EKSPERIMENTALNA I NUMERIČKA KALIBRACIJA SILE PREDNAPREZANJA U VISOKOVREDNIM ZAVRTNJEVIMA

CALIBRATION OF THE BOLT PRETENSION BY STRAIN GAUGES VS. FEA

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1 UVOD

Prednapregnuti visokovredni zavrtnjevi imaju nezamenljivu ulogu u izgradnji čeličnih konstrukcija. Posebno su značajni u tarnim spojevima, gde se njihovom primenom znatno povećava nosivost dinamički opterećenih konstrukcija na zamor materijala. U smičućim spojevima, sila se prenosi smicanjem tela zavrtnja i pritiskom po omotaču rupe. Kod tarnih spojeva, smičuća sila se prihvata i prenosi putem trenja koje se realizuje na kontaktu elemenata u spoju. Nosivost ovakvog spoja zavisi od koeficijenta trenja u tarnim površima i od intenziteta sile prednaprezanja u zavrtnjevima. Pouzdano određivanje sile prednaprezanja u visokovrednom zavrtnju predstavlja osnov eksperimentalnih istraživanja spojeva s visokovrednim zavrtnjevima, ali i zavrtnjeva samih. Takođe, u slučaju dinamički opterećenih konstrukcija (kao što su, na primer, mostovi i antenski stubovi), veoma je važno primenjivati metode za ugradnju visokovrednih zavrtnjeva, koje će garantovati vrednost unete sile prednaprezanja, ali čak i tada potrebno je

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1 INTRODUCTION

High strength bolts are irreplaceable when it comes to steel structures. They are of special importance in friction connections, meaning that a load–bearing capacity in dynamically loaded structures is significantly increased in terms of fatigue endurance when such connections are applied. In regular shear connections shear force is transferred by bolt shearing and pressure applied to the hole surface. Instead, in a friction connection, a shear force is transferred by friction between the adjoining plates. Load-bearing capacity of this connection depends on a friction coefficient at the friction surfaces as well as on the pretension force. Deciding the accurate pretension force in high strength bolts is a chief ground of experimental research from the standpoint of those connections that come into contact with high strength bolts as well as from the standpoint of the bolts themselves. Moreover, when considering dynamically loaded structures such as bridges, antenna towers etc., it is very important to implement those methods which

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izvršiti kontrolu intenziteta unete sile prednaprezanja u određenom broju zavrtnjeva.

Sila u zavrtnju može se meriti na nekoliko načina [5]: pomoću ultrazvučnih uređaja, mernih ćelija s mernim trakama ili piezoelektričnim, kao i mernim trakama koje mogu biti zalepljene na telo zavrtnja ili ugrađene u telo zavrtnja. Najsavremenija metoda svakako je pomoću piezoelektričnih mernih ćelija. Međutim, nije ih racionalno primenjivati u slučaju velikog broja zavrtnjeva (s obzirom na njihovu cenu), pa su u tom slučaju merne trake ugrađene u telo zavrtnja i dalje nezamenljive. Svetski proizvođači merne opreme razvili su merne trake [14] i adheziono sredstvo [15] baš za ovu namenu i time značajno olakšali njihovu primenu.

Postojeća istraživanja u kojima se sila prednaprezanja u visokovrednim zavrtnjevima meri pomoću mernih traka zalepljenih na telo zavrtnja [16] ili ugrađenih u njega, mogu se podeliti na: istraživanja u kojima nije vršena kalibracija zavrtnjeva [17], istraživanja u kojima se na malom broju zavrtnjeva sila dodatno kontroliše pomoću mernih ćelija [11] i istraživanja u kojima je izvršena kalibracija svakog zavrtnja ponaosob [10], [9]. Eksperimentalnim istraživanjem [8] na 126 zavrtnjeva, pokazano je da je jedino ispravno i prihvatljivo vršiti kalibraciju svakog zavrtnja, s obzirom na velike razlike u krutosti zavrtnjeva različite dužine, kao i u krutosti delova zavrtnja, što dovodi do odstupanja merenih od nominalnih dilatacija zavrtnja. Stoga, proizvođači mernih traka insistiraju da se one ugrađuju u deo tela zavrtnja bez navoja, deo s konstantnom površinom poprečnog preseka, čime se umnogome sužava mogućnost njihove primene (nije ih preporučeno koristiti za zavrtnjeve koji imaju navoj celom dužinom tela). U ovom radu će biti prikazani postupak i rezultati eksperimentalne i numeričke (primenom metode konačnih elemenata) kalibracije zavrtnjeva. Dobijeni rezultati će se porediti s nominalnim vrednostima, a numerički modeli će se iskoristiti za proveru opravdanosti primene mernih traka i kod zavrtnjeva koji imaju navoj celom dužinom tela.

2 EKSPERIMENTALNA KALIBRACIJA SILE PREDNAPREZANJA U VISOKOVREDNIM ZAVRTNJEVIMA

Za potrebe merenja sile prednaprezanja u visokovrednim zavrtnjevima, ugrađene su merne trake u telo 126 zavrtnjeva [6], od toga – 63 HV [1] i 63 HBT [7] (slika 2a i slika 2b). Ugradnja mernih traka sprovedena je u svemu prema preporukama proizvođača, što je detaljno prikazano u [5].

Pomoću specijalno dizajniranog alata i kidalice „Schenck Trebel" kapaciteta 400 kN, izvršena je eksperimentalna kalibracija zavrtnjeva tako što je svaki zavrtanj izložen dejstvu tri ciklusa *opterećenje–rasterećenje* (slika 1a). U toku kalibracije, zavrtnjevi su izloženi maksimalnoj sili od 170 kN, što odgovara proračunskoj vrednosti sile prednaprezanja za ove zavrtnjeve [2], [4]. Takođe, nakon prvog ciklusa opterećenja zavrtnja do maksimalne vrednosti sile, ona

refer to installation of high strength bolts that will guarantee a value of introduced pretension force, but even then it is necessary to check the intensity of introduced pretension force in some specific number of bolts.

The bolt force can be experimentally obtained in several ways [5]: by means of ultrasound devices, measuring instruments with strain gauges or by a piezoelectric sensor, as well as with strain gauges that can either be glued to the shank or fitted inside the shank. The latest trend is most certainly application of piezoelectric sensors. On the other hand, they are not recommended for use when it comes to large number of bolts (considering their price), all of which leads to a conclusion that strain gauges that are fitted into the shank are still irreplaceable. World renowned manufacturers of strain measurement devices have improved strain gauges [14] as well as adhesive agents [15] for this purpose only, and therefore their use has been facilitated.

