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NON-DESTRUCTIVE MEASUREMENTS OF RESIDUAL STRESSES IN STRUCTURAL DETAILS OF BRIDGES MERENJE ZAOSTALIH NAPONA BEZ RAZARANJA U KONSTRUKCIONIM DELOVIMA MOSTOVA

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Abstract

Bridges are vital in our society for uninterrupted transportation of goods and people on roads and railways and timely maintenance and repair of bridges are of outmost importance. The residual stresses have a significant effect on the process of the initiation and propagation of the fatigue cracks in welded elements and are responsible for many bridge failures. Knowledge of residual stresses, their distribution and their nature is, therefore, of paramount importance in all stages of bridge's design, building and maintenance. Among non-destructive methods for residual stress measurements the use of ultrasonic waves is gaining popularity and acceptance. A portable instrument, UltraMARS that is capable of measuring residual stresses in materials either averaged through thickness or in surface and subsurface layers using ultrasonic waves of different frequencies and displaying the results in a form of a continuous curve on the screen of the instrument was developed and used successfully in many investigations [1, 2].

The main principles of operation and used methodology are briefly discussed, with actual measurement examples using the bulk, the surface and the subsurface presented. A new transducer for measurement of surface and subsurface stresses with a variable base between the ultrasonic wave sender and receiver was designed and manufactured recently. By changing the distance between the sender and receiver it is possible to obtain nondestructively information on residual stress distribution through a certain range of thicknesses of the interrogated materials and structures. Results of calibration of the new variable base ultrasonic transducer (VBUT) for a number of selected materials will be presented.

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Abstrakt

Mostovi su od vitalnog značaja za naše društvo radi neprekinutog prevoza robe i ljudi na putevima i železnicama, a blagovremeno održavanje i popravke mostova su od najvećeg značaja. Zaostali naponi imaju značajan uticaj na proces pokretanja i širenja prslina usled zamora u zavarenim elementima i odgovorni su za mnoge lomove mosta. Znanje o zaostalim naponima, njihovoj distribuciji i njihovoj prirodi su, dakle, od najvećeg značaja u svim fazama projektovanja, izgradnje i održavanja mosta. Među metodama bez razaranja za merenje zaostalih napona, upotreba ultrazvučnih talasa dobija sve veću popularnost i prihvatanje. Razvijen je prenosni instrument, UltraMARS koji je sposoban za merenje zaostalih napona u materijalima bilo u preseku kroz debljinu ili površinskim i podpovršinskim slojevima koristeći ultrazvučne talase različite frekvencije i prikazivanje rezultata u obliku kontinuirane krive na ekranu instrumenta i uspešno se koristi u mnogim istraživanjima [1, 2].

Glavni principi rada i korišćena metodologija su ukratko razmotreni, sa stvarnim primerima merenja koristeći zapreminu, površinu i podpovršinu. Nedavno je dizajniran i proizveden novi pretvarač za merenje površinskih i podpovršinskih napona sa promenljivom bazom između ultrazvučnog talasa i prijemnika. Promenom udaljenosti između odašiljača i prijemnika moguće je dobiti, bez razaranja, informacije o raspodeli zaostalog naprežanja kroz određeni raspon debljina ispitivanih materijala i konstrukcija. Biće predstavljeni rezultati kalibracije novog promenljivog baznog ultrazvučnog pretvarača (VBUT) za određeni broj odabranih materijala.

Takođe su prikazani rezultati zaostalih napona merenih u konstrukcionim delovima mosta koji je



The results of residual stresses measured in structural details of a bridge that was damaged as well as in a number of welded bridges before and after application of improvement treatment used to beneficially redistribute the residual stresses are also presented. The obtained data on residuals stress distribution had proven that the non-destructive ultrasonic method for measurement of residual stresses is a practical and useful tool in maintenance and repair of bridges.

1. Introduction

Bridges are vital in our society for uninterrupted transportation of goods and people on roads and railways and timely maintenance and repair of bridges are of outmost importance. Too many examples exist of catastrophic failures of bridges when these important safety procedures are ignored. A growing number of studies has been and are conducted to improve the existing methods and diagnostic tools and to come up with new procedures and methods for inspection, testing, monitoring and condition assessment, of railway bridges [1-6].

Residual stress can significantly affect engineering properties of materials and structural components, notably, fatigue life, distortion, dimensional stability, corrosion resistance etc.. Such effects usually lead to considerable expenditures in repairs and restoration of parts, equipment and structures. For that reason, the knowledge of residual stresses and their analysis are compulsory stages in the design of structural elements and in the estimation of their reliability under real service conditions.

