IMK-14 – Istraživanje i razvoj u teškoj mašinogradnji 24(2018)1, SR11-16
UDC 621 ISSN 0354-6829

Analiza čvrstoće teretnog vagona za prevoz naftnih derivata sa kliznom vijčanom vezom

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U radu je prikazana analiza čvrstoće vagona za prevoz naftnih derivata sa kliznom vijčanom vezom u skladu sa TSI standardom i normom EN 12663:2010. U cilju optimizacije broja konačnih elemenata modela i kompleksnosti problema, autori su ispred sebe imali zadatak da na što jednostavniji način analiziraju uticaj vijčanih veza, koje će u potpunosti odgovarati vezama realnog modela. Primarni cilj analize je bio da pokaže dobro slaganje vrednosti napona dobijene primenom MKE analize sa vrednostima napona koje su izmerene mernim trakama na prototipu vagona. Na osnovu uporedne analize dobijenih i izmerenih vrednosti napona došlo se do zaključka da modelirane vijčane veze na prikazani način realno prenose opterećenja na ostali deo vagonske konstrukcije i da se mogu koristiti za analizu kompleksnih konstrukcija izloženih različitim vrstama opterećenja.

Keywords: Proračun čvrstoće vagona, MKE, Vijčane veze, Eksperiment

0.UVOD

Numeričke simulacije su postale deo standardnih inženjerskih alata koji svoju primenu pronalaze u širokom spektru problema. Numeričkim simulacijama se može još u fazi projektovanja sprečiti pojava mogućih grešaka koje dovode do narušavanja integriteta konstrukcija. Međutim mogu se i napraviti greške prilikom MKE modeliranja koje će dovesti do rezultata sa većim ili manjim odstupanjima od realnog ponašanja konstrukcije.

Iako široko primenjena i opšte poznata metoda konačnih elemenata (MKE) sa novim verzijama softvera postaje sve dostupnija i jednostavnija za korišćenje, još uvek postoji veliki broj specifičnosti u procesu kreiranja modela za analizu koji direktno zavisi od samo korisnika. Ovaj problem može biti veći ukoliko se analiziraju sklopovi konstrukcija sa velikim brojem kontaktnih regiona, različitih kinematskih veza i ostalih posebno dizajniranih funkcionalnih veza. Jedan od takvih problema je pravilan način modeliranja vijčanih veza različitih vrsta čeličnih konstrukcija [1].

U literaturi se mogu naći radovi koji su se na različite načine bavili ovom tematikom sa ciljem da se nađe rešenje koje bi dalo najbolje slaganje sa eksperimentalnim rezultatima [2]. Sa tim ciljem razvijen je veliki broj studija zasnovanih na teorijskim, eksperimentalnim i numeričkim procedurama [3]. Razmatrane su vijačne veze opterećene uglavnom na zatezanje ili savijanje, dok se veoma mali broj radova bavio vijčanim vezama opterećenim na smicanje [4]. U većini radova bez obzira na način modeliranja, vrstu opterećenja ili tip procedure kojom je vijčana veza analizirana, autori su se uglavnom bavili manje složenim konstrukcijama [5]. U tim slučajevima MKE modeli su se sastojali od manjeg broja elemenata i MKE analize nisu bile previše zahtevne.

Problem razmatran u ovom radu se odnosi na pravilno modeliranje klizne vijčane veze prilikom proračuna statičke i zamorne čvrstoće teretnog vagona cisterne namenjenog za prevoz naftnih derivata u skladu sa odgovarajućim standardima. Zbog složenosti geometrije i kompleksnosti modela koji ima veliki broj kontaktnih parova i vijčanih veza postavljen je zadatak da se na što jednostavniji način izmodeliraju vijčane veze, koje će odgovarati vijčanim vezama na realnom modelu.

