdoću, udarnu žilavost), a za posebne vrste opterećenja i radne uslove još i zamornu čvrstoću, parametre mehanike loma, otpornost prema koroziji i karakteristike puzanja. Ako podaci o materijalu nisu dostupni iz dokumentacije ili su nepouzđani, moraju se odrediti ispitivanjem. Stanje materijala (izgled površina,

Experimental and testing methods

For structures in service, for which diagnostics should be performed, it is necessary to know general material properties (chemical composition, mechanical properties, hardness, impact toughness) and for some loading types and service conditions also fatigue strength, fracture mechanics parameters, corrosion resistance and creep properties. If data on the material are not known from documents or are uncertain, they have to be determined by testing. Material

debljina ploča i AKZ, dvoplatnost, prisustvo prslina i zaostali naponi) se određuju ispitivanjem bez razaranja. Primjenjuju se standardne metode ispitivanja, ali za neka ispitivanja se zahteva posebna oprema i iskustvo.

Ovo je po pravilu slučaj sa konstrukcijama koje se već dugo koriste, a njihovo održavanje nije bilo redovno.

Sem ispitivanja za karakterizaciju materijala, značaj imaju eksperimentalna ispitivanja na samoj konstrukciji, za koja služi merno-akvizicioni sistem, sl. 3. Ovaj sistem, koji treba da pruži bitne podatke o stanju konstrukcije, je razvijen kao podloga za numeričko-eksperimentalnu dijagnostiku čvrstoće konstrukcija. U pitanju su različita ispitivanja, od kojih su mnoga vrlo zahtevna, pa je izuzetna i složenost sistema, potrebna da bi se pokrile sve oblasti dijagnostike.

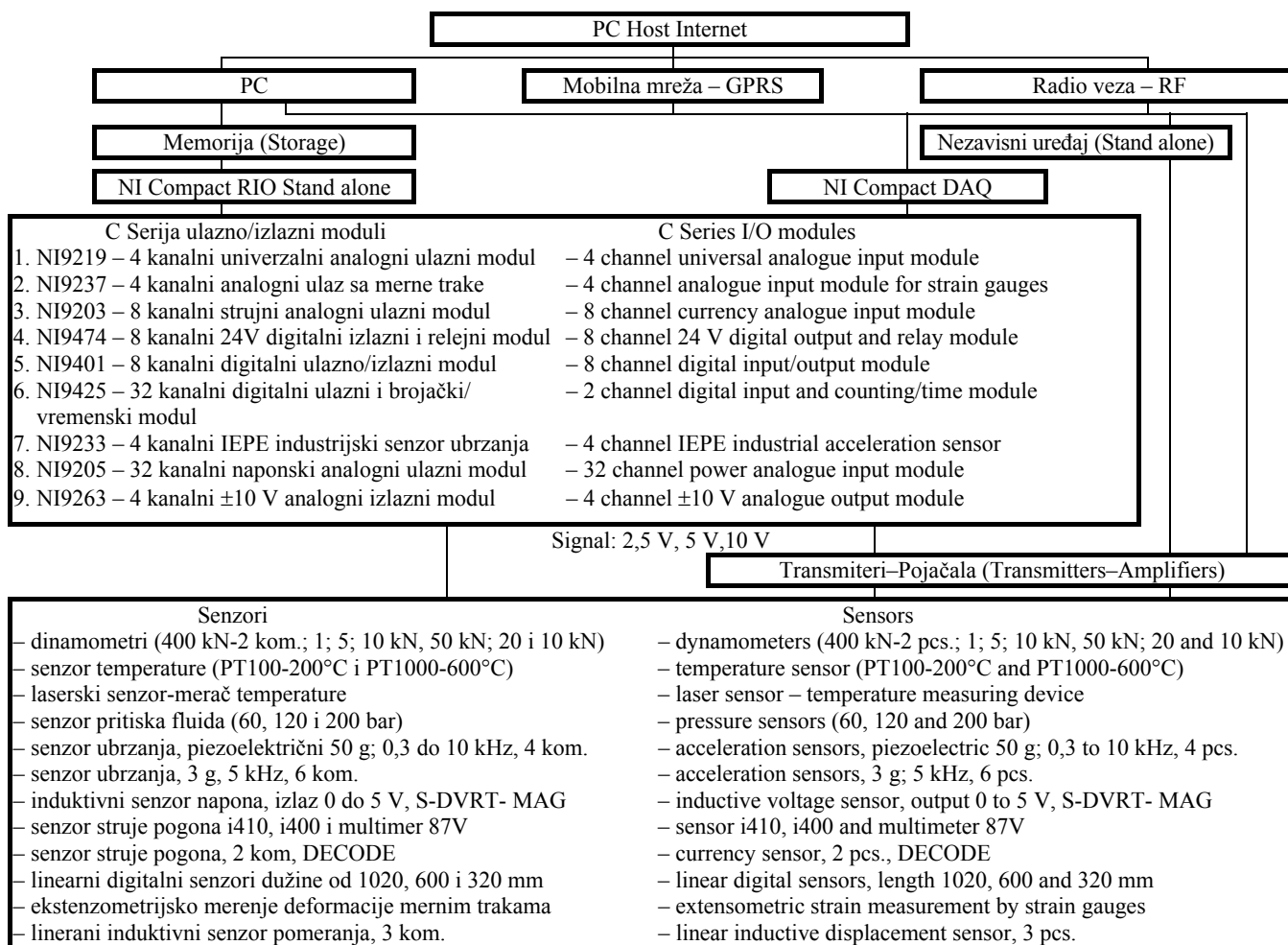
Merno-akvizicioni sistem čine uređaji Kompact Rio i Kompact Dak (Nešanel instruments – NI). U sistem ulaze brojni senzori (za pomeranja, deformacije, silu, pritisak fluida, napon, temperaturu, vlagu, vibracije, napon struje, analogni-digitalni ulazi i izlazi). U eksperimentima treba izabrati broj i položaj mernih mesta, meriti veličine (pomeranja, deformacije mernim trakama, brzine, ubrzanja), pratiti opterećenja, deformacije i nivo vibracija (rezonanca, debalans, nesaosnost, uležištenja, zazore, vibracije od struje).