Systematic studies had shown that welding residual stresses may lead to a drastic reduction in fatigue strength of welded elements. In multi-cycle fatigue ($N > 106$ cycles) the effect of residual stresses can be compared with the effect of stress concentration. Even more significant are the effects of residual stresses on the fatigue life of welded elements in the case of relieving harmful tensile residual stresses and introducing beneficial compressive residual stresses in the weld toe zones. The results of fatigue testing of welded specimens in as-welded condition and after application of ultrasonic peening showed that in case of non-load caring fillet welded joint in high strength steel, the redistribution of residual stresses resulted in approximately two-fold increase in the limit stress range [7, 8].

The residual stresses, therefore, are one of the main factors determining the engineering properties of materials, parts and welded elements and this factor should be taken into account during the design and manufacturing of bridges. Although certain progress has been achieved in the

oštećen kao i u većem broju zavarenih mostova pre i posle primene poboljšanog tretmana korišćenog za korisnu redistribuciju zaostalih napona. Dobijeni podaci o raspodeli zaostalih naprežanja dokazali su da je nerazorna ultrazvučna metoda za merenje zaostalih napona praktično i korisno sredstvo u održavanju i popravci mostova.

1. Uvod

Mostovi su od vitalnog značaja za naše društvo za neprekinuti prevoz robe i ljudi na putevima i železnicama, a blagovremeno održavanje i popravka mostova su od najvećeg značaja. Previše je primera katastrofalnih kvarova mostova kada se ovi važni sigurnosni postupci zanemaruju. Sve veći broj studija je sproveden kako bi se poboljšale postojeće metode i dijagnostički alati i došlo do novih postupaka i metoda za inspekciju, ispitivanje, praćenje i procenu stanja železničkih mostova [1-6].

Zaostali naponi mogu značajno uticati na inženjerska svojstva materijala i konstrukcijskih komponenti, naročito na vek trajanja usled zamora, izobličenje, dimenzionu stabilnost, otpornost na koroziju itd. Takvi efekti obično dovode do znatnih troškova za popravke i restauraciju delova, opreme i konstrukcija. Iz tog razloga, poznavanje zaostalih napona i njihova analiza obavezni su koraci u projektovanju konstrukcijskih elemenata i proceni njihove pouzdanosti u stvarnim uslovima rada.

Sistematske studije su pokazale da zaostali naponi usled zavarivanja mogu dovesti do drastičnog smanjenja čvrstoće zavarenih elemenata. Kod višecikličnog zamora ($N > 106$ ciklusa) efekat zaostalih napona može se uporediti sa efektom koncentracije napona. Još značajniji su efekti zaostalih napona na vek trajanja usled zamora zavarenih elemenata u slučaju otpuštanja štetnih zatezanih zaostalih napona i uvođenja korisnih pritisanih zaostalih napona u zonama podnožja zavarenih spojeva. Rezultati ispitivanja zamorom zavarenih uzoraka u stanju zavarivanja i nakon ultrazvučne obrade površine, pokazali su da u slučaju neopterećenog ugaonog zavarenog spoja od čelika visoke čvrstoće, preraspodela zaostalih napona dovodi do približno dvostrukog povećanja graničnog opsega napona [7, 8].

Preostali naponi su, dakle, jedan od glavnih faktora koji određuju inženjerska svojstva materijala, delova i zavarenih elemenata i taj faktor treba uzeti u obzir tokom projektovanja i izrade mostova. Iako je postignut određeni napredak u razvoju tehnika za upravljanje zaostalim naponima, još uvek je



development of techniques for residual stress management, a considerable effort is still required to develop efficient and cost-effective methods of residual stress measurement and analysis.

2. Measurement of residual stresses by ultrasonic method

The measurements of residual stresses (RS) by UltraMARS® system are based on solid theory, original technique and use of precise instrumentation. It is possible to use ultrasound for measurement of stresses in materials, because, according to the acousto-elastic theory of interaction of ultrasound with materials, the changes in travel velocities (or frequencies) of ultrasound in a material depend linearly on the stresses in the materials over a certain range of stresses [9-11].

For measurement of RS in parts, welded elements and structures, as a prerequisite, the determination of acoustic-elastic coefficients of the considered material has to be performed that is based on measurement of ultrasonic wave velocities in a sample under different loadings and calculation of the acousto-elastic coefficients, based on these measurements. Once the acousto-elastic coefficients are determined, they are added to the UltraMARS® device microprocessor for further computation of RS.