1. OPIS PROBLEMA

Razmatrani vagon – cisterna je namenjen za prevoz naftnih derivata, Slika 1. Prilikom eksploatacije vagon je izložen termičkim dejstvima. Kako bi se omogućilo slobodno širenje i izbegla pojava značajnih deformacija jedna strana vagona je konstruisana tako da omogući relativno klizanje cisterne duž podužne ose u odnosu na postolje i bočne strane za koje je vezana kliznom vijčanom vezom. Sa druge strane cisterna je vezana fiksnom vijčanom vezom za bočne strane.

Sl. 1: *Vagon – cisterna za prevoz naftnih derivata*

1.1. Opis MKE modela

MKE model je kreiran u softveru FEMAP [6]. U skladu sa tipom konstrukcije za kreiranje MKE modela korišćeni su elementi ljuske odgovarajuće debljine, 3D osmočvorni elementi (za modeliranje oslonih ploča, rasteretnog prstena, vučne spreme) i gredni elementi kojima su modelirani vijci. Konstrukcija je detaljno modelirana i sastoji se iz 236800 elemenata i 234418 čvorova. Prosečna dužina stranice elementa je oko 30mm. MKE model uključuje 14 kontaktnih parova i 68 vijčanih veza.

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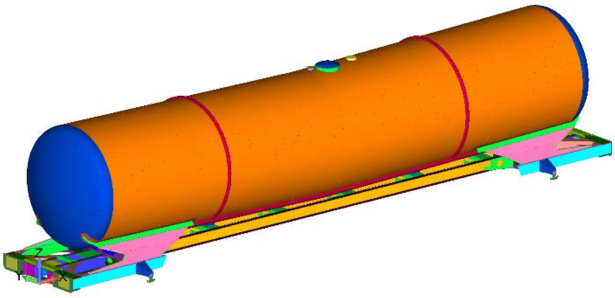
Na Slici 2 je prikazan je 3D model celog vagona bez obrtinih postolja. Različite boje na Slici 2. označavaju različite debljine elemenata ljuske. Zbog odgovarajuće simetrije za slučajeve opterećenja je korišćena samo polovina modela, dok je ceo model vagona je korišćen za nesimetrične slučajeve opterećenja.

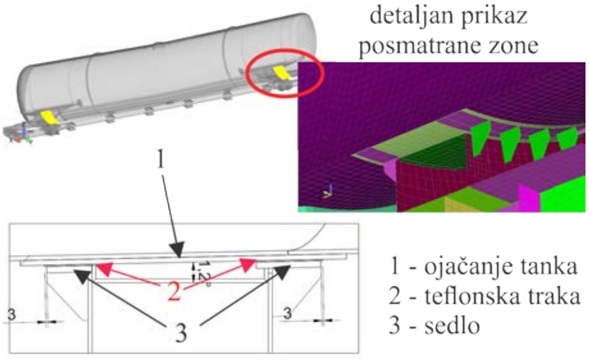


Sl. 2: *Mreža konačnih elemenata – 3D model vagona*

1.2. Definisanje kontaktnih parova i vijčanih veza

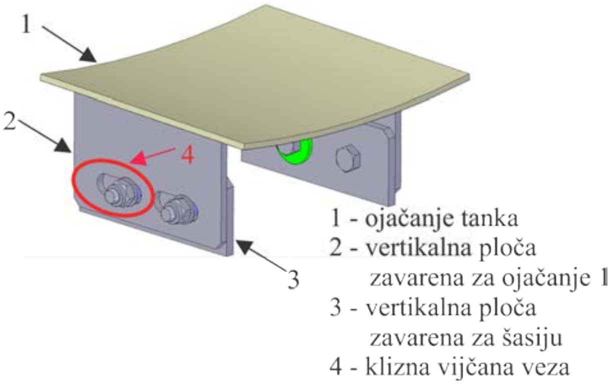
Konstrukcija vagona je izvedena tako da postoje tri osnovne veze između njenih delova: veza između tanka i sedla vagona (kontakt), srednja veza (kombinacija kontakta i klizne vijčane veze) i bočne veze između šasije vagona i tanka (kombinacija kontakta i klizne vijčane veze sa jedne strane i kombinacija kontakta i fiksne vijčane veze sa druge strane). Način modeliranja i detalji svih veza radi boljeg razumevanja biće prikazani dalje u tekstu.