state (surface condition, plate and AKZ thickness, delamination, crack presence and residual stresses) is determined by non-destructive tests. Standard test methods are applied, but sometime special devices and experience is required.

In general, it is the case with structures in service for a long time, and when maintenance is not regular.

In addition to the tests for material characterisation, experimental tests on the structure itself are important, using the measuring-acquisition system, Fig. 3. This system, aimed to deliver substantial data of structural state, is developed as the basis for numerical and experimental diagnostics of structural strength. Different tests are in question, some of them very requiring, so the complexity of the system, necessary to cover the whole diagnostics area, is pronounced.

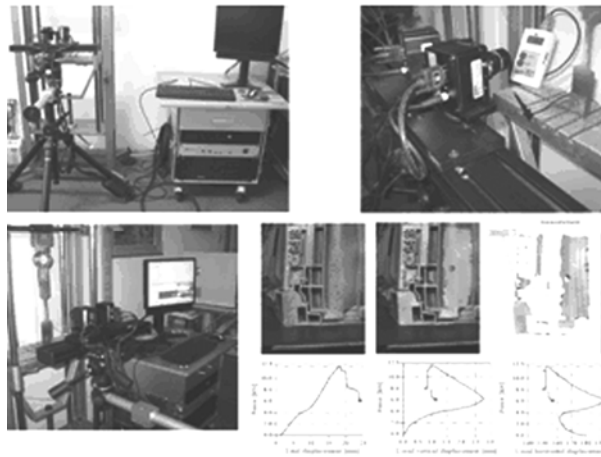
Devices Compact Rio and Compact Daq (National Instruments – NI) are built in the system. A series of sensors are used (displacement, strain, load, fluid pressure, stress, temperature, humidity, vibration, voltage, analogue-digital inputs and outputs). In experiments, the measuring point number and location should be selected, values measured (displacement strain by gauges, rate, acceleration), and monitored load, strain and vibration level (resonance, disbalance, misalignment, supports, clearances, electrically induced vibration).



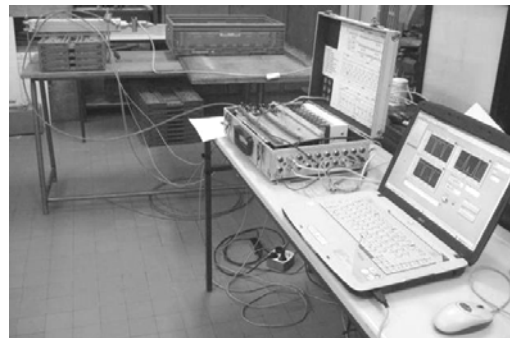
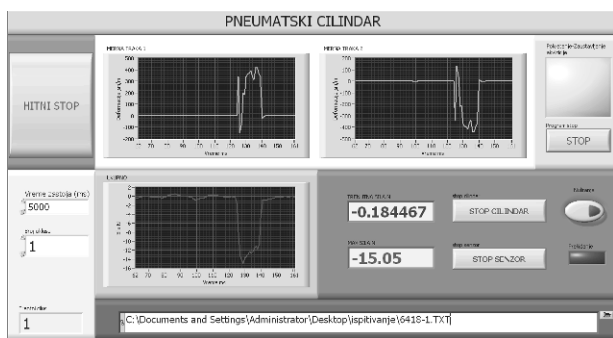
Slika 3. Merno-akvizicioni sistem
Figure 3. Measuring-acquisition system.



