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PRIMENA STEREOMETRIJSKOG MERENJA DEFORMACIJA ZA OCENU INTEGRITETA KONSTRUKCIJE BRODA

APPLICATION OF STEREOMETRIC STRAIN MEASUREMENT FOR SHIP STRUCTURAL INTEGRITY ASSESSMENT

Originalni naučni rad / Original scientific paper
UDK /UDC:
Rad primljen / Paper received:

Adresa autora / Author's address:
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Ključne reči

- stereometrijsko merenje
- napon
- deformacije
- integritet konstrukcija
- podobnost za upotrebu

Izvod

Ovaj rad opisuje primenu digitalne stereometrije za merenje mikrodeformacija na površini. To se postiže upoređujući slike rasporeda tačaka na označenoj površini uzorka pri različitom nivou opterećenja i time izazvanih napona. Na primerima je prikazana mogućnost merenja koncentrisanih deformacija u okolini vrha prsline na metalnom uzorku i na koštanom tkivu. Primenom dve video kamere i odgovarajućeg sofvera može se slika raspodele deformacija dobiti u različitim oblicima, u 3D i 2D formatu.

UVOD

Statistički podaci pokazuju da su otkazi u eksploataciji posledica statičkog preopterećenja (32%), plastičnog popuštanja (14%), zamora (26%), korozije (17%) i puzanja (1%), /1/. Blagovremenim otkrivanjem oštećenja mogu se u znatnoj meri smanjiti ovi otkazi. Poseban doprinos u tom pogledu predstavlja kontinualno praćenje ponašanja konstrukcije. To se može postići stereometrijskim merenjem deformacija tokom rada, pratećom analizom integriteta konstrukcije i ocenom preostalog veka.

Za ocenu integriteta i preostalog veka potrebni su podaci o odgovoru elemenata konstrukcije na dejstvo opterećenja tokom eksploatacije. Uticaj opterećenja i njegove promene sa vremenom na ponašanje elemenata konstrukcije se može oceniti na osnovu izazvane lokalne promene deformacija na površini. Značajno je da se unapred izabere područje očekivanih maksimalnih deformacija i napona u skladu sa pretpostavljenom koncentracijom napona, jer od toga zavisi lokalna raspodela napona i deformacija. Merenje deformacija treba izvesti na odabranom segmentu u tom području.

Keywords

- stereometric measurement
- stress
- strains
- structural integrity
- fitness-for purpose

Abstract

This paper describes the use of digital stereometry in measuring microstrains on the surface. This can be achieved by comparing images of point distribution on faced surface at different load levels and thus introduced stresses. The examples present the possibility to measure strain concentration in the vicinity of crack tip on metallic sample and on bone tissue. By applying two video cameras and corresponding software the image of strain distribution can be obtained in different forms, in 2D and 3D formats.

INTRODUCTION

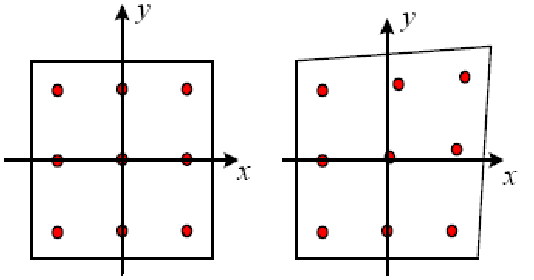
Statistical data revealed that service failures are the consequence of static overloading (32%), plastic collapse (14%), fatigue (26%), corrosion (17%), and creep (1%), /1/. These failures can be significantly reduced by timely detection of damages. Special contribution in that sense presents continuous monitoring of structural behaviour. This can be achieved by stereometric measurement of strains during operation, followed by the structural integrity analysis and residual life assessment.

The data on response of a structural element to the applied load during operation are required for structural integrity and life assessment. The effect of loading on structural element behaviour and its variation in time can be assessed based on produced local changes in strains on the surface. It is important to predict in advance the region of expected maximal strains and stresses according to supposed stress concentration, since local stress and strain distribution depends on that. Strain measurement has to be performed on a selected segment in this region.