2.1 Residual Stress Measurement System - UltraMARS®

In general, the change in the ultrasonic wave velocity in structural materials under mechanical stress amounts only to tenths of a percentage point. Therefore the equipment for practical application of ultrasonic technique for residual stress measurement should be of high resolution, reliable and fully computerized. The major parts of the developed system for residual stress analysis [12-17] include a measurement unit with supporting software, a preamplifier with a magnetic, electromagnetic or mechanical holder and interchangeable transducers (Fig. 1). For selection of the appropriate reflected wave and tuning in manual mode an oscilloscope is, usually, used. The designed system allows determining uni- and biaxial applied and residual stresses for a wide range of materials and structures.

potreban veliki napor da se razviju efikasne i ekonomične metode merenja i analize zaostalih napona.

2. Merenje zaostalih napona ultrazvučnom metodom

Merenja zaostalih napona (RS) po UltraMARS® sistemu zasnivaju se na teoriji čvrstoće originalnoj tehnici i upotrebi precizne instrumentacije. Moguće je koristiti ultrazvuk za merenje naprezanja u materijalima, jer, prema akustično-elastičnoj teoriji interakcije ultrazvuka sa materijalima, promene brzine kretanja (ili frekvencije) ultrazvuka u materijalu zavise linearno od napona u materijalu u određenom rasponu napona [9-11].

Za merenje RS u delovima, zavarenim elementima i konstrukcijama, kao preduslov, mora se odrediti akustično-elastičnog koeficijent razmatranog materijala koji se zasniva na merenju brzina ultrazvučnih talasa u uzorku pod različitim opterećenjima i izračunavanju akousto-elastičnih koeficijenata na osnovu ovih merenja. Nakon što se utvrde akustično-elastični koeficijenti, oni se dodaju na mikroprocesor uređaja UltraMARS® za dalje računanje RS.

2.1 Sistem za merenje zaostalih napona UltraMARS®

Generalno, promena brzine ultrazvučnog talasa u konstrukcionim materijalima pod mehaničkim naponom iznosi samo desetina procenta. Stoga oprema za praktičnu primenu ultrazvučne tehnike za merenje zaostalih napona treba da bude visoke rezolucije, pouzdana i u potpunosti kompjuterizovana. Glavni delovi razvijenog sistema za analizu zaostalih napona [12-17] uključuju mernu jedinicu sa pratećim softverom, predpojačalo sa magnetnim, elektromagnetnim ili mehaničkim držačem i izmenjive pretvarače (Sl. 1). Za izbor odgovarajućeg refleksnog talasa i podešavanje u ručnom režimu obično se koristi osciloskop. Dizajnirani sistem omogućava određivanje jedno- i dvoosnih i zaostalih napona za širok spektar materijala i konstrukcija.



Fig.1 Ultrasonic Computerized Complex for residual and applied stress measurement. - Measurement unit with supporting software, (2a) – Preamplifier, (2b) – Magnetic holder, (3) – Transducer, (4) – Oscilloscope, (5) – Sample
Sl. 1 Ultrazvučni kompjuterizovani kompleks za merenje zaostalih i primenjenih naprezanja. - Merna jedinica sa pratećim softverom, (2a) - Predpojačalo, (2b) - Magnetni držač, (3) - Pretvarač, (4) - Osciloskop, (5) - Uzorak..

2.2 Determination of Acousto-elastic Coefficients

The samples for determination of acousto-elastic coefficients can be loaded in compression or in tension. Depending on the loading scheme, the geometry of the sample is selected. Fig. 2a shows a schematic view of a standard sample that is used for determination of acoustoelastic coefficients in tension. Fig. 2b shows a standard sample for determination of acoustoelastic coefficients in compression. During the loading of the sample, the dependence of all three ultrasonic frequencies (the longitudinal and two shear orthogonally polarized) on the applied force should remain linear in the whole range of testing. Fig. 3a and Fig. 3b show laboratory set-ups for measurement of acousto-elastic coefficients using a tension sample or a compression sample, respectively. Fig. 4 presents the linear relationships between all three ultrasonic frequencies and the applied forces obtained in the process of determining the acousto-elastic coefficients.