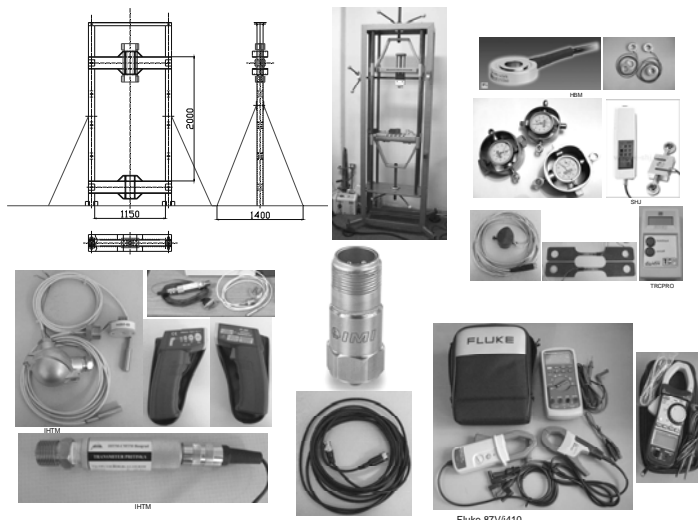
Oprema za akviziciju podataka
Equipment for data acquisition



3D optičko merenje deformacija
3D optical strain measurement



Sistem za kontrolu i merenje opterećenja
System for load control and measurement



Kidalica i pripadajući senzori
Tensile testing machine and sensors

Slika 4. Komponente merno-akvizicioniog sistema i senzori
Figure 4. Components of measuring-acquisition system and sensors.

Vremenska i frekventna analiza signala, praktični aspekti merenja vibracija, kao i optička 3D analiza deformacije (ARAMIS i PONTOS sistemi GOM) su znatno povećali mogućnosti predstavljenog postupka numeričko-eksperimentalne dijagnostike čvrstoće konstrukcija.

Komponente opreme i neki uređaji sistema, kao i njihove osobine su prikazani na sl. 4.

Time and frequency signal analysis, practical aspects of vibration measurements as well as optical 3D strain analysis (GOM systems ARAMIS and PONTOS), significantly increased the capacity of presented procedure for numerical and experimental diagnostics of structural strength.

Equipment components and some system devices, with their properties, are presented in Fig. 4.

DOPRINOS IZ PRETHODNIH ISTRAŽIVANJA

Jedan od osnovnih razloga razvoja KOMIPS sistema i sve veće primene eksperimentalnih ispitivanja u dijagnostici treba tražiti u stanju opreme domaće industrije. Tokom proteklih 30 godina je došlo do naglog smanjenja investicija i obnavljanja opreme u industriji, pa je bilo neophodno proveriti da li postojeća oprema može dalje da se koristi i koliko dugo. Takođe je značajna analiza otkaza i lomova u eksploataciji, praćena dijagnostikom i ekspertizom sa merama sanacije ili popravke, odnosno, isključenjem opreme iz eksploatacije kada je sigurnost u radu ugrožena.

Jedna od potpora u takvom pristupu je Međunarodna letnja škola mehanike loma (IFMASS), koja periodično radi od 1980. godine. Sledeći značajni doprinos je osnivanje Društva za integritet i vek konstrukcija 2001. godine (DIVK, www.divk.org.rs). Iste godine je pokrenut i časopis Integritet i vek konstrukcija (IVK), preko koga su stručnjacima, ne samo domaćim, postale dostupne reference i informacije o relevantnim aspektima: teorijskom razvoju mehanike loma i srodnih disciplina, o numeričkim metodama, koje su pratile dostignuća u razvoju softvera i kompjutera, i o eksperimentalnim metodama, kroz razvoj novih mernih uređaja i njihovu primenu.