Ispitivanje realnih konstrukcija mernim trakama daje prihvatljive rezultate, ali je prilično je složeno u praktičnoj primenii /2/. Koncept mernih traka je merenje izduženja male početne merne dužine. Osnovni koncept stereometrijske metode je bezkontaktno merenje pomeranja tačaka odabranog segmenta površine konstrukcije izložene dejstvu opterećenja i određivanje unetih deformacija i napona /2/.

STEREOMETRJSKO MERENJE POMERANJA

Na osnovu izmerenog relativnog pomeranja odabranih tačaka segmenta površine mogu se proračunati lokalne deformacije i naponi. Na sl. 1. je prikazan segment površine elementa konstrukcije sa mrežom tačaka u neopterećenom stanju i njihovim položajem pri dejstvu opterećenja. Položaj tačaka se kontinualno prati u prostoru merenjem trenutnih koordinata /2, 3/. Model ovakvog mernog sistema sa dve video kamere je prikazan na sl. 2. Na sl. 3. prikazana je video kamera Aramis /4/, a na sl. 4. „“ /5/ sa ispitivanom epruvetom sa dva tipa ??? središnja zareza /6/.



Slika 1. Položaj izabranih i obeleženih tačaka na segmentu površine u neopterećenom (levo) i opterećenom stanju (desno)

Digitalno stereometrijsko merenje je bazirano na fotometriji kojom se pomeranja tačaka na površini materijala određuju poređenjem slika u dva uzastopna naponska stanja /2, 3/. U tom cilju niz tačaka u referentnom (početnom) stanju je ucrtan na mikrodijagram - mrežu redova i kolona odabrane gustine. Za praćenje promene pomeranja potrebna je procedura sa algoritnom upravljanja normalizovanom slikom, pri čemu $r(u, v)$ definiše stepen korelacije između zona slike, I je naponska zona područja slike, M je model lokacije piksela (x_i, y_i), I_i je zona lokacije piksela $(u + x_i, v + y_i)$, N je broj piksela na modelu slike, i je redni broj od 1 do N. Kvalifikovani region slike je kvadratni niz (matrica) piksela strana N oko svake merne tačke mreže /7/. Korelaciona vrednost $r = 1$ označava savršeno slaganje, za $r = 0$ nema korelacije i za $r = -1$ je neslaganje potpuno. Ovaj algoritam određuje položaj tačaka površine deformisanog materijala u odnosu na početnu sliku. Rotacija nije uzeta u obzir. Procesiranje slike, centriranje i korelacija mernih funkcija se obavljaju softverom napisanim za grafički programski jezik LabVIEW /8/, prilagođen Pentium kompjuteru. Softver koristi korelaciju indeksa (r) između traženog regiona za interpolaciju unutar pikselske lokacije i procenjenih podpiksela pomeranja. Posle određivanja komponenti pomeranja svake merne tačke, dvodimenzioni tenzor napona se proračunava izjednačavanjem i diferenciranjem polja pomeranja /9/.

Testing of real structures by strain gages produces acceptable results, but it is pretty complicated in practical use /2/. Concept of strain gages is elongation measurement of small initial measuring length. Basic concept of streometric method is contactless measurement of points displacement of selected segment on structure surface exposed to loading and determination of induced strains and stresses /2/.

STEREOMETRIC MEASUREMENT OF DISPLACEMENT

It is possible to calculate local strains and stresses of selected points on surface segment based on measured relative displacement. One segment of structural element surface with the points grid in non-loaded state and their positions when loaded is presented in Fig. 1. The position of points is continuously monitored in space by measuring instantenous coordinates /2, 3/. The model of this measuring system with two video cameras is presented in Fig. 2.Video camera Aramis is presented in Fig. 3 /10/, and in Fig. 4 „“ /11/ with tested specimen with two central notches /6/.