Tank je oslonjen na sedla koja se nalaze u pravcu obrtnih postolja vagona, odnosno glavnih poprečnih nosača. Da bi klizanje cisterne po sedlu vagona bilo moguće između tanka i čeličnih ploča postavljene su teflonske (PTFE) trake kako bi se smanjilo trenje. Detalj ove veze sa prikazanim kontaktnim parom na MKE modelu prikazan je na Slici 3. Kontaktni par između tanka i sedla modeliran je kao kontakt čelik-teflon sa koeficijentom trenja prema [7].

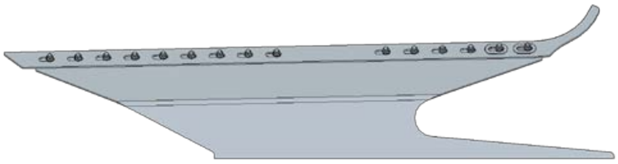


Sl. 3: *Kontaktni parovi čelik-teflon između tanka i sedla vagona*

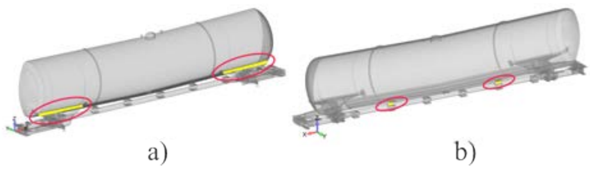
Kao što je već napomenuto, prilikom eksploatacije vagon je izložen termičkim dejstvima. Da bi se omogućilo slobodno širenje i izbegla pojava značajnih deformacija jedna strana vagona je konstruisana tako da omogući relativno klizanje cisterne u odnosu na šasiju vagona. Zbog toga je srednja veza tanka vagona i šasije (Slika 4), kao i jedna bočna veza tanka i šasije modelirana kliznom vijčanom vezom (Slika 5), dok je sa druge strane cisterna vezana fiksnom vijčanom vezom za bočne strane. Kod svih ovih veza pored definisanja odgovarajućih vijačnih veza, modelirani su i odgovarajući kontaktni parovi kao kontakt čelik-čelik sa odgovarajućim koeficijentom trenja prema [7]. Prikaz ovih kontaktnih parova definisanih u MKE modelu dat je na Slici 6.



Sl. 4: *CAD model srednje veze tanka i šasije*

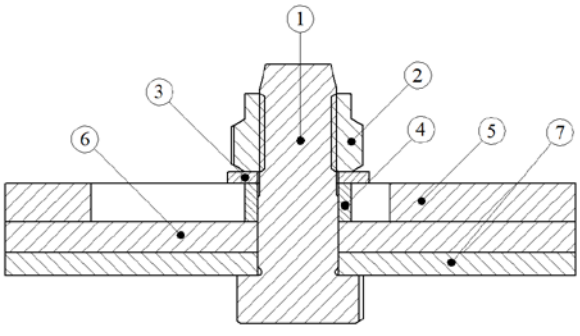


Sl. 5: *CAD model bočne veze cisterne i postolja sa kliznom vijčanom vezom*


a) b)

Sl.6: *a) Kontaktni parovi čelik-čelik između bočnih strana i tanka; b) Kontaktni parovi čelik-čelik između tanka i srednjeg dela šasije*

Cisterna je za bočne strane vezana sa ukupno 60 vijaka, 15 po jednoj bočnoj vezi, dok je srednja veza ostvarena pomoću 8 vijaka. To znači da u MKE modelu postoji 30 fiksnih i 38 kliznih vijčanih veza. Fiksna strana predstavlja klasičnu podešenu vijčanu vezu. Normalan presek klizne vijčane veze prikazan je na Slici 7.



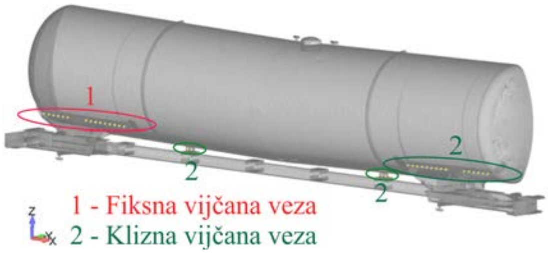
Sl. 7: *Normalan presek klizne vijčane veze*

Elementi koji čine kliznu vijčanu vezu (Slika 7) su:

1. Vijak M20 – 10.9
2. Navrtka
3. Podloška
4. Distancna čaura
5. T – ploča zavarena za tank
6. Bočna stranica
7. Ojačanje

Funkcija distancne čaure (pozicija 4), zajedno sa profilisanim otvorom jeste da obezbedi postojanje zazora između podloške i T ploče (pozicija 5) kako bi se omogućilo slobodno klizanje duž otvora na T ploči a u isto vreme da ograniči druga pomeranja.

Zbog znatog broja čvorova i elemenata u MKE modelu sve vijčane veze su modelirane uprošćeno, korišćenjem elementa grede. Na mestu fiksne klasične podešene vijčane veze sprečeni su svi stepeni slobode, dok je kod klizne vijčane veze korišćenjem opcije “beam release” omogućeno klizanje u pravcu žljeba (Slika 8). Početno prednaprezanje svih vijaka u vijčanim vezama zadato je u skladu sa [8].



Sl. 8: *Vijčane veze vagona*

2. STEPEN SIGURNOSTI, DOZVOLJENI NAPONI, SLUČAJEVI I USLOVI OPTEREĆENJA

2.1. Stepen sigurnosti i dozvoljeni naponi

U skladu sa BS EN 12663-2:2010 [9], Klauzula 6.2.2.1, Tabele 18 i Tabele 19, i u zavisnosti od materijalnih karakteristika materijala od kojih je vagon napravljen (konstrukcioni čelik srednje čvrstoće S355J2+N [10] i čelik za izradu posuda pod pritiskom P355GH [11]), definisane su vrednosti dozvoljenih napona u osnovnom materijalu i u okolini zavarenih spojeva usled statičkih opterećenja. Odnos napona tečenja R_e i proračunatog napona σ_c mora biti veći ili jednak stepenu sigurnosti S_1, Tabela 1.

Tabela 1: *Faktor sigurnosti i dozvoljeni napon za statičko opterećenje – osnovni materijal i u okolini zavarenih spojeva*

Materijal	Stepen sigurnosti S_1	Maksimalni dozvoljeni napon σ_{cmax}[MPa]
S355J2+N	1.0	355
P355GH	1.0	355
Zavareni spojevi	1.1	323

Na osnovu činjenice da se zamorno opterećenje uzima u opsegu ±30% vertikalnog statičkog opterećenja mogu se sračunati vrednosti maksimalnih napona za svaki tip zavarenog spoja u zavisnosti od referentne vrednosti zamorne (dinamičke) čvrstoće za 2 miliona ciklusa [12-13].

U Tabeli 2 prikazane su granične vrednosti napona za statička opterećenja kojima se potvrđuje zamorna čvrstoća u skladu sa Eurocode 3, Deo 1.9 [14], pomoću slike 7.1 i tabele 3.1.

2.2. Slučajevi i uslovi opterećenja

U skladu sa TSI standardom [15] i BS EN 12663-2:2010 [9], neophodno je proračunati statičku i zamornu čvrstoću vagona u odnosu na različite vrste opterećenja.