Iz izloženog teksta je jasno da je u pitanju materija, koja je sa jedne strane vrlo složena, a sa druge strane obimna. Treba podvući da se zajedno sa postupcima ocene integriteta i veka konstrukcija neprekidno razvija i poboljšava i numeričko-eksperimentalna dijagnostika čvrstoće konstrukcija. Sem već navedenih osnovnih radova, /1, 2/, mnogo detaljniji pristup je omogućen pregledom literature, razvrstane u dve grupe. Prva grupa se odnosi na tematska područja koja su korišćena pri razvoju numeričkih metoda i softvera, a druga grupa su reference koje prikazuju kako su razvijene metode primenjene na rešavanje praktičnih industrijskih problema. Pri tom treba imati u vidu da su u mnogim radovima paralelno obrađene teme iz obe grupe.

Podrška razvoju

Mnogo potpuniji prikaz problema su dali autori u monografijama IFMASS, /7-10/. Raznovrsnost konstrukcija na koje je metoda primenjena i različiti radni uslovi pokazuju univerzalnost metode, sa jedne strane, ali sa druge strane upućuju na potrebu da se za svaki pojedinačni primer osnovne postavke provere i koriguju kada je to potrebno.

Ovom treba dodati i priloge drugih autora, /11-19/. Ponovo dolazi do izražaja raznorodnost problema i konstrukcija na kojima se problemi javljaju. Posebno treba istaći radove koji se odnose na numeričke metode i njihovu primenu u različitim uslovima, /11, 13, 15, 16, 17/.

Primeri praktične primene u eksploataciji

Brojni su radovi posvećeni problemu dijagnostike u eksploataciji jer je potrebno obezbediti kako sigurnost, tako i pouzdanost konstrukcija u redovnom radu. Problemi veka su više usmereni na dopušteni period eksploatacije između dve inspekcije, ali se traži i ocena ukupno preostalog veka. I ovde se raznovrsnost konstrukcija uočava u pogledu namene i funkcije, pa se razlikuju radni uslovi i vrste opterećenja i u skladu sa tim i upotrebljeni materijal.

CONTRIBUTION OF PREVIOUS INVESTIGATION

One basic reason for KOMIPS system development and extended application of experimental testing in diagnostics could be searched in the state of the domestic industry equipment. In the last 30 years investment and replacement of equipment is drastically reduced, and it was necessary to check whether its further use is possible and how long. The analysis of failures and fractures in service is also important, followed by diagnostics and expertise for recovery or repair, or by the exclusion of equipment from exploitation, if service safety is endangered.

One of supports to such an approach is the International Fracture Mechanics Summer School (IFMASS), operating from 1980 periodically. Next important support is founding of the Society for Structural Integrity and Life in 2001 (DIVK, www.divk.org.rs). Also the journal Structural Integrity and Life began the same year, with available references and information on relevant aspects of theoretical development of fracture mechanics and allied subjects, of numerical methods, succeeded achievements and development in software and computers, as well as in experimental methods, through the design of new measuring devices and their application.

From the presented it is clear that the matter in question is very complex, on one hand, and widespread, on the other. It is to underline that together with structural integrity and life assessment numerical and experimental diagnostics of structural strength is continuously developed and improved. In addition to the already referred basic papers, /1, 2/, a more detailed approach is enabled in reviewing references, classified into two groups. The first group is related to thematic areas used for development of numerical methods and software, the second includes references demonstrating how developed methods are applied to solving practical industrial problems. However, in many papers both topics are elaborated in parallel.

Supporting the development

A more complete review of the problem is given by authors in IFMASS monographs, /7-10/. Diversity of structures to which the method is applied and different operating conditions indicate universality, on one hand, but on the other show the need to check for each individual case the basic assumptions and to correct them, if necessary.

It is also necessary to mention the contribution of other authors, /11-19/. Again problem diversity is expressed regarding the considered structures. Of special interest are papers related to numerical methods in different conditions /11, 13, 15, 16, 17/.

Examples of practical use in service

Numerous papers deal with diagnostics problems in service, since it is required to provide structural safety, but also the reliability in regular exploitation. Life problems are more directed to the allowed time period between two inspections, but also the total residual life is requested. The diversity regarding the purpose and function is presented also here, and the operating conditions and type of loading are different, and accordingly, the used material.

S obzirom na pojavu otkaza i njihov znatan broj, u literaturi su saopšteni radovi o dijagnostici nosećih čeličnih (elektroenergetska postrojenja, procesna industrija, mostovi), a problemi koji se prikazuju su sličnog karaktera, /20-24/. Druga velika grupa se odnosi na opremu pod pritiskom /25-31/. Kod ovih konstrukcija poseban problem su zavareni spojevi, jer je njihova dijagnostika zahtevna i složena. Detalji o tom problemu su opisani u navedenoj literaturi.