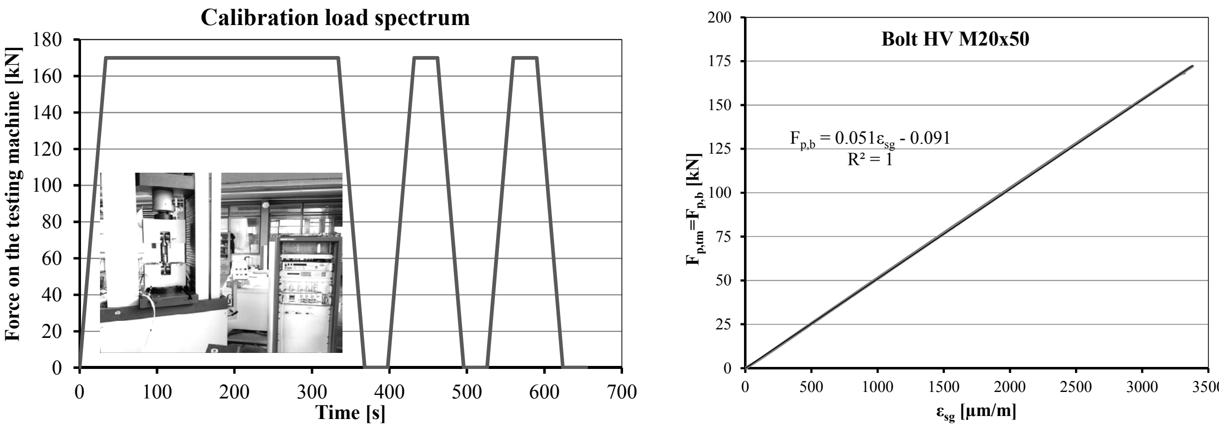
The existing research in which pretension force in high strength bolts is measured either by strain gauges glued to the bolt shank [16] or by strain gauges fitted inside the shank can be divided into those explorations in which no bolt calibration has ever been carried out [17], into explorations in which a force is additionally controlled by strain gauges in a few bolts [11] and explorations in which calibration of every bolt has been performed separately [10], [9]. Experimental research [8] performed on 126 bolts showed that the only thing that was right and acceptable was to calibrate each bolt separately given a big difference in rigidity of bolts that are of various lengths and rigidities in some parts of the bolt, all of which leads to a deviation from measured strains in the bolt compared to nominal ones. For this reason, manufacturers of strain gauges insist that gauges are fitted inside the bolt shank without the thread, i.e., into the part of the bolt with a constant cross section. This requirement significantly narrows down the possibility of their application, i.e. they are not recommended for bolts that are threaded along their entire length. This paper will show both the procedure and results obtained from the experimental calibration and FEA bolt calibration. Obtained results will be compared with the nominal values, whereas FEA models will be employed so as to check whether strain gauges may also be used in bolts that are threaded along their entire length.

2 EXPERIMENTAL CALIBRATION OF THE BOLT PRETENSION

In order to measure the pretension force, strain gauges were placed inside the shank of 126 bolts [6], out of which 63 were HV [1] and 63 HBT [7], Figure 2a and Figure 2b. Strain gauges were inserted in full compliance with manufacturers requirements, as shown in details in [5].

Experimental calibration of bolts was performed by means of specially designed tools and "Schenck Trebel" 400 kN testing machine, meaning that every bolt was exposed to a three-load cycle see Figure 1a. During the calibration process, bolts were exposed to a maximum force of 170 kN, which meets the design value of the pretension force [2], [4]. In addition, after the first load cycle has been completed and maximum force value se zadržava konstantnom 300 sekundi, nakon čega se nastavlja s postupkom kalibracije.

attained, the same force will remain constant for 300 seconds after which calibration process will follow.



a) *b)*

Slika 1. a) Spektar opterećenja i kidalica; b) Primer kalibracione krive
Fig. 1. a) Load spectrum and testing machine, b) Example of calibration curve

Eksperimentalnom kalibracijom visokovrednih zavrtnjeva, dobijena je linearna veza dilatacije merne trake u telu zavrtnja i sile izmerene na kidalici, koja je dobijena primenom metode najmanjih kvadrata na dobijene rezultate (Slika 1b). Nakon zamene zavrtnjeva kod kojih je uočeno histerezisno ponašanje u toku kalibracije [5], rezultat eksperimentalne kalibracije svakog zavrtnja ponaosob može se prikazati jednačinom:

Experimental calibration of the high strength bolts showed a linear correlation between the longitudinal strains in the bolt shank and the measured force. Therefore, the calibration curves are obtained by the *least square method* (Fig. 1b) for each bolt, as shown in the equation below. Some bolts have been replaced in which hysteresis behaviour was observed [5].

$$F_{\mathrm{p,tm}} = F_{\mathrm{p,b}} = a \cdot \varepsilon_{\mathrm{sg}} + b \tag{1}$$

gde su:
F_{tm} – sila izmerena na kidalici;
F_{pb} – aksijalna sila u telu zavrtnja;
ε_{sg} – dilatacija merne trake ugrađene u telo zavrtnja;
a, *b* – koeficijenti kalibracione krive.

Takođe, svaka kalibraciona kriva ocenjena je koeficijentom korelacije R^2. Prosečna vrednost i koeficijent varijacije koeficijenta korelacije za HV i HBT zavrtnjeve iznose: R^2_{HV}=0.99993 (V_{HV}=0,01%), odnosno R^2_{HBT}=0.99992 (V_{HBT}=0,02%).

where:
F_{tm} – is a force measured on a testing machine,
F_{pb} – is an axial force in the shank,
ε_{sg} – is the strain in gauge fitted inside the shank,
a, *b* – are coefficients of a calibration curve.

Furthermore, each and every calibration curve is assessed by R^2 correlation coefficient. Mean values and variation coefficients of the correlation coefficient, for both HV and HBT areR^2_{HV}=0.99993 (V_{HV}=0,01 %) andR^2_{HBT}=0.99992 (V_{HBT}=0,02 %), respectively.

2.1 Nominalna vrednost dilatacije zavrtnja

Pri punoj sili prednaprezanja, očekivana nominalna dilatacija u zavrtnju može se odrediti kao odnos nanete vrednosti sile ($F_{p,C}$) i aksijalne krutosti tela zavrtnja:

2.1 Nominal value of bolt strain

The expected nominal strain in the bolt can be obtained as a relation between the applied full pretension force $F_{p,C}$ and the axial stiffness of the bolt shank cross section:

$$\varepsilon_{\mathrm{nom}} = \frac{F_{\mathrm{p,C}}}{E_{\mathrm{z}} \cdot A_{\mathrm{z}}} \tag{2}$$

gde su:
$F_{p,C}$ – sila prednaprezanja u zavrtnju;
E_z – modul elastičnosti materijala zavrtnja;
A_z – površina poprečnog preseka zavrtnja.

Pri određivanju nominalne površine poprečnog preseka, za zavrtnjeve tipa HV korišćen je nazivni prečnik zavrtnja (d = 20 mm), dok je za zavrtnjeve tipa HBT korišćen izmereni spoljašnji prečnik navoja

where:
$F_{p,C}$ – is the pretension force in the bolt,
E_z – is the elastic modulus of a bolt material and
A_z – is the bolt gross cross section area.

As to HV bolts, a bolt nominal diameter (d = 20 mm) was used when deciding the nominal cross section area, whereas a measured external thread diameter (d = 19,6 mm) was used for HBT bolts. Such decided (d = 19,6 mm). Za ovako određene nominalne vrednosti dilatacija zavrtnjeva utvrđeno je da se - u određenim slučajevima - značajno razlikuju (od 5% do 19%) od dilatacija dobijenih eksperimentalnim putem (tabela 1). Kako bi se objasnile ove razlike i otklonile dileme oko valjanosti postavke eksperimentalnog istraživanja, izvršena je numerička analiza postupka kalibracije zavrtnjeva.

3 ANALIZA PRENAPREGNUTIH ZAVRTNJEVA PRIMENOM METODE KONAČNIH ELEMENATA

Za oba tipa zavrtnjeva (HV i HBT) i za njihove različite dužine, eksperimentalnim putem dobijene su različite vrednosti relativnih odnosa merenih i nominalnih dilatacija u zavrtnjevima. Pretpostavlja se da je uzrok za to različit položaj mernih traka u odnosu na deo zavrtnja na kom se nalazi navoj, kao i odnos dužine dela zavrtnja s navojem i bez navoja. Za potrebe analize ovog fenomena, korišćeni su numerički modeli čija geometrija i granični uslovi odgovaraju postavci eksperimentalne kalibracije zavrtnjeva. Numerička analiza sprovedena je primenom široko rasprostranjenog softverskog paketa za proračun primenom metode konačnih elemenata ABAQUS [3].

3.1 Prikaz geometrije primenjenog modela

U okviru primenjenih modela, definisani su delovi: zavrtanj (HV i HBT), HV podloška, lepak za mernu traku i alat za unošenje sile prednaprezanja. Svi delovi u okviru modela definisani su svojom tačnom geometrijom (slika 1 i slika 2), kako bi uticaj geometrije na mestu navoja i u zoni glave, kao i međusobne interakcije ovih delova, bile uzete u obzir. Na taj način, moguće je vršiti i dalje analize prednaprezanja zavrtnjeva, kao i njihovog ponašanja u različitim tipovima spojeva, kao na primer u [12] i [13]. Specifičan oblik i odgovarajuća dubina navoja za zavrtnjeve tipa HBT adekvatno su reprodukovani u modelima na bazi MKE (slika 1b), a na osnovu izmerenih dimenzija. Svi zavrtnjevi modelirani su s rupama u kojima su bili smešteni lepak i merna traka u toku eksperimentalnog ispitivanja. Dubine rupa u numeričkim modelima odgovaraju srednje izmerenim dužinama rupa za različite dužine zavrtnjeva u okviru eksperimentalnih ispitivanja.