2.2 Određivanje akustično-elastičnih koeficijenata

Uzorci za određivanje akousto-elastičnih koeficijenata mogu se opteretiti pritiskom ili zatezanjem. U zavisnosti od šeme opterećenja, bira se geometrija uzorka. Sl. 2a prikazuje šematski prikaz standardnog uzorka koji se koristi za određivanje akustično -elastičnih koeficijenata u zatezanju. Sl. 2b prikazuje standardni uzorak za određivanje akousto-elastičnih koeficijenata pri pritisku. Za vreme optrećivanja uzorka, zavisnost sve tri ultrazvučne frekvencije (uzdužna i dva pravougaono polarizovana smicanja) od primenjene sile trebalo bi da ostane linearna u celom opsegu ispitivanja. Sl. 3a i sl. 3b prikazuju laboratorijske postavke za merenje akustično-elastičnih koeficijenata pomoću zateznog uzorka odnosno uzorka pod pritiskom. Sl. 4 prikazuje linearne odnose između sve tri ultrazvučne frekvencije i primenjenih sila dobijenih u procesu određivanja akousto-elastičnih koeficijenata.

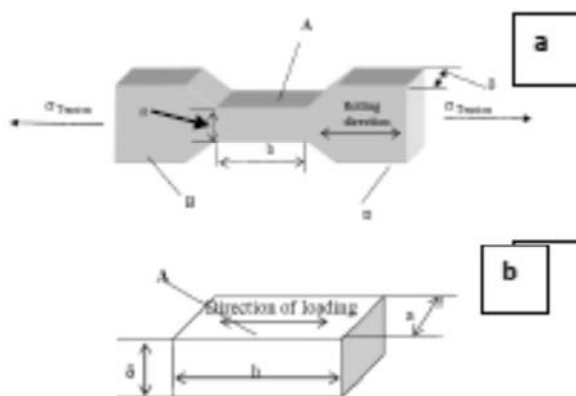


Fig. 2 Schematic presentation of samples used for determination of the acoustic-elastic coefficients of considered material: a) Tensile sample: $a = 50-60\text{ mm}$; $b = 70-80\text{ mm}$; δ – material thickness; A – zone of installation of ultrasonic gauge(s) during loading of sample; B-grip surfaces; b) Compression sample: $a = 50-60\text{ mm}$; $b = 70-80\text{ mm}$; δ – material thickness; A – surface used for installation of ultrasonic gauge(s).

Sl. 2 Šematski prikaz uzoraka koji se koriste za određivanje akousto-elastičnih koeficijenata razmatranog materijala: a) Zatezni uzorak: $a = 50-60\text{ mm}$; $b = 70-80\text{ mm}$; δ - debljina materijala; A - zona postavljanja ultrazvučnih merača tokom opterećenja uzorka; B-stisnuta površina; b) Uzorak pritiskivanja: $a = 50-60\text{ mm}$; $b = 70-80\text{ mm}$; δ - debljina materijala; A - površina koja se koristi za ugradnju ultrazvučnih merača.

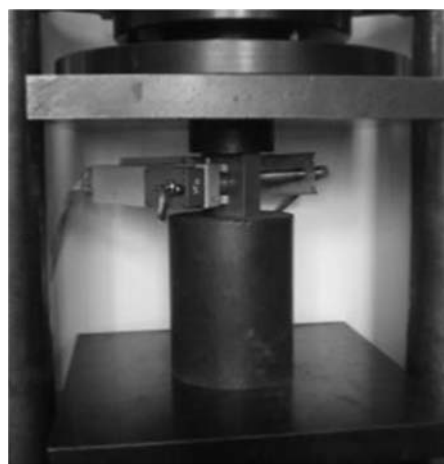


Fig. 3 General view of the loading set-up for measurement for determination of acousto-elastic constants; a) set-up for measurements on a tension sample; b) set-up for measurements on a compression sample. In both cases the attached to the sample transducer is marked with arrows.

Sl. 3 Opšti prikaz podešavanja opterećenja za merenje za određivanje akustično-elastičnih konstanti; a) postavljanje za merenja na uzorku na zatezanje; b) postavljanje za merenja na uzorku na pritisak. U oba slučaja su zakačeni uz uzorke a pretvarači su obeleženi strelicama.

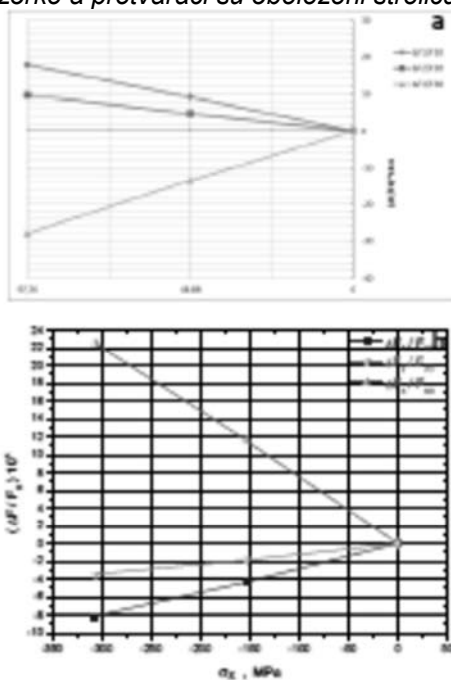


Fig. 4 Graph of ultrasonic frequencies changes in the sample versus applied stresses; a) applied stresses are tensile; b) applied stresses are compressive.