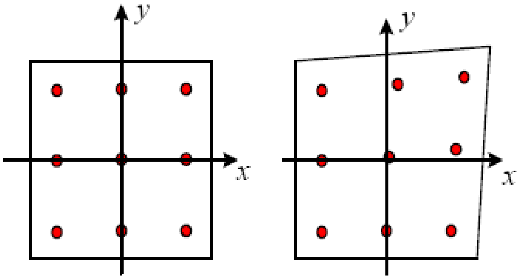
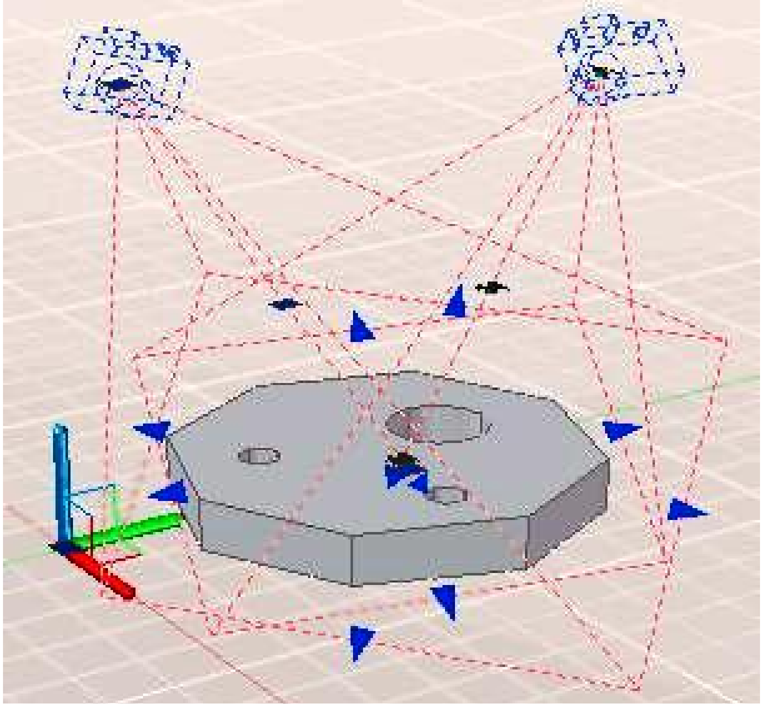


Figure 1. The position of selected and labeled points on the surface segment in non-loaded (left) and loaded state (right)

Digital stereometric measurement is based on the photogrammetry allowing to obtain displacements of material surface points comparing images in two successive stress states /2, 3/. For that, an array of points in the reference (initial) state is imposed on a micrograph - grid of rows and columns. For displacement change monitoring a control procedure with algorithm for normalized image is necessary, where $r(u, v)$ defines the correlation degree between image areas, I is the stressed image region, M - the model of pixel location (x_i, y_i), I_i - the pixel location $(u + x_i, v + y_i)$, N - number of pixels in the image model, i - rang from 1 to N. The trained image region is a square array (matrix) of pixels with sides N around each grid measurement point /7/. A correlation value $r = 1$ indicates a perfect matching, correlation is nil at $r = 0$, and by $r = -1$ complete mismatch is given. This algorithm determines the surface points position on deformed material relative to initial image. Rotation is not accounted. Image processing, alignment, and correlation of measurement functions are done with software written by LabView /8/ program language adopted to Pentium PC. The software uses the correlation index (r) within the search region to interpolate between pixel locations and estimated subpixel displacement. Upon displacement components determination in each measurement point, two-dimensional stress tensor is calculated by smoothing and differentiating displacement field /9/.



Slika 2. Snimanje konstrukcije video kamerama(shema)

Figure 2. Recording structure with video cameras (scheme)

Slika 3. Video kamera Aramis /4/

Figure 3. Video camera Aramis /4/

Slika 4. Video kamera „“ sa ispitivanim uzorkom u sredini /5/

Figure 4. Video camera „“ with the tested sample in the middle /51/

PRIMENA STEREOMETRIJSKOG MERENJA NA BRODOVE

U velikim čeličnim konstrukcijama, pa i u slučaju brodova, korozija predstavlja jedan od osnovnih razloga otkaza. Na sl. 5. je prikazana izražena korozija lanca brodskog čekrka /10/. Na sl. 6. su označeni položaji otkrivene površinske korozije na koroziji /11/.