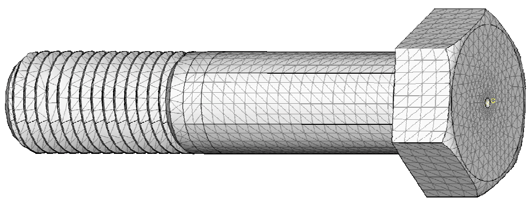
nominal values of bolt strains have shown that in some specific cases they differ significantly (from 5% to 19%) from those strains obtained experimentally, see Table 1. In order to explain such differences and exclude dilemmas when it comes to adequacy of experimental research, FEA analysis was conducted with regard to bolt calibration process.

3 FEA OF BOLT IN PRETENSION

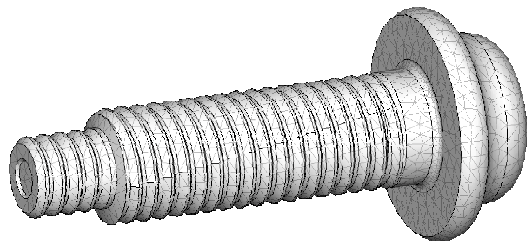
Different values of relative relations when considering measured and nominal strains in the bolts were obtained through the experiment for both types of bolts (HV and HBT) as well as for their different lengths. It is assumed that it is due to different position of strain gauges compared to the threaded part of the bolt, as well as ratio of lengths of the threaded and unthreaded part of the bolt. Numerical models, whose geometry and boundary conditions meet the experimental calibration of bolts, was performed in order to analyze this phenomenon. Numerical analysis was conducted by use of a wide–spread finite element software package ABAQUS [3].

3.1 Geometry of FE models

In the finite element (FE) models, the following parts were defined: bolt (HV and HBT), HV washer, strain gauge glue and the special tool which is designed to apply the force in the bolt. All parts within the model are defined by their accurate geometry (Fig. 2 and Fig. 3) so that the influence that comes from the geometry at the tread and at the head, as well as from mutual interactions between the parts would be taken into account. Thus, it is possible to carry out further bolt pretension analyses as well as analyses of bolts in various connection types, such as [12] and [13]. Specific shape and adequate bolt thread depth of HBT type was reproduced in an adequate fashion in FE models (Fig. 2b), all of which was done according to the measured dimensions. All bolts incorporated holes into which both glue and a strain gauge were placed in the course of an experimental research. A hole depth in numerical models corresponded well to average measured hole dimensions for various types of bolts over the course of experimental research.



a) standardni prednapregnuti zavrtnjevi tipa HV
a) standard pretension bolts of HV type

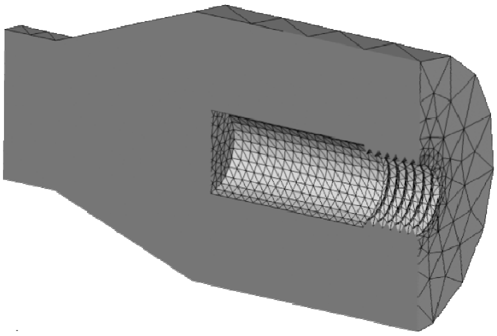


b) zavrtnjevi tipa Huck BobTail (HBT)
b) bolts of Huck BobTail type (HBT)

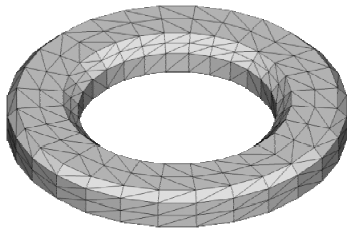
Slika 2. Geometrija zavrtnjeva u modelima na bazi MKE
Fig. 2.Bolt geometry in FE models

Za sve delove u modelima korišćeni su prostorni desetočvorni tetraedarski konačni elementi drugog reda, s kvadratnim interpolacionim funkcijama (C3D10M). Pored toga što ovi konačni elementi pružaju mogućnost automatskog formiranja mreže na komplikovanim geometrijskim oblicima kakvi su ovde analizirani (slika 2 i slika 3), oni su i iz celokupne biblioteke softverskog paketa ABAQUS preporučeni za primenjeni tip analize [3].

For all parts in the FE models, second-order ten-node tetrahedral elements(C3D10M) were used to form the mesh. Apart from the fact that these finite elements allow automatic formation of the mesh on more complicated and complex geometric forms such as those that have been analyzed here (Fig. 2 and Fig. 3), they are recommended for the applied type of analysis [3].



a) Alat za unošenje sile prednaprezanja
a) Load application tool

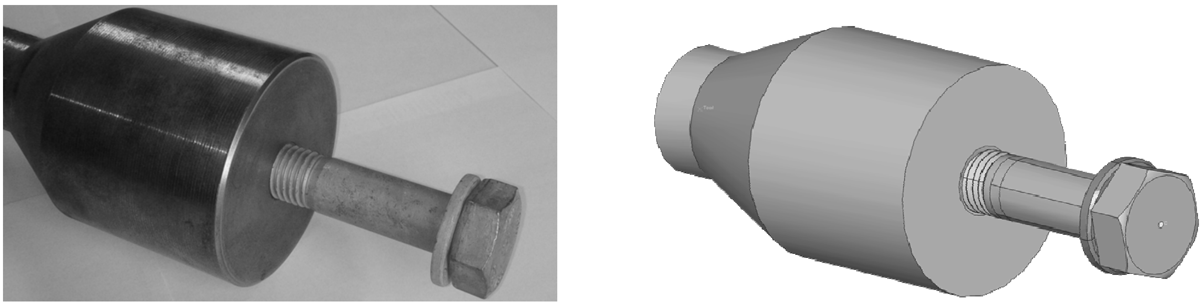


b) Podloška za zavrtnjeve tipa HV
b) Washer for HV bolts

Slika 3. Geometrija ostalih delova u modelima
Fig. 3. Geometry of other parts in models

Ova numerička analiza predstavlja direktno poređenje sa eksperimentalnim ispitivanjima kalibracije zavrtnjeva, zbog čega je za potrebe ovih analiza modeliran i alat za unošenje sile prednaprezanja (slika 4). U ovom modelu opterećenje je naneto identično kao i u eksperimentu, pomeranjem alata u pravcu podužne ose zavrtnja. Prilikom unošenja sile kontrolisanim deformacijama, drugi deo alata, koji ovde nije modeliran, držao je na mestu podlošku koja se nalazi ispod glave zavrtnja. U modelu na bazi MKE, ovaj granični uslov idealizovan je tako što je donja površina podloške (slika 4) imala sprečene deformacije u pravcu podužne ose zavrtnja.

This numerical analysis represents a direct comparison with experimental research of bolt calibration process, and therefore the tool for pretension force introduction has been modelled for this purpose (Fig. 4). As far as this model is concerned, the load is applied in exactly the same way as in the experiment, i.e., by the displacement control of the loading tool shown in Fig. 3a, i.e. displacement in the direction of a longitudinal bolt axis. When introducing the force by controlled deformations, the second part of the tool, which was not modelled here, supports the washer positioned below the bolt head. This boundary condition was idealized in the FE model by restraining the longitudinal displacements of lower washer surface (Fig. 4).