Sl. 4 Grafikon promene ultrazvučnih frekvencija u uzorku u odnosu na primenjena naprezanja; a) primenjeni naponi su zatezni; b) primenjeni naponi su pritiski.

3. Measurement of residual stresses on bridges

3.1 Evaluation of Residual Stresses in a Damaged Bridge

To evaluate the state of residual stresses in a damaged steel bridge girder region the UltraMARS complex was used. Fig. 5a shows the initial examination of the bridge span that was damaged. Fig. 5b and Fig. 5c show a similar not damaged span of the bridge where residuals stresses were also measured on a girder to compare the state of stresses and assessing the situation..

3. Merenje zaostalih napona na mostovima

3.1 Određivanje zaostalih napona na oštećenom mostu

Za procenu stanja zaostalih napona u području nosača oštećenog čeličnog mosta korišćen je UltraMARS kompleks. Sl. 5a prikazuje početni pregled raspona mosta koji je oštećen. Sl. 5b i Sl. 5c prikazuju sličan neoštećeni deo raspona mosta gde su zaostali naponi mereni i na nosaču da bi se uporedilo stanje napona i procenila situacija..



Fig. 5 Views of the steel bridge that was struck by a truck where the UltraMARS system was used for evaluation of the residual stresses.

Sl. 5 Prikazi čeličnog mosta koji udarila staza na kome se sistem UltraMARS koristio za procenu zaostalih napona.

According to the standard measurement protocol that was developed for measurements of RS in real structures using UltraMARS methodology, firstly, a small cube sample, measuring 50x70x20 mm, similar to the one shown in Fig. 2b was cut and used for measurements of ultrasonic frequencies in compression mode. The sample was installed in a press and the acousto-elastic coefficients were determined using developed methodology (Fig. 4b). The frequencies were measured at three different stresses, i.e at zero stress and at two compressive stresses that were selected at 0.3 σ_y and 0.6 σ_y (ultimate tensile strength of the selected material, $\sigma_y = 385$ MPa) and applied to the cube sample.

Fig. 4b presents the frequency changes measured for the longitudinal wave, F1 and two shear orthogonally polarized waves, F2 and F3 as a function of applied load. Three measurements were made, one at no load and at two compressive loads of -116 MPa (0.3 σ_y) and -232 MPa (0.6 σ_y).

Once the acousto-elastic coefficients were established, the actual measurements of residuals stresses in the damaged span and in a span away from the damage were conducted. Fig. 6 presents the region on the bridge that was affected by the impact. The multiple paint layers were removed in the measurement area to ensure that the ultrasound signal is not attenuated.

Prema standardnom protokolu merenja koji je razvijen za merenja RS u stvarnim konstrukcijama po UltraMARS metodologiji, prvo je isečen mali uzorak kocke dimenzija 50x70x20 mm, sličan onome prikazanom na slici 2b i korišćen za merenje ultrazvučnih frekvencija u režimu pritiska. Uzorak je ugrađen u presu i određivani su akustično-elastični koeficijenti primenom razvijene metodologije (slika 4b). Frekvencije su merene na tri različita naprezanja, tj. na nultom naprezanju i na dva pritiska naprezanja koja su odabrana pri 0,3 σ_y i 0,6 σ_y (krajnja zatezna čvrstoća izabranog materijala, $\sigma_i = 385$ MPa) i primenjena na uzorak kocke.

Sl. 4b prikazuje promene frekvencije izmerene za uzdužni talas, F1 i dva pravougaona polarizovana talasa smicanja, F2 i F3, kao funkciju primenjenog opterećenja. Obavljena su tri merenja, jedno bez opterećenja i pri dva pritiska opterećenja od -116 MPa (0,3 σ_y) i -232 MPa (0,6 σ_y).

Jednom kada su utvrđeni akustično-elastični koeficijenti, izvršena su stvarna merenja zaostalih napona u oštećenom rasponu i u rasponu udaljenom od oštećenja. Slika 6 prikazuje region na mostu na koji je uticao udar. U području merenja uklonjeno je više slojeva boje da bi se osiguralo da signal ultrazvuka nije oslabljen.