Međutim, kontinualno praćenje oštećenja tokom rada nije jednostavno. U nekim je slučajevima to i nemoguće, kao je slučaj sa primerima na sl. 5. i 6, pa se kontrola izvodi u prekidu, između dve faze rada. Takođe treba uočiti da se stereometrijskim merenjem mogu pratiti samo golim okom vidljiva oštećenja, kao što su površinske zamorne prsline, pod uslovom da su dovoljno velike, ili jasno izražene lokalne deformacije. Od stereometrijskog merenja zavisi i postupak za ocenu integriteta i veka konstrukcije.

THE APPLICATION OF STEREOMERIC MEAUREMENT ON SHIPS

In large steel structures, and also in the case of ships, corrosion presents one of basic failure causes. In Fig. 5 exagareted corrosion of chain of ship windlass is presented /10/, and in Fig. 6 the locations of detected corrosion on the submarine surface are labelled /11/.

However, damage continuous monitoring is not simple. In some cases it is impossible, as it is the case with examples in. Figs. 5 and 6, and than the inspection is performed in break between two operation stages. It is also to notice that by stereometric measurement only the damages visible by nacked eye can be monitored, as fatigue surface crack, under condition of sufficient size, or clearly expressed local strains. The procedure for structural integrity and life assessment depends on stereometric measurement.

Slika 5. Korozija lanca brodskog čekrka /10/
Figure 5. Corrosion of chain of ship windlass /10/

Slika 6. Korozija spoljnje površine podmornice /11/
Figure 6. Corrosion of submarine outer surface /11/

Mreža tačaka na sl. 1. je korišćena za određivanje polja deformacija poređenjem prostornih (3D) slika u početnom stanju i pri dejstvu opterećenja dobijenim bezkontaktnim stereometrijskim merenjem veličine pomeranja tačaka /12/. To se postiže sa dve video kamere (sl. 2), koje mogu biti postavljene stalno ili ponovo pri svakom merenju, koje treba pre merenja kalibirsati. Nakon postavljanja plana merenja u softveru, slike se snimaju pri različitim nivoima opterećenja. Nakon uspešne obrade, rezultati merenja su dostupni u 3D vidu /3/, a mogu se dobiti i drugi prikazi u obliku izveštaja, statističkih podataka ili radova.

Veoma je teško otkriti koroziju ispod izolacije na podmornici podmornice (sl. 6), i neprekidna kontrola razvoja otkrivene korozije zahteva značajno unapređenje odgovarajućeg sistema.

ANALIZA MIKROPRSLINE

Razvoj loma iz otkrivene prsline u određenom periodu je moguće kontinualno pratiti postupkom stereometrijskog merenja polja deformacija oko vrha prsline, pri čemu je potrebna i neprekidna procena podobnosti za upotrebu. Značajna prednost primene ovog postupka je ilustrovana sa dva suštinski različita primera analize razvoja mikroprsline, u zavarenom spoju čelične konstrukcije /1/ i u koštanom tkivu /13/. Sem postupka ispitivanja, različito je i prikazivanje dobijenog 3D rezultata. U prvom primeru je raspodela deformacija prikazana prostorno (sl. 7). Drugi detalji ovog ispitivanja se mogu naći u radu /1/.

U drugom slučaju je praćeno ponašanje vrha prsline u mikrostrukturi kosti, karakterističnoj zbog poroznosti i prisustva šupljina /13/. Merna mreža koraka 11 μm obuhvata složeno polje deformacija na ovom mikrostrukturnom nivou i ukazuje na uticaj mikrostrukturnih karakteristika Na preklopljenom mikrodijagramu se vidi efektivno polje deformacija(sl. 8). Dijagram efektivnih deformacija u ispitanoj oblasti, 1 i 2 su glavni pravci, otkriva područje koncentrisane lokalne deformacije tkiva u okolini vrha postojeće mikroprsline u kortikalnoj kosti od 0,030% (30.000 mikrodefromacija). Isprekidana linija pokazuje položaj vrha mikroprsline. Pik lokalne deformacije od 0,010% (10.000 mikrodeformacija) je pripisan uticaju mikrostrukturnih karakteristika, u ovom slučaju pora koštanog tkiva, označene strelicama.