Slika 4. Model za direktno poređenje eksperimentalne i numeričke kalibracije zavrtnjeva tipa HV
Fig. 4.Model for direct comparison between experimental and numeric calibration of HV bolts

Spoj između lepka i rupe unutar zavrtnja definisan je direktnim kinematskim vezama između susednih čvorova delova modela koji predstavljaju zavrtanj i lepak (*Tie Constraint*). Za sve ostale kontaktne parove (parove površina) u modelima, definisan je opšti kontaktni kriterijum (*General Contact*) s mogućnošću odvajanja (*„Hard” contact – Normal Behaviour*) i koeficijentom trenja od 0,14 (*„Penalty” formulation – Tangential Behaviour*). Softverski paket, za primenjeni tip analize, automatski detektuje sve kontaktne parove u modelu i za te parove primenjuje zadati kriterijum.

Connection between the glue and the hole inside the bolt shank is defined by direct kinematic coupling of the adjacent nodes of the model representing the bolt and the glue (*Tie Constraint*). As for all other contact pairs in models (surface pairs) one general contact interaction has been defined (*General Contact*) allowing separation in normal direction (*„Hard“ contact – Normal Behaviour*), as well as a friction coefficient of 0,14 (*„Penalty“ formulation – Tangential Behaviour*). The solver automatically detects all contact pairs in the model and applies beforehand set criterion for such pairs.

3.2 Modeli materijala

Numerička analiza u okviru ovog istraživanja sprovedena je za potrebe analize rezultata koje se uglavnom nalaze u elastičnoj oblasti. Zbog toga je za delove podloške i alata za unošenje sile prednaprezanja usvojen jednostavan, elastičan, model ponašanja materijala. Usvojena je vrednost modula elastičnosti od $E = 210 \cdot 10^3$ N/mm^2 i Poasonov koeficijent $v = 0{,}3$. Za zavrtnjeve je usvojen idealan elasto-plastičan model, bez ojačanja s granicom razvlačenja od f_y = 1000 MPa, u skladu s rezultatima sprovedenih eksperimentalnih ispitivanja [8]. Razlog za definisanje plastičnog ponašanja zavrtnjeva je moguća lokalna plastifikacija u zoni navoja, čak i pri elastičnom ponašanju ostalih delova zavrtnjeva na nivou naprezanja, koji odgovara punoj sili prednaprezanja. Lepak za ugradnju mernih traka opisan je prostim linearno-elastičnim modelom ponašanja, s modulom elastičnosti $E = 3{,}5 \cdot 10^3$ N/mm^2, prema preporuci proizvođača.

3.3 Tip analize

U ovako definisanim modelima postoji veliki broj kontaktnih interakcija, s obzirom na to što su zavrtnjevi i ostali elementi definisani sa svojom tačnom geometrijom u zoni navoja. Takođe, primenjen je elasto-plastičan model materijala, što sve zajedno predstavlja problem pri rešavanju numeričkog modela konvencionalnim *implicitnim* metodama zbog poteškoća s konvergencijom rezultata. Ovakve probleme je dosta uspešno moguće rešiti kvazistatičkom analizom primenom dinamičkih *eksplicitnih* solvera. Ovakav pristup je primenjen i za rešavanje ovde prikazanih numeričkih modela u okviru softverskog paketa „Abaqus” (*Abaqus/Explicit*). U dinamičkoj eksplicitnoj analizi nije potrebno vršiti inverziju matrice krutosti, pa zbog toga i nema problema s konvergencijom rezultata. S druge strane, pošto se vrši numerička integracija diferencijalne jednačine kretanja, veoma je važno usvojiti dovoljno mali vremenski interval integracije kako bi rezultati bili ispravni. Potrebni vremenski interval integracije softver određuje automatski, u zavisnosti od veličine najmanjeg elementa u okviru mreže i brzine prostiranja smičućih talasa kroz taj element (karakteristika materijala). Dinamički proračun u realnom vremenu eksperimenata zbog toga bi trajao jako dugo, čak i po nekoliko dana primenom današnjih konvencionalnih računara. Pošto je u okviru ovog istraživanja od interesa statičko ponašanje uzoraka, u kvazistatičkoj analizi može se izvršiti ili skraćenje vremena ili uvećanje masa, kako bi vreme potrebno za proračun bilo skraćeno. U okviru analiza prikazanih u ovom istraživanju, primenjena je tehnika prostorno neuniformnog i kroz vreme promenljivog uvećanja masa konačnih elemenata (*variable non-uniform mass scaling*). Ovaj proces softverski paket „Abaqus” obavlja automatski za zadati željeni vremenski interval integracije. U modelima koji su ovde prikazani korišćen je interval vremenske integracije od $\Delta t = 0{,}0005$ s, a vreme nanošenja opterećenja iznosilo je 10 s.

3.2 Material models

Numerical analysis within the research was conducted for the purpose of results analyses usually found in the elastic area. Therefore, a simple elastic model of a material behaviour with elastic modulus of $E = 210 \cdot 10^3$ N/mm^2 and Poisson’s ratio $v = 0{,}3$, was adopted for the washer and load application tool. As for bolts, idealized elastic-plastic model with f_y = 1000 MPa yield strength and no strain hardening was used in line with the results obtained throughout experimental research [8]. The reason to model the plastic behaviour of the bolts is a possible local plastic behaviour at the thread, even when other parts of the bolt show elastic behaviour at the tension level which meets the full pretension force. Glue used for placement of strain gauges is described by simple linear-elastic model with elastic modulus $E = 3{,}5 \cdot 10^3$ N/mm^2, as recommended by a manufacturer.

3/3 Type of the analysis

Such defined models encompass a large number of contact interactions as both the bolts and other elements are defined by their accurate geometry at the thread zone. Also, materially nonlinear behaviour of the model with plastic material behaviour altogether poses a problem when trying to solve a numeric model with a conventional *„implicit“* methods due to difficulties that may arise out of convergence of the results. These issues can be resolved successfully by a quasi-static analysis and by application of dynamic ‘*explicit’* solvers. Such approach was also applied to solve already shown numerical models within *“Abaqus“* (*Abaqus/Explicit*) software package. Inversion of the stiffness matrix does not need to be performed in the dynamic explicit analysis; therefore there are no issues with convergence results. On the other hand, since numeric integration of differential equation of the dynamic system is performed, it is very important to adopt sufficiently small time step of integration so that the results would prove valid. The integration time step is something that software determines automatically depending on a size of the smallest element within the mesh and velocity of shear waves through the element (material property). Therefore, dynamic analysis in the real time of experiment would last very long, i.e., for several days when applying conventional computers. Since sample static behaviour is exceptionally significant in this research, it is important to emphasize that time can either be shortened or mass increased in the quasi-static analysis so that the time needed for the calculation would be shortened. Analyses shown in the research apply a technique of spatially non-uniform and time variable increase of a mass in finite elements (*variable non-uniform mass scaling*), which is done automatically by the solver. Models shown here use time integration interval of $\Delta t = 0{,}0005$s, whereas load application time in the model lasted for 10 s.