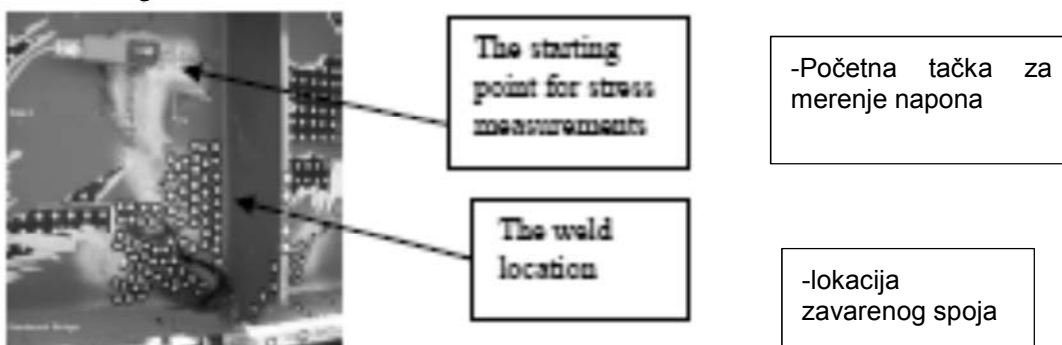


Fig. 6 The damaged region of the bridge where residual stresses were evaluated using the UltrMARS system.
Sl. 6 Oštećena oblast mosta gde su zaostali naponi ocenjeni pomoću UltrMARS sistema

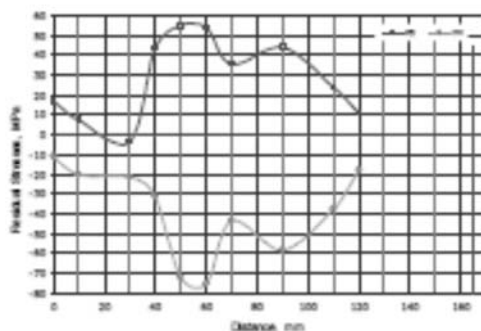


Fig. 7 Distribution of residual stresses as measured along line #2 (marked in Fig. 6) in the impact zone.
SI. 7 Distribucija zaostalih napona izmerena duž linije 2 (označena na slici 6) u zoni udara.

One of the results of measurement of the RS in the impact zone is shown in Fig. 7. The distance in Fig. 7 is measured from the starting point, marked in Fig. 6 towards the weld that is marked also in Fig. 6. The two measured components of the residual stress represent the stresses that are perpendicular to the weld (σ_y) and parallel to the weld (σ_x). Fig. 8 presents one of the results of measurement of the RS in a zone selected away from the impact zone (marked with an arrow in Fig. 5b).

Jedan od rezultata merenja RS u udarnoj zoni prikazan je na slici 7. Udaljenost na slici 7 meri se od početne tačke, koja je na slici 6 označena prema zavarenom spoju koji je takođe označen na slici 6. Dve izmerene komponente zaostalog napona predstavljaju napon koji je upravan na zavareni spoj (σ_y) i paralelan sa zavarenom (σ_x). Slika 8 prikazuje jedan od rezultata merenja RS u zoni koja je odabrana iz zone udara (obeležena strelicom na slici 5b).

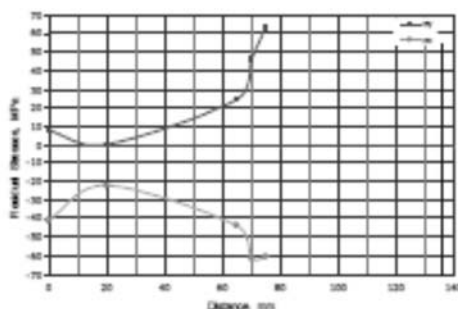


Fig. 8 Distribution of residual stresses σ_y and σ_x measured in a similar girder area on a span of the bridge far away from the impact zone (as shown in Fig. 5b and Fig. 5c).

SI. 8 Raspodela zaostalih napona σ_y i σ_x izmerena u sličnom području nosača na rasponu mosta udaljenom od zone udara (kao što je prikazano na slikama 5b i slici 5c).

As can be seen from Fig. 7 and Fig. 8, the values and sign of both components of the residual stresses in both measured regions were comparable, suggesting that the impact did not introduce any dangerous stress levels into the structure.