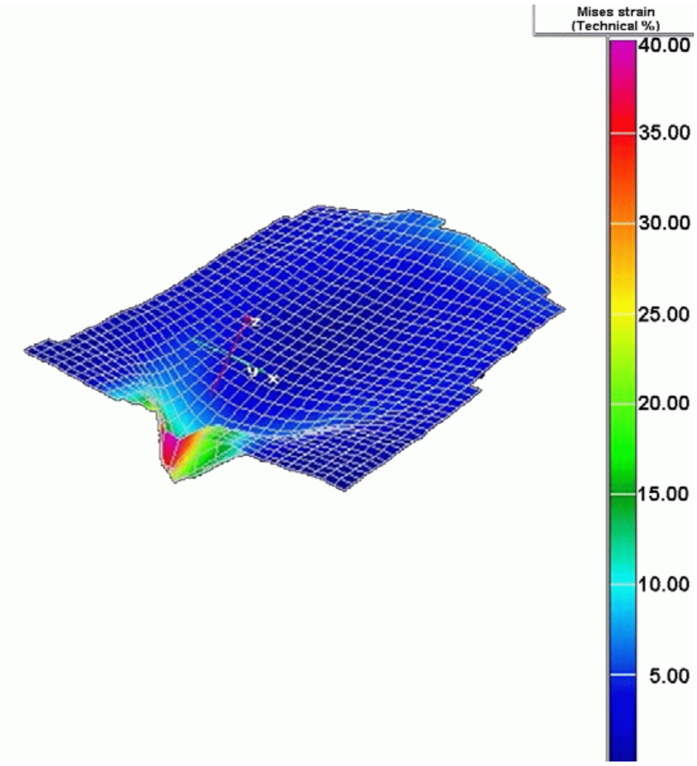
The grid of points in Fig. 1 was used for determination of strain field comparing space (3D) images in initial stage and at applied load obtained by contactless stereometric measurement of points displacement values /12/. This can be achieved with two video cameras (Fig. 2), which can be positioned stacionary or again for each measurement and calibrated before measuring. After creating the measuring project in the software, images are recorded in various load levels. After successful computation, the measuring results are available as 3D view /3/, and additional presentations in the form of reports, statistics or papers can be abtained.

It is very dificult to detect corrosion under insulation on submarine (Fig. 4), and continuous inspection of detected corrosion growth requires for improvement of the corresponding system.

THE ANALYSIS OF A MICROCRACK

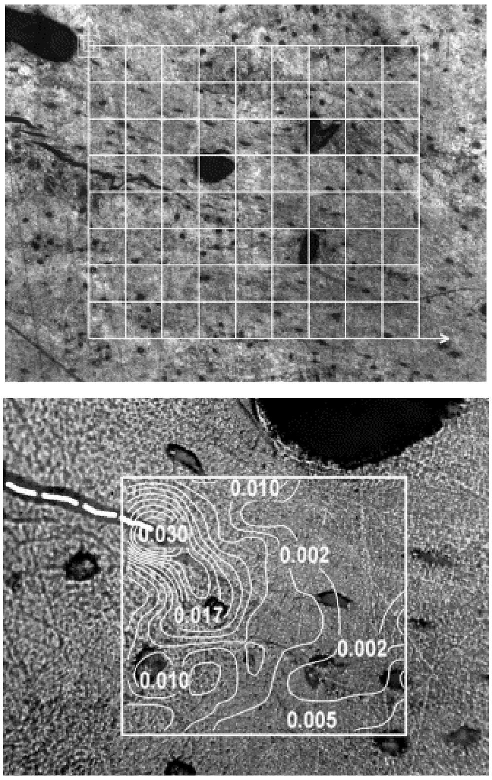
Frature development from detected crack can be monitored continuously by stereometric measurement of strain field around crack tip, with consecutive application of fitness for service assessment. An important advantage of this procedure has been illustrated by two substancially different examples of microcrack growth analysis, in the welded joint of steel structure /1/ and in bone tissue /13/. In addiition to testing procedure, the presentation of obtained 3D results is quite different. In the first example strain distribubtion is presented spatially (Fig. 7). The next details of this testig can be found in Reference /1/.

In the second case the crack behavior has been monitored in bone micorstructure, typical by porosity and lacunae (voids) /13/. The measurement grid spacing used, 11 μm, captures the complex strain field at this microstructural level and indicates the effect of microstructural features. Superimposed on the micrograph is the resulting effective strain field (Fig. 8). A plot of the effective strain over tested area, 1 and 2 are the principal directions, reveals a region of tissue concentrated local strains in the vicinity of existing microcrack in a cortical bone of 0.030% (30,000 microstrain). Dashed line indicates the position of microcracktip. The pik of local strain of 0.010% (10,000 microstrain) is attributed to the effect of microstructural feature, in this case of pores in bone tissue, indicated by the arrows.



Slika 7. Raspodela deformacija oko vrha prsline dobijena stereometrijskim merenjem /1/

Figure 7. Strain distribution around crack tip obtained by stereometric measurement /1/



Slika 8. Digitalni mikrograf površine snimljen sa 500X povećanja

Figure 8. Digital micrograph of surface taken at 500X magnification

DISKUSIJA

Položaj svakog para podudarnih tačaka za svaku sliku može se izračunati za sva tri 2D pomeranja prema slikama deformisanog i početnog nedeformisanog stanja. Sve ove podudarne tačke predstavljaju iste tačke objekta za dva stanja opterećenja, te 3D coordinate mogu biti izračunate preko leđne projekcije. Kada su određene 3D prostorne koordinate svake izdvojene merne tačke u području koje se razmatra na površini objekta (broda), određivanje deformacija postaje samo stvar numeričkog proračuna na osnovu polja pomeranja. Izabrani system izračunava površinsku deformaciju preko transformacije 3D u 2D raspodelu pomeranja, tako da je deformacija sračunata u 2D prostoru /14/. Prethodno je za svaku tačku objekta sračunata tangencijalna ravan za oba stanja opterećenja, zajedno sa obližnjim tačkama objekta (broda). Dobijene pravougaone oblasti pokazuju kako je objekt oivičen. Tačke u oivičenom objektu su zatim projekovane na tangencijalnu ravan u pravcu njenog normalnog vektora, što problem ograničava na ravanski. Dalje izračunavanje gradijenta deformacije je moguće primenom teorije velikih deformacija, koja obuhvata plastične deformacije i kretanje krutog tela /15/. U izvedenoj analizi korišćen je objekt veličine ivica 11 x 11 piksela. Ekstremni gradijent deformacije i izražena lokalna pomeranja iz ravni mogu se očekivati u tankom sloju epruvete blizu vrha prsline. Profil površine je izdvojen digitalnim modelom, koji omogućava određivanje pomeranja otvora prsline na vrhu.

DISCUSION

The position of each homologous points pair for each image can be calculated of all three 2D displacements according to the images of deformed and initial undeformed states. As these homologous points represent the same object point in two loaded stages, its 3D coordinates can be calculated via back projection. When the distinctive 3D spatial coordinates of each measurement point in the considered region are determined on the object's (ship's) surface, strain determination becomes merely a matter of numerical calculation from the displacement field. The chosen system calculates surface strain through transformation of the 3D into a 2D displacement distribution, thus strain is calculated in 2D space /14/. Initially, for each of the object points, a tangential plane is calculated for both loading conditions, together with the surrounding object points. The obtained rectangular area is referred to as the object facet. Points in this object facet are then projected onto the tangential plane in the direction of its normal vector, which renders the problem as planar. Further calculation of the deformation gradient is possible using the theory of large deformations, which allows plastic deformations as well as rigid body motion /15/. The performed strain analysis considered facet sizes to 11 x 11 pixels. The extreme strain gradients and extensive local out of- plane displacement can be expected in the tiny specimen area near the crack tip. Surface profile is extracted by digital model, enabling the determination of crack tip opening displacement.