3.4 Poređenje rezultata eksperimentalnog istraživanja i numeričke analize

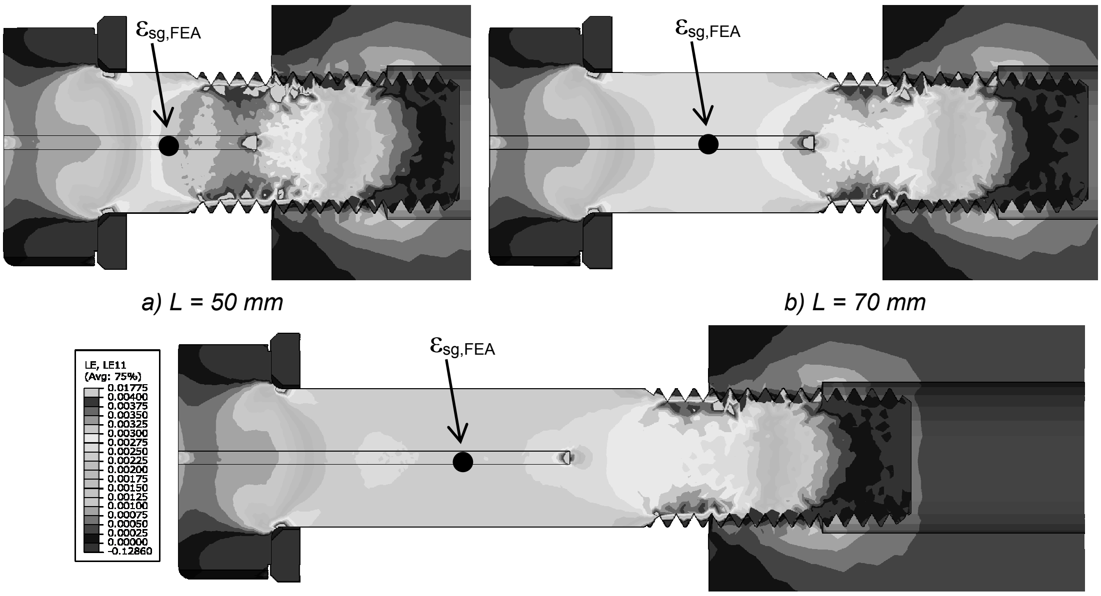
Prikazano je poređenje rezultata numeričke analize i eksperimenata, na bazi stvarnih dilatacija i nominalnih dilatacija na mestu merne trake u zavrtnjevima. Ovaj deo praktično predstavlja potvrdu verodostojnosti rezultata numeričke analize i detaljnije prikazuje podužnu raspodelu dilatacija u zavrtnjevima.

Prikazi podužnih dilatacija zatezanja, u podužnom preseku kroz zavrtanj tipa HV i HBT, dati su na osnovu rezultata numeričke analize, za različite dužine zavrtnjeva na slici 5 i slici 6 respektivno. Podužne dilatacije predstavljene su bojama spektra u granicama od 0,0 do 0,004 mm/mm, i prikazane su pri istom nivou naprezanja koji odgovara sili prednaprezanja $F_{p,C}$ = 171,5 kN, radi lakšeg poređenja.

3.4 FEA vs. experimental results

The results obtained in numerical analyses and during the experiment were presented based on actual and nominal strains at a place where strain gauges sit in the bolts. This chapter represents a confirmation in terms of credibility of numerical analysis results and in more detail represents longitudinal distribution of strains in the bolts.

The review of longitudinal tension strains in longitudinal section through the bolt of HV and HBT type is enclosed based on the results obtained in the numerical analysis for various bolt lengths as shown in Figure 5 and Figure 6, respectively. Longitudinal strains are presented in colour spectrum from 0,0 to 0,004 mm/mm, and as such they are shown at the same tension level which meets the pretension force $F_{p,C}$ = 171,5 kN for easier comparison.



a) L = 50 mm *b) L = 70 mm*

c) L = 90 mm

Slika 5. Rapodela podužnih dilatacija u zavrtnjevima tipa HV, pri punoj sili prednaprezanja $F_{p,C}$=171,5 kN
Fig. 5. Distribution of longitudinal strains in HV bolts at a full pretension force $F_{p,C}$=171,5 kN

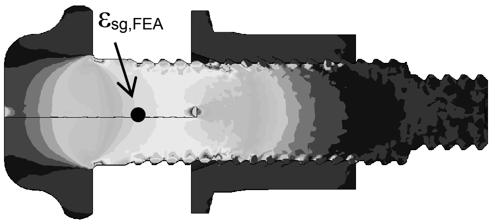
U numeričkoj analizi, položaj i dubina rupa za merne trake koje su ispunjene lepkom u potpunosti odgovara položaju ovih rupa u eksperimentima. Preporuka proizvođača mernih traka jeste da se ona nalazi u sredini debljine steznog paketa. Takođe, preporučeno je i da se sredina merne trake nalazi na približno 8-10 mm od dna rupe [14]. Sve ovo uzrokovalo je to da se u tri razmatrana slučaja merna traka nalazila u tri različite zone u odnosu na položaj navoja na zavrtnju. Ova činjenica umnogome utiče na vrednost dilatacije na mestu merne trake, u tri različita slučaja, pri istoj vrednosti sile, što potvrđuju i eksperimentalni rezultati (videti tabelu 1). Naime, dilatacija na mestu navoja je veća od dilatacije na mestu tela zavrtnja, zbog redukovane površine poprečnog preseka. Analogno tome, dilatacije na mestu glave su znatno manje od dilatacija na mestu tela zavrtnja. Konačno, koncentracija dilatacija na dnu rupe je veoma izražena, što se može uočiti u rezultatima za sve tri razmatrane dužine HV

Both, the position and depth of holes intended for strain gauges filled with glue, modelled in numerical analysis completely meet the position of these holes found in the experiment. Manufacturers of strain gauges recommend position of the strain gauge in the middle of the clamping package. Moreover, it is recommended that the middle of the strain gauge is located at approximately 8-10 mm from the hole bottom [14]. All this leads to a conclusion that in all three cases a strain gauge was placed at three different zones compared to the position of a thread on the bolt. This fact influences strain value to some great extent at a place in which a strain gauge stands, i.e., it influences the value in three different cases exposed to exactly the same force value which has been proved and can be seen in experimental results, see Table 1. The strain at the thread is larger than the strain at the shank due to the reduced cross section surface. At the same time, strains at the bolt head are significantly smaller compared to the strains zavrtnjeva (slika 5).

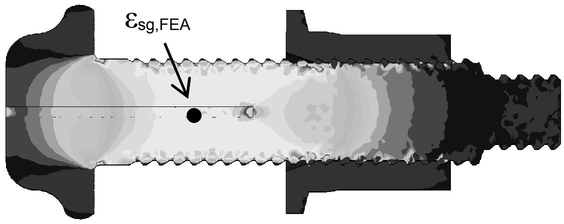
Za zavrtnjeve tipa HBT karakteristično je to što imaju navoj skoro čitavom dužinom. Zbog toga je nivo dilatacija u zoni paketa, pri skoro identičnoj sili prednaprezanja, veći nego u slučaju zavrtnjeva tipa HV, gde je prisutno puno telo zavrtnja (slika 5 i slika 6). S druge strane, zavrtnjevi tipa HBT imaju znatno veći prečnik na mestu navoja: $d_3 = 18{,}2$ mm prema $d_3 = 16{,}1$ mm za HBT i HV, respektivno. Zbog toga je koncentracija dilatacija, a samim tim i napona, znatno manja u poređenju s klasičnim zavrtnjevima za prednaprezanje tipa HV. Ova činjenica svakako ukazuje na poboljšanu otpornost na zamor zavrtnjeva tipa HBT.

occurring at the bolt shank. And finally, concentration of the strains at the bottom of the hole is quite accentuated and obvious, which can be seen in the results of all three analyzed HV bolt lengths (Fig. 5).

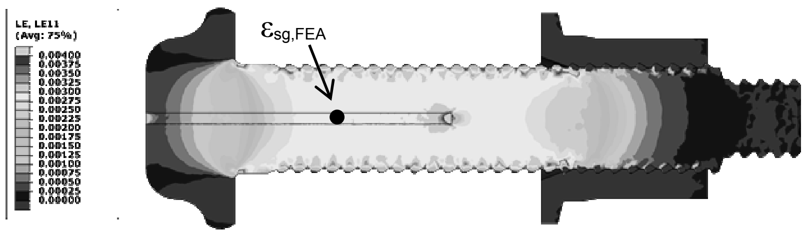
A thread stretching across almost the entire length of the bolt is typical for bolts of HBT type. Therefore, the strain level at the package zone exposed to almost identical pretension force is bigger than in the case of HV bolts with a full bolt shank (Figure 5 and Figure 6). On the other hand, bolts of HBT type have a significantly bigger diameter at a thread: $d_3 = 18{,}2$ mm to $d_3 = 16{,}1$ mm for HBT and HV, respectively. Thus, the concentration of strains as well as tension concentration is considerably less when compared to classic HV high strength bolts. This fact certainly proves the enhanced resistance to HBT bolt fatigue.



a) L = 55 mm



b) L = 70 mm



c) L = 85 mm

Slika 6. Rapodela podužnih dilatacija u zavrtnjevima tipa HBT, pri punoj sili prednaprezanja $F_{p,C}$=170,7 kN
Fig. 6. Distribution of longitudinal strains in bolts of HBT type at full pretension force F=170,7 kN

U svim slučajevima - za oba tipa zavrtnjeva i za sve tri dužine, u eksperimentima koji odgovaraju kalibraciji zavrtnjeva - uočene su uvećane dilatacije koje su očitane s mernih traka u odnosu na očekivane nominalne dilatacije za datu vrednost sile. Uvećane dilatacije na mestu merne trake mogu biti posledica tri fenomena: 1. redukovanog poprečnog preseka zavrtnja zbog postojanja rupe za mernu traku; 2. lokalne koncentracije dilatacija u zoni dna rupe; 3. uvećanih dilatacija u zoni navoja.