PRAVCI DALJEG RAZVOJA

Dalji razvoj dijagnostike za potrebe ocene integriteta i veka konstrukcija zavisi od razvoja industrijske opreme i njenog projektovanja, ali i od mogućnosti za razvoj i usavršavanja kompjuterske tehnike, merne opreme i uređaja. Zahtevi proizvodnje su usmereni na opremu veće produktivnosti, povećanu pouzdanost i sigurnost.

U nekim područjima kao što su zamor materijala, pužanje, korozija i korozija pod naponom još uvek nije moguće postići zahtevani nivo dijagnostike. Posebnu pažnju treba posvetiti prslinama i njihovom razvoju u tim uslovima, jer teorijski razvijeni mehanizmi ne daju uvek zadovoljavajuće odgovore, pa je empirijski pristup neizbežan. Modeliranje primenom kompjutera ima ovde veliki značaj, ali numerička i eksperimentalna dijagnostika su još uvek najpouzdaniji postupak za praćenje opreme u eksploataciji.

Otvaranje novih oblasti donosi nove zahteve, ali i promene u pristupu. Kao primer može da posluži razvoj nanomaterijala i konstrukcija, /32/, čija svojstva mogu da budu različita od poznatih osobina definisanih za mnogo veće dimenzije i razmere. Atomski modeli čvrstoće i loma konstrukcija ne mogu da se primene na nano nivou, jer prslina ne može da se definiše na klasični način. Neophodan je novi pristup da bi se razvila numerička i eksperimentalna dijagnostika, već potrebna u skladu se oštrim zahtevima pouzdanosti mikro i nano struktura.

Merni uređaji se stalno usavršavaju, često baš razvojem nano tehnologija, uglavnom u sledećim pravcima:

- merna veličina se pojačava kod senzora, tako da se prenos signala ostvaruje na visokom nivou napona;
- akvizicija signala i podataka se ostvaruje sa i bez primene PC (nezavisni uređaj);
- signali se uglavnom prenose primenom bežične, GPRS i RF tehnologije;
- sve se više koristi televizija, naročito kada se zahteva trajno praćenje pojava, jer je primenom kompjutera i odgovarajućih softvera moguć ne samo kontinualni monitoring, već i upravljanje sistemom, /14/.

Stečeno iskustvo u dijagnostici pokazuje da praktično ne postoje granice: ono što je i nedavno bilo nezamislivo danas je već u svakodnevnoj upotrebi u eksploataciji.

ZAKLJUČAK

Predstavljena numeričko-eksperimentalna metoda dijagnostike čvrstoće konstrukcija, razvijena tokom 30 godina, je u praksi potvrđena na brojnim rešenim problemima.

Having in mind failure occurrences and their great number, papers on diagnostics of loaded steel structures are referred (electrical power plants, process industry, bridges), and presented problems are of similar character, /20-24/. The second large group of pressure equipment is considered /25-31/. Welded joints are an important problem in these structures, since their diagnostics is requiring and complex. The details can be found in given references.

DIRECTION OF FURTHER DEVELOPMENT

Further diagnostics development needed for structural integrity and life assessment depends on industrial equipment development and its design, also on the capacity to develop and improve computer techniques, and on measuring equipment and devices. Production requirements call for equipment of high productivity, increased reliability and safety.

In some areas, like material fatigue, creep, corrosion and stress corrosion, it is not possible to achieve the required level of diagnostics. Special attention should be paid to cracks and their growth in these conditions, since developed theoretical mechanisms do not always offer satisfactory response, so the empirical approach cannot be avoided. Computer modelling has great importance here, so numerical and experimental diagnostics of structural strength is still a most reliable procedure for in-service equipment monitoring.

Opening new areas involves new requirements and changes in the approach. Development of nano materials and structures can serve as an example, /32/, with properties that can differ from known properties of much higher dimensions and scales. The atomic models for strength and fracture cannot be applied at nano level, because the crack cannot be defined in a classical way. A new approach is necessary for developing numerical and experimental diagnostics, already needed according to strict reliability requirements for micro and nano structures.

Measuring devices are steadily improved, often by nano technology development, mostly in the following directions:

- the measured value is amplified at the sensor, enabling signal transfer at high level voltage;
- signal and data acquisition is with or without PC application (stand alone);
- signals are transmitted using wireless, GPRS and RF technologies;
- application of television increases, particularly when continuous monitoring is requested, since application of computer software makes continuous monitoring possible, as well as system control, /14/.

The gained experience in diagnostics practically shows unlimited possibilities: even what was considered impossible in the near past is already in every day exploitation.

CONCLUSION

The presented numerical-experimental method for structural strength diagnostics, developed in past 30 years, has been proved by numerous solved problems.

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