ZAKLJUČAK

Složenost istraživanja integriteta konstrukcija može se sagledati iz raznolikosti podataka potrebnih za oecnu podobnosti za upotrebu. Ovde je ukazano i na pravac istraživanja i razvoja, u skladu sa potrebama iskazanim kroz iskustvo i praksu postupaka ocene integriteta konstrukcija i podobnosti za upotrebu. .

Analiza lokalnih mikrodeformacija i napona na površini omogućava bolje razumevanje razvoja oštećenja i loma. Klasična eksperimentalna tehnika za merenje deformacija ne karakterizaciju podataka potrebnih na mikrostrukturnom nivou na površini. Stereometrijska metoda omogućava uvid u naponsko polje koje odgovara raspodeli osobina materijala za brodove. Kako su deformacije na označenoj površini u blizini vrhu prsline otkrivene i izmerene ovom metodom, može se očekivati da će ova tehnika u budućnosti biti u stanju da se koristi za eksperimentalna ispitivanja loma zahtevane tačnosti.

CONCLUSION

The complexity of structural integrity research may be recognized from the diversity of the data necessary for fitness for purpose assessment. The direction of research and development is here also shown, consistent with needs defined through experience and through practice of structural integrity and fitness for purpose assessment procedures.

The analysis of local microstrains and stresses on the surface may lead to better understanding of damage and fracture development. Traditional experimental techniques for strain measuring do not allow characterization of necessary data at the microstructural level on surface. The stereometric method provides views in a stress field corresponding to the distribution of the ship's material properties. As the deformation on the surface facet at the vicinity of the crack tip is observed and measured by this method, one can expect that this technique will in future produce experimental fracture testing of required accuracy.

LITERATURA – REFERENCES

1. Nenad Gubeljak, *Primena stereometrijskog merenja na integritet konstrukcija*, Integritet i vek konstrukcija, Vol. 6, br 1-2 (2006), str 65-74.
2. Merne trake (Uzeti iz IVK)
3. N. Gubeljak, J. Lozanovic, A. Sedmak, *CRACK TIP STRAIN AND CTOD IN SITU MEASUREMENT*, First Serbian (26th YU) Congress on Theoretical and Applied Mechanics Kopaonik, Serbia, April 10-13, 2007.
4. Aramis GOM mbH, http://www.gom.com
5. www.ni.com
6. Measurement of Fracture Toughness. Annual Book of ASTM Standards. American Society for Testing andMaterials, West Conshohocken, PA, USA.
7. LOZANOVIĆ J., Crack tip stress determination and structural integrity evaluation by computerized stereometric measurement, Ph.D. thesis – working version, Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia 2007.
8. LabView v.8.0, National Instruments, Austin, TX, USA
9. Williams, D.R., Davidson, D.L. and Lankford, J.,1980, Fatigue-Crack-Tip Plastic Strains by the Stereoimaging Technique, Experimental Mechanics 20, pp.134–139. Full Text via CrossRef | View Record in Scopus |Cited By in Scopus (30)
10. Čekrk
11. Podmornica
12. ?????
13. Daniel P. Nicolella, Arthur E. Nichollsa, James Lankforda and Dwight T. Davyb, Machine vision photogrammetry: a technique for measurement of microstructural strain in cortical bone, Volume 34, Issue 1, January 2001, Pages 135-139.
14. Davidson, D.L. and McClung, R.C., 1997. Local constraint near fatigue cracks in alloys and particulate *composites,* International Journal of Fracture 84, pp. 81–98. Full Text via CrossRef | View Record in Scopus | Cited By in Scopus (20)
15. Gomerčić, M. (1999) The compensation of out-ofplane displacements in deformation measurement by grating method. O¨ sterr. Ing. Architek. Z. (OIAZ) 144, 223–227.
16. Franke, E.A., Wenzel, D.L. and Davidson, D.L., 1991. Measurement of microdisplacements by machine vision photogrammetry (DISMAP), Review of ScientificInstruments 62, pp. 1270–1279. Full Text via CrossRef
17. Jasmina Lozanović, Nenad Gubeljak, Aleksandar Sedmak, Marko Rakin, Dragan Lazić, *CRACK TIP STRAIN ON SHIP AND IN SITU MEASUREMENT IN SHIPYARDS,*