3.2 Measurement of Residual Stresses in a Bridge

Before and After Stress Relieving Operation In a different project, using a similar to the described above approach, average through thickness residual stresses were measured in the main wall of a bridge span near the ends of two welded vertical attachments (Fig. 9) that often are the zones of origination and propagation of fatigue cracks in welded bridges [15].

Kao što se može videti sa slika 7 i slike 8, vrednosti i znak obe komponente zaostalih napona u obe merene oblasti su uporedivi, što sugeriše da udar nije uneo opasne nivoje napona u konstrukciju.

3.2 Merenje zaostalih napona na mostu

Pre i posle operacije oslobađanja od napona u drugom projektu, koristeći sličan gore opisanom pristup, izmereni su po debljini zaostali naponi u glavnom zidu raspona mosta blizu krajeva dva zavarena vertikalna pričvršćenja (slika 9) koji su često zone nastanka i širenja prslina usled zamora u zavarenim mostovima [15].



4. Summary

In summary, it was demonstrated that residual stresses can be measured effectively in welded bridge structures using the non-destructive ultrasonic method and, based on it, UltraMARS methodology and equipment. Average through thickness residual stresses were measured in a damaged span of a bridge and away from the damage, and it was shown that the residual stresses in the damaged region did not differ significantly from the control undamaged areas. Also, a dramatic decrease in the residual stresses was measured in a bridge after a post-weld ultrasonic peening treatment, with the stresses near the weld changing from high tensile to compressive.

The substantial technological progress made in the nondestructive measurement of applied and residual stresses by ultrasonic method allowed to use the UltraMARS system that incorporates new software and new functional capabilities, in projects on evaluation of stresses in large welded structures imitating bridge details and in field conditions in bridges. We continue to develop the measurement methodologies and the hardware. Thus, recently, a new methodology and instrumentation, including transducers and other hardware and software for measurement of residual stresses at different depth of material were developed and are being evaluated.

References

Reference

- [1] Integrated Research Project "Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives" funded by the European Commission within 6th Framework Programme, "Condition assessment and inspection of steel railway bridges, including stress measurements in riveted, bolted and welded structures, Sustainable Bridges SB-3.4 2007-11-30 2 (94), Rev. 2007-11-30.
- [2] Lukić, M., Urushadze, S., Fryba, L., et al, 2013, Bridge Fatigue Guidance — Meeting Sustainable Design and Assessment (BRiFaG), Final report, Directorate-General for 00033, 1 July 2008 to 30 June 2011, EUR 25866 EN
- [3] Nagy, W., van Bogaert, Ph. And de Backer, H., 2015, Determining Residual Stresses in Welded Connections of Orthotropic Steel Bridge Decks with a Hole-drilling Technique, in "Implementing Innovative Ideas in Structural Engineering and Project Management", Ed. Saha, S., Zhang, Y., Yazdani, S., and Singh, A., PP. 155-160.

4. Pregled

Ukratko, pokazano je da se zaostali naponi mogu efikasno meriti u zavarenim konstrukcijama mostova upotrebom nerazorne ultrazvučne metode i na osnovu nje, UltraMARS metodologije i opreme. Prosečni zaostali naponi po debljini izmereni su u oštećenom rasponu mosta i dalje od oštećenja, a pokazalo se da se zaostali naponi u oštećenom području ne razlikuju značajno od kontrolnih neoštećenih područja. Takođe, drastično smanjenje zaostalih napreznja izmereno je na mostu posle tretmana nakon zavarivanja ultrazvučnim „čekičanjem“, pri čemu se napreznja u blizini zavarenog spoja menjaju iz visokog zateznih u pritisna.

Značajan tehnološki napredak postignut u nerazornom merenju primenjenih i zaostalih napona ultrazvučnom metodom, omogućava upotrebu sistema UltraMARS koji uključuje novi softver i nove funkcionalne mogućnosti, u projektima procene napreznja u velikim zavarenim konstrukcijama koje imitiraju delove mosta i u poljskim uslovima. Nastavljamo sa razvojem metodologija merenja i hardverom. Tako je nedavno razvijena i vrednovana nova metodologija i instrumentacija, uključujući pretvarače i drugi hardver i softver za merenje zaostalih napona na različitim dubinama materijala.

- [4] Miyashita, T., Inaba, N., Hirayama, S., Liu, C. and Nagai, M., 2015, Measurement Method for Welding Residual Stress in Steel I-shaped Girder with Thick Flange and its Influence on Load-carrying Capacity for Bending, Journal of JSCE, Vol. 3, 191-208.