Odnos nominalne dilatacije ($\varepsilon_{\mathrm{nom}}$) i stvarne dilatacije na mestu merne trake ($\varepsilon_{\mathrm{sg,EXP}}$, $\varepsilon_{\mathrm{sg,FEA}}$), pri punoj sili prednaprezanja, određen je na osnovu rezultata eksperimenata α_{EXP} i na osnovu numeričke analize α_{MKE} (tabela 1):

In all cases, increased strains were detected for both types of bolts and all three lengths in those experiments which meet the bolt calibration process, and such increased strains were read from strain gauges compared to expected nominal strains for the given force value. The increased strains at a place in which a strain gauge sits can be the consequence of three phenomena: 1. reduced cross section in a bolt as there is a hole for a strain gauge insertion, 2. local concentration of strains at the hole bottom and 3. increased strains at the thread.

Relation between the nominal ($\varepsilon_{\mathrm{nom}}$) and actual strain at a place where a strain gauge sits ($\varepsilon_{\mathrm{sg,EXP}}$, $\varepsilon_{\mathrm{sg,FEA}}$), at a full pretension force, is decided based on the results obtained from the experiment α_{EXP} and numerical analysis α_{MKE} (Table 1):

$$\alpha_{\mathrm{EXP}} = \frac{\varepsilon_{\mathrm{nom}}}{\varepsilon_{\mathrm{sg,EXP}}} \tag{3}$$

$$\alpha_{\mathrm{FEA}} = \frac{\varepsilon_{\mathrm{nom}}}{\varepsilon_{\mathrm{sg,FEA}}} \tag{4}$$

Baza merenja merne trake jeste 6 mm, pa je dilatacija u numeričkoj analizi $\varepsilon_{sg,FEA}$, koja odgovara osrednjenim eksperimentalno određenim vrednostima $\varepsilon_{sg,EXP}$, određena kao osrednjena vrednost na dužini od 6 mm (slika 7 i slika 8 - osenčene zone).

A base at which a strain gauge carries out its measurement is 6 mm; therefore, the strain in the numerical analysis is $\varepsilon_{sg,FEA}$, which meets the average values decided in the experiment $\varepsilon_{sg,EXP}$, and it is decided as an average value of 6 mm in length (Fig. 7 and Fig. 8 - shaded zones).

Tabela 1. Odnos nominalnih i stvarnih dilatacija na mestu merne trake
Table 1. Relations between nominal and actual strains at a place where strain gauges are fitted

Zavrtanj Bolt		$F_{p,C}$ [kN]	Nominalna dilatacija Nominal strain ε_{nom} [mm/mm]	MKE dilatacija FEA strain $\varepsilon_{sg,FEA}$ [mm/mm]	Eksperim. dilatacija Experimen. strain $\varepsilon_{sg,EXP}$ [mm/mm]	Koeficijent varijacije Coefficient of variation $V_{X,EXP}$ [%]	α_{FEA}	α_{EXP}	$\alpha_{FEA}/\alpha_{EXP}$
Tip Type	Dužina Length [mm]								
HV	50	171,5	0,00258	0,00322	0,00327	4,81	0,81	0,81	1,01
HV	70	171,5	0,00258	0,00281	0,00294	5,31	0,92	0,89	1,04
HV	90	171,5	0,00258	0,00263	0,00278	4,16	0,98	0,95	1,05
HBT	55	170,7	0,00268	0,00293	0,00307	4,02	0,92	0,87	1,05
HBT	70	170,7	0,00268	0,00309	0,00315	4,44	0,87	0,86	1,02
HBT	85	170,7	0,00268	0,00308	0,00317	3,75	0,87	0,84	1,03

Razlika u rezultatima eksperimentalno i numerički određenog faktora α jeste od 1 % do 5 % (tabela 1), pa se može zaključiti da numerička analiza dosta verno oslikava stvarno ponašanje oba tipa zavrtnjeva ispitanih u okviru ovog istraživanja. Razlike u rezultatima numeričke analize i eksperimenata mogu poticati od nominalno usvojene vrednosti modula elastičnosti u numeričkoj analizi ($E_{FEA} = 210 \cdot 10^3$ N/mm^2) i stvarne vrednosti koja eksperimentalno nije utvrđena, ali najčešće iznosi $205 \cdot 10^3$ N/mm^2.

A difference in the results of experimentally and numerically determined coefficient α varies from 1 % to 5 % (Table 1), therefore it can be concluded that the numerical analysis depicts the actual behaviour of two bolt types tested in the research. Differences in the results that are shown in the numerical analysis and in the experiments can arise out of difference between nominally adopted value of elasticity modulus shown in the numerical analysis ($E_{FEA} = 210 \cdot 10^3$ N/mm^2) and actual value undetermined in the experiment, but which very often amounts $205 \cdot 10^3$ N/mm^2.

4 ANALIZA REZULTATA NUMERIČKE ANALIZE

Da bi se uočene razlike u vrednostima dilatacija na mestu merne trake lakše objasnile, na osnovu rezultata numeričke analize, prikazane su podužne dilatacije po dužini zavrtnja u osi, tj. duž lepka u rupi (slika 7 i slika 8). Ovakvi dijagrami prikazani su za oba tipa zavrtnjeva, za tri različite dužine, pri vrednostima sila koje odgovaraju silama prednaprezanja: $F_{p,C}$ = 171,5 kN [2] i $F_{p,C}$ = 170,7 kN [4], za zavrtnjeve tipa HV i HBT, respektivno. Odmah se može uočiti da su dilatacije u zoni glave i u početnom delu koji odgovara telu zavrtnja identične za različite dužine zavrtnjeva, što na još jedan način potvrđuje tačnost primenjenog načina vršenja numeričke analize.

U skoro svim slučajevima, uočljiv je svojevrstan „plato dilatacija" koji odgovara središnjoj zoni zavrtnja s konstantnim poprečnim presekom: telo zavrtnja u slučaju tipa HV i slobodan navoj u slučaju tipa HBT. Svakako da je očitavanje vrednosti dilatacije u eksperimentima najpouzdanije ukoliko se merna traka nalazi u zoni ovog „platoa". U slučajevima koji su ovde analizirani, položaji

4 DISCUSION OF THE FEA RESULTS

Longitudinal strains across bolt length at an axis were shown, i.e., across the glue found in the hole (Fig. 7 and Fig. 8) in order to explain the observed differences in strain values at a place in which a strain gauge is placed, i.e., differences that emerged in the results of numerical analysis. Such diagrams are shown for both types of bolts and for all three different lengths at those force values that meet pretension force: $F_{p,C}$ = 171,5 kN [2] and $F_{p,C}$ = 170,7 kN [4], for bolts of HV and HBT type, respectively. It can be observed instantly that those strains that are located at the bolt head zone and at the start of a bolt that meets the bolt shank are identical for various bolt lengths which once again proves the accuracy of an implemented method by which numerical analysis was carried out.