Neuobičajena opterećenja koja pokrivaju: horizontalna opterećenja, maksimalno vertikalno opterećenje, kombinacije opterećenja, podizanje i oslanjanje i druga neuobičajena opterećenja definisana su TSI standardom [15] Klauzula 4.2.2.3.2 i BS EN 12663-2:2010 [9], Klauzule 5.2.2-5.2.3. Za sva neuobičajena opterećenja maksimalna vrednost napona mora biti manja od odgovarajućih dozvoljenih napona prikazanih u Tabeli 1. Radna (dinamička) opterećenja ili jednostavno zamorna opterećenja definisana su TSI standardom [15], Klauzula 4.2.2.3.3 i BS EN 12663-2:2010 9], Klauzula 5.2.5. Za sva zamorna opterećenja maksimalne vrednosti napona moraju biti manje od odgovarajućih dozvoljenih napona prikazanih u Tabeli 2, za bezbedan životni vek.

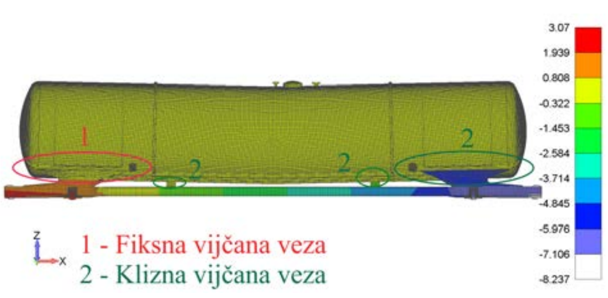
Tabela 2: *Granične vrednosti napona za statička opterećenja kojima se potvrđuje zamorna čvrstoća za čelike S355J2+N i P355GH*

Kategorija detalja amplitudni napon $\Delta\sigma_C$[MPa]	Maksimalna vrednost dozvoljenog napona $\Delta\sigma_{doz}$[MPa]	Granična vrednost dozvoljenog napona za trajnu dinamičku čvrstoću [MPa] – bezbedan životni vek	
		Nadgradnja $\gamma_{Mf}=1.15$	Postolje $\gamma_{Mf}=1.35$
160	347	301	257
140	303	264	225
125	271	236	201
100	217	188	160
90	195	170	144
80	173	151	128
71	154	134	114
63	136	119	101
56	121	106	90
50	108	94	80
45	98	85	72
40	97	75	64
36	78	68	58

3. FUNKCIONALNOST MODELIRANIH VIJČANIH VEZA

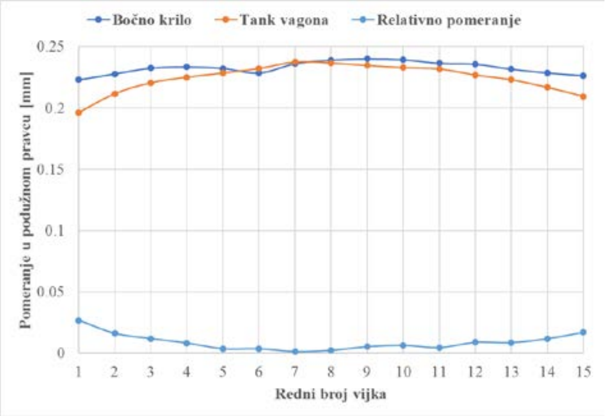
Kao što je već napomenuto sve vijčane veze modelirane su konačnim elementima grede. Na mestima fiksnih klasičnih podešenih vijčanih veza sprečeni su svi stepeni slobode, dok je kod kliznih vijčanih veza korišćenjem opcije “beam release” omogućeno klizanje u pravcu odgovarajućih žljebova.

U cilju verifikacije pravilnog načina modeliranja i funkcionalnosti vijčanih veza prikazani su rezultati proračuna koji pokazuju ponašanje MKE modela pri različitim vrstama opterećenja. Zbog činjenice da je klizanje, odnosno relativno pomeranje tanka u odnosu na šasiju vagona, najdominantnije kod horizontalnih opterećenja, na Slici 9 prikazano je polje pomeranja vagona u podužnom pravcu za slučaj opterećenja kad na odbojnicima deluje pritisna sila od 100 t.



Sl.9: *Polje pomeranja u podužnom pravcu – horizontalno opterećenje 100 t po odbojniku*

Na osnovu polja pomeranja prikazanog na Slici 9 jasno se vidi karakter ponašanja vijčanih veza. Na mestu fiksne vijčane veze jasno se vidi da nema relativnog pomeranja tanka u odnosu na šasiju vagona. Modelirana fiksna vijčana veza grednim konačnim elementom ne dozvoljava relativno pomeranje tanka i bočnog krila vagona. Dijagram sa vrednostima podužnog pomeranja tanka vagona i bočnog krila na mestima vijaka (15 vijaka) na strani vagona gde se nalazi fiksna vijčana veza prikazan je na Slici 10.



***Sl. 10:** Pomeranja u podužnom pravcu – fiksna vijčana veza*

Na osnovu polja pomeranja prikazanog na Slici 9 vidi se da postoji razlika u vrednostima pomeranja tank i šasije vagona na mestu klizne vijčane veze. Modelirana klizna vijčana veza grednim konačnim elementom korišćenjem opcije "beam release" dozvoljava relativno pomeranje tanka i bočnog krila vagona u pravcu žljebova. Dijagram sa vrednostima podužnog pomeranja tanka vagona i bočnog krila na mestima vijaka (15 vijaka) na strani vagona gde se nalazi klizna vijčana veza prikazan je na Slici 11.

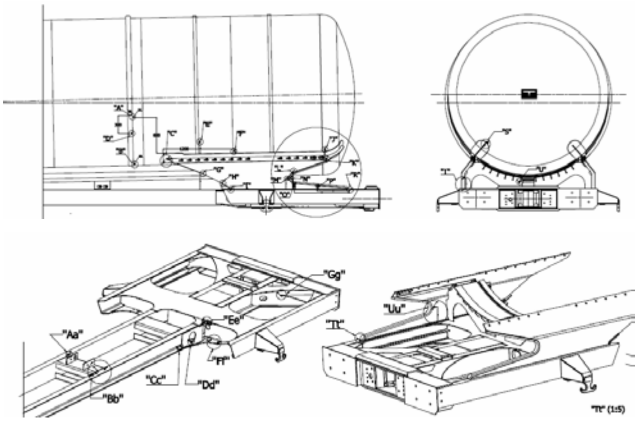
***Sl. 11:**: Pomeranja u podužnom pravcu – klizna vijčana veza*

4. MERENJE I POZICIJE MERNIH TRAKA

Na osnovu tehničke dokumentacije izrađen je prototip vagona za prevoz naftnih derivata i na njemu su izvršena merenja za sve slučajeve opterećenja definisane u skladu sa odgovarajućim standardima u oblasti vagonske industrije [9] i [15]. Na prototip vagona zalepljene su merne trake sa ciljem da se uporede vrednosti napona dobijene eksperimentalno i numeričkom MKE analizom.

Pozicije mernih traka su odabrane tako da pokriju sva mesta na vagonu gde je numerički proračun pokazao koncentraciju napona. Za potrebe ispitivanja na vagon su postavljene 32 merne trake i 17 rozeta. Vagon pripremljen za eksperimentalna ispitivanja, kao i pozicije mernih traka i rozeta prikazani su na Slikama 12 i 13 respektivno [16].

***Sl. 12:** Prototip vagona pripremljen za eksperimentalna ispitivanja [16]*



***Sl. 13:** Pozicije mernih traka*

Na osnovu dobijenih vrednosti napona na odgovarajućim mernim mestima, eksperimentalnim i