- [5] Acevedo, C., Evans, A., and Nussbaumer, A., 2012, Neutron diffraction investigations on residual stresses contributing to the fatigue crack growth in ferritic steel tubular bridges, International Journal of Pressure Vessels and Piping, International Journal of Pressure Vessels and Piping 95:31-38.

- [6] Clark, Al V., Lozev, M. G. and Fuchs, P.A., 1996, "Bridgesafety evaluation using ultrasonic stress measurement", Proc. SPIE 2946, Nondestructive Evaluation of Bridges and Highways, 13 November 1996); doi: 10.1117/12.259153; <https://doi.org/10.1117/12.259153>

- [7] Trufyakov, V., Mikheev, P. and Kudryavtsev, Y., 1995, "Fatigue Strength of Welded Structures. Residual Stresses and Improvement Treatments", London. Harwood Academic Publishers GmbH.



- [8] Kudryavtsev, Y., 1994, "Effect of Residual Stresses on the Endurance of Welded Joints", "International Institute of Welding", IIW Doc. XIII - 1568 - 94.
- [9] Hughes, D.S.; Blankenship, E.B.; Mims, R.L. Variation of elastic moduli and wave velocity with pressure and temperature in plastics. *J. Appl. Phys.* 1950, 21, 294–297. [CrossRef]
- [10] Crecraft, D.I. The measurement of applied and residual stresses in metals using ultrasonic waves, *J. Sound. Vibr.* 1967, 5, 173–192.
- [11] Guz', A.N.; Makhort, F.G., 2000, *The Physical Fundamentals of the Ultrasonic Nondestructive Stress Analysis of Solids*, *Int. Appl. Mech.* 2000, 36, PP. 1119–1149.
- [12] Kleiman, J. and Kudryavtsev, Y., 2012, "Residual Stress Management in Welding: Residual Stress Measurement and Improvement Treatments", in *Proceedings of ASME 2012, 31st International Conference on Ocean, Offshore and Arctic Engineering*, v 6: *Materials Technology; Polar and Arctic Sciences and Technology; Petroleum Technology Symposium*, Rio de Janeiro, Brazil, July 1–6, 2012, pp. 73-79.
- [13] Kleiman, J. and Kudryavtsev, Y., , 2014, *Ultrasonic Measurement of Residual Stresses in Welded Elements*, 5TH Annual CWA CanWeld Conference and IIW Congress, Westin Bayshore Hotel Vancouver, Canada, September 28 – October 1, 2014.
- [14] Kudryavtsev, Y., 1985, *Application of the ultrasonic method for residual stress measurement. Development of fracture toughness requirement for weld joints in steel structures for arctic service.* VTT-MET. B-89. Espoo. Finland, pp. 62-76.
- [15] Kudryavtsev, Y., Kleiman. J., and Gushcha, O., 2000, *Residual Stress Measurement in Welded Elements by Ultrasonic Method*, IX International Congress on Experimental Mechanics, Orlando, Florida, USA, June 5-8, 2000, pp. 954-957.
- [16] Kudryavtsev, Y., Kleiman, J. and Gushcha, O., 2000, *Ultrasonic Measurement of Residual Stresses in Welded Railway Bridge*, *Structural Materials Technology: An NDT Conference*. Atlantic City, NJ. February 28-March 3, 2000, pp. 213-218.
- [17] Kudryavtsev, Y., Kleiman, J., Gushcha, O., Smilenko, V., and Brodovy, V., 2004, *Ultrasonic Technique and Device for Residual Stress Measurement*, X International Congress and Exposition on Experimental and Applied Mechanics, Costa Mesa, California USA, June 7-10, 2004, pp. 1-7.
- [18] Ghahremani, K., Walbridge, S., *Fatigue Testing and Analysis of Peened Highway Bridge Welds Under In-service Variable Amplitude Loading Conditions*, *International Journal of Fatigue* 33 (2011) 300–312
- [19] Hui, J. F., Lloyd, J. B., & Connor, R. J. (2018). *Fatigue life improvement of welded girders with ultrasonic impact treatment*. West Lafayette, IN: Purdue University. <https://doi.org/10.5703/1288284316654>
- [20] Fisher, J.W. , Statnikov, E. and Tehini, L. *Fatigue Strength Improvement of Bridge Girders by Ultrasonic Impact Treatment (UIT)*, *Welding in the World*, September 2002, Volume 46, Issue 9–10, pp 34–40.
- [21] Günther, H-P, Kuhlmann, U., Dürr, A., *Rehabilitation of Welded Joints by Ultrasonic Impact Treatment (UIT)*, IABSE Symposium, Lisbon, 2005, 1-7.