Almost all cases show a so-called "strain plateau" which converge the part located in the middle of the bolt with a constant cross section: bolt shank in the case of HV type and a free thread in the case of HBT type. Most certainly, strain value reading throughout the mernih traka (slika 7 i slika 8) poklapaju se sa zonom „platoa dilatacija”. Dakle, preporuka proizvođača mernih traka da se njihova sredina nalazi na 8-10 mm od dna rupe jeste ispravna [14].

Analizirajući prikazane dijagrame, mogu se izvesti zaključci o razlozima različitih vrednosti dilatacija za različite dužine zavrtnjeva pri istoj sili prednaprezanja. Za zavrtnjeve tipa HV (slika 5 i slika 7) karakteristične su sledeće tri situacije.

- U slučaju najkraćih zavrtnjeva (L=50 mm), zona „platoa” nalazi se na mestu navoja, zbog veoma male dužine tela zavrtnja (slika 5a). Zbog toga je odnos stvarnih dilatacija i nominalnih dilatacija u ovom slučaju znatno veći nego u preostala dva.

- U slučaju zavrtnjeva srednje dužine (L=70 mm), dno rupe se nalazi u prelaznoj zoni između tela zavrtnja i slobodnog navoja (slika 5b), gde su dilatacije uvećane zbog redukovanog poprečnog preseka. Zbog toga je u zoni duž merne trake (6 mm) uočljiva promena dilatacija u nekoj meri, pa će osrednjena vrednost dilatacije merne trake zavisiti od dubine na kojoj se ona tačno nalazi. Upravo zato je baš za ove zavrtnjeve vrednost koeficijenta varijacije za eksperimentalno određeni kalibracioni koeficijent α_{EXP} najveća od svih ispitivanih zavrtnjeva tipa HV (V_X = 5,31, Table 1).

- U slučaju najdužih zavrtnjeva (L=90 mm), dno rupe nalazi se u središnjoj zoni tela zavrtnja (slika 5c), tj. na „platou” dilatacija koji je u ovom slučaju izražen zbog velike dužine konstantnog poprečnog preseka na mestu tela zavrtnja. Kako je u ovom slučaju merna traka dosta udaljena od svih prelaznih zona, dilatacije u zoni trake su konstantne, pa je i dobijeno najveće poklapanje stvarnih dilatacija i nominalnih dilatacija ($\alpha \approx 0{,}95$), s najmanjim koeficijentom varijacije (V_X = 4,16, Table 1).

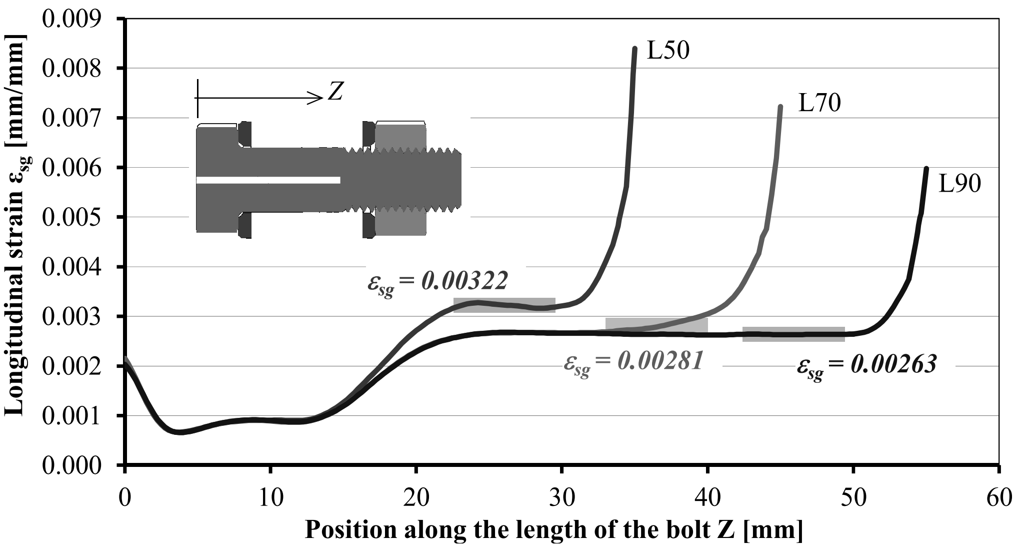
experiments is more reliable when the strain gauge is located at the “strain plateau“. As for cases analyzed here, positions of strain gauges (Fig. 7 and Fig. 8) correspond to the “strain plateau” zone. Therefore, the recommendation of strain gauges manufacturer that their middle part is located at 8-10 mm from the hole bottom is perfectly correct [14].

By analyzing the displayed diagrams one can draw a conclusion on the reasons as to why different strain values occur for various bolt lengths when exposed to exactly the same pretension force. For bolts of HV type (Fig. 5 and Fig. 7), there are three typical situations:

- for the shortest bolts (L=50 mm), a “strain plateau“ zone is located at the thread due to relatively small bolt shank length (Fig. 5a). Thus, relation between actual and nominal strains in this case is significantly bigger when compared to two other remaining cases,

- for the threads of an average length (L=70 mm), a hole bottom is located at the transitional zone between the shank and a free thread (Fig. 5b) where strains are bigger due to the reduced cross section. Therefore, there is a change in strain along the strain gauge (6 mm) to some extent, meaning that the average value of the strain depends on a depth at which it is precisely located. Thus, the variation coefficient value for experimentally decided calibration coefficient α_{EXP} for these bolts is the highest compared to tested HV bolts (V_X = 5,31, Table 1),

- for the longest bolts (L=90 mm), a hole bottom is located in the middle of the shank (Fig. 5c), i.e., at a “strain plateau“, which is quite accentuated in this case due to a big length of the constant cross section at a place in which there is a shank. As in this case a strain gauge is significantly spaced apart from all transitional zones, strains at the strain gauge are constant; therefore the biggest matching of actual and nominal strains was obtained ($\alpha \approx 0{,}95$) with the smallest variation coefficient (V_X = 4,16, Table 1).



Slika 7. Podužne dilatacije HV zavrtnjeva pri punoj sili prednaprezanja - $F_{p,C}$ =171,5 kN
Fig. 7. Longitudinal strains of HV bolts at a full pretension force - $F_{p,C}$ =171,5 kN

Kada su u pitanju zavrtnjevi tipa HBT, prelazne zone su znatno manje izražene. Za tri različite dužine, karakteristične su sledeće dve situacije:

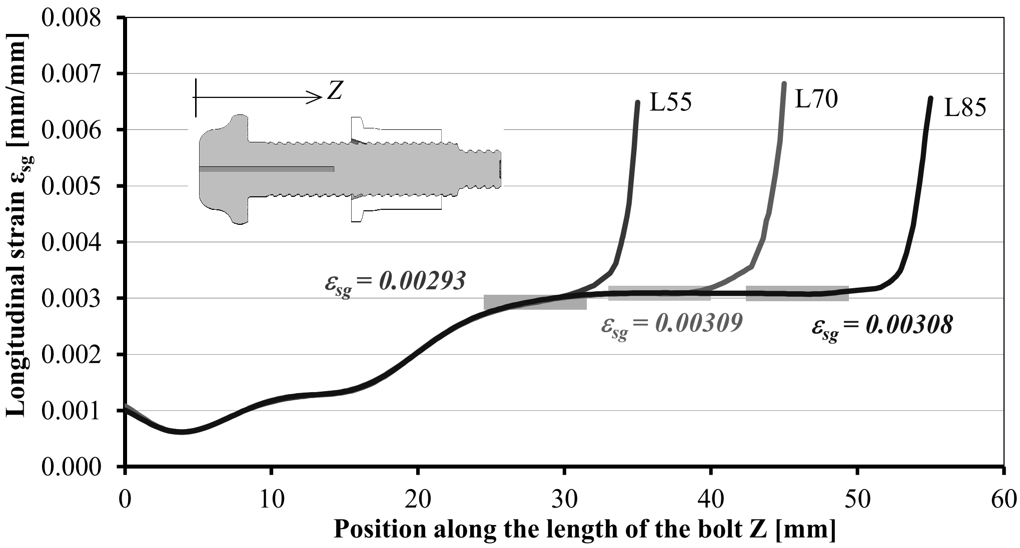
- za najkraće zavrtnjeve (L=55 mm) dužina slobodnog navoja je relativno mala u odnosu na dužinu glave i kratkog tela (slika 6a), zbog čega ne postoji izražen „plato dilatacija”, već su prelazne zone spojene. Dno rupe nalazi se u prelaznoj zoni između slobodnog i angažovanog navoja, pa postoji varijacija dilatacija duž merne trake (6 mm), što se odražava na nešto manje očitane vrednosti dilatacija nego u preostala dva slučaja (slika 8).

- za najduže zavrtnjeve (L=85 mm) i za zavrtnjeve srednje dužine (L=70 mm) postoji izražen „plato dilatacija”, jer je dužina slobodnog navoja znatna u poređenju sa ostalim delovima zavrtnja. Zbog toga su stvarne vrednosti dilatacija u ova dva slučaja skoro identične i približne su očekivanoj nominalnoj dilataciji koja bi odgovarala prečniku zavrtnja koji je definisan unutrašnjom linijom navoja (d_3 = 18,2 mm).

In the bolts of HBT type, transitional zones are much less obvious. For all three lengths the two situations are typical:

- for the shortest bolts (L=55 mm), the length of a free thread is relatively small compared to the head and short shank length (Fig. 6a), so there is no clear „strain plateau“, but transitional zones are connected. The bottom of the hole is located at the transitional zone between the free and applied thread, meaning that strain variation along the strain gauge (6 mm) is present, which is reflected in somewhat smaller strain values than in two other cases (Fig. 8),

- for the longest (L=85 mm) bolts and for those of an average length (L=70 mm) there is a quite obvious strain plateau as the length of the free thread is significant compared to other parts of the bolt. That is the reason why actual strain values are almost identical in these two cases and are close to expected nominal strain which relates the bolt diameter defined in the interior thread line (d_3 = 18,2 mm).



Slika 8. Podužne dilatacije HBT zavrtnja pri punoj sili prednaprezanja – $F_{p,C}$ =170,7 kN

Fig. 8. Longitudinal strains of HBT bolt at the full pretension force - $F_{p,C}$ =170,7 kN

5 ZAKLJUČAK

Prikazanim istraživanjem pokazano je da su razlike između nominalnih dilatacija i dilatacija merenih mernim trakama, postavljenih prema uputstvima proizvođača - od 5% do 20%.

Preporuke proizvođača o pravilnom pozicioniranju mernih traka u telu zavrtnja, u kojem se želi izmeriti sila prednaprezanja, opravdane su i u većini slučajeva obezbeđuju pozicioniranje trake u zonu „platoa dilatacije”. U slučaju HV zavrtnjeva, još bolji rezultati mogu se dobiti pozicioniranjem mernih traka ne u sredini steznog paketa - kako zahteva proizvođač, već u sredini dela tela zavrtnja bez navoja. Za ovako ugrađene merne trake, odnos nominalne i stvarne dilatacije iznosi približno - 0,95.

Iako proizvođači mernih traka ne predviđaju merenje sile prednaprezanja u zavrtnjevima koji imaju navoj celom dužinom tela zavrtnja, ovo istraživanje - u slučaju

5 CONCLUSIONS

The research presented in this paper has shown that differences between nominal strains and those measured by strain gauges inside the bolt, placed as instructed by a strain gauge manufacturer, are 5% to 20%.

Manufacturer’s recommendations on proper positioning of strain gauges in the bolt shank have been justified and in most cases allow strain gauges to be positioned at a „strain plateau“ zone. It has been shown that more reliable results can be obtained in the case of HV bolts by positioning the strain gauge in the middle of the threadless part of the shank. In that case, ratio of the nominal and actual strain is approximately 0,95.

Even though manufacturers of strain gauges do not anticipate pretension force measurement in bolts with threads along the entire bolt shank, this research shows quite the opposite in the case of HBT bolts. All of these

HBT zavrtnjeva - pokazuje suprotno. U slučaju ovakvih zavrtnjeva, uočljiv je „plato dilatacije” duž slobodnog dela navoja u steznom paketu. Odnos nominalne i stvarne dilatacije u ovoj zoni iznosi približno 0,85, ukoliko se za nominalni prečnik zavrtnja usvoji spoljašnja dimenzija navoja. Za ostale tipove zavrtnjeva koji imaju navoj celom dužinom tela zavrtnja, na sličan način mogu se odrediti odgovarajući koeficijenti.

Ovde prikazani odnosi nominalnih i stvarnih dilatacija za HV i HBT zavrtnjeve, uz poštovanje preporuka o dužinama zavrtnjeva i o načinu ugradnje mernih traka, mogu se koristiti za približno određivanje sile u zavrtnjevima, merene mernim trakama, bez kalibracije. Problemi se mogu javiti kod kratkih zavrtnjeva, kod kojih je „plato dilatacije” slabo izražen. U tom slučaju, pravilno sprovedena kalibracija zavrtnjeva je neizbežna kako bi se pouzdano odredila sila u zavrtnju.

bolts show quite obvious "strain plateau" along a free threaded part of the bolt in the clamping package. The ratio of the nominal and actual strain in this zone is approximately 0,85, if the external thread dimension is adopted as the nominal diameter. As for all other types of bolts which have a thread along their entire shank, adequate coefficients can be estimated in a similar way.

The ratios of the nominal and actual strains for HV and HBT bolts, considering recommendations related to bolt length and strain gauge placement presented in this research, can be used to obtain the approximate force in the bolts, without performing strain-force calibration. Problems may arise in relatively short bolts in which "strain plateau" is not pronounced. In that case, proper calibration is inevitable in order to obtain more reliable measurement of the bolt force.

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REZIME

EKSPERIMENTALNA I NUMERIČKA KALIBRACIJA SILE PREDNAPREZANJA U VISOKOVREDNIM ZAVRTNJEVIMA

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U slučaju smičućih spojeva s visokovrednim zavrtnjevima s punom silom prednaprezanja, nosivost spoja zavisi kako od intenziteta sile prednaprezanja u visokovrednom zavrtnju, tako i od koeficijenta trenja na tarnim površinama. Veoma je važno odrediti pouzdanu vrednost sile prednaprezanja u visokovrednim zavrtnjevima, pa su tarni spojevi često predmet eksperimentalnih istraživanja. Kako bi se za određivanje intenziteta sile prednaprezanja mogle koristiti merne trake ugrađene u telo zavrtnja, zavrtnjeve je neophodno kalibrisati pre početka njihove primene u eksperimentalnom istraživanju. Sprovedeno istraživanje pokazalo je veliku razliku između nominalnih i eksperimentalno određenih dilatacija zavrtnjeva, zbog čega je sprovedena kalibracija zavrtnjeva numeričkom analizom (primenom metode konačnih elemenata). Dobijeno je dobro poklapanje rezultata, a primena mernih traka kod zavrtnjeva koji imaju navoj celom dužinom tela takođe se pokazala kao opravdana.

Ključne reči: visokovredni zavrtnjevi, sila prednaprezanja, kalibracija, eksperiment, numerička analiza, podužne dilatacije, „plato dilatacija"

SUMMARY

CALIBRATION OF THE BOLT PRETENSION BY STRAIN GAUGES VS. FEA

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When applying high strength bolts in friction connections, a load–bearing capacity depends on pretension force in the bolts as well as on friction coefficient found on friction surfaces. It is important to get the reliable value of the pretension force, so friction connections often undergo experimental research. In order to use strain gauges, which are inserted into the bolt shank, bolts need to be calibrated before we even use them in experimental research. Research that has been conducted shows a great difference between nominal and experimental strain in bolts, therefore FEA calibration of the bolts had to be carried out. Good results matching were obtained, hence a use of strain gauges was justified even for bolts without a shank.

Key words: high strength bolts, pretension force, calibration, experiment, FEA, longitudinal strain,"strain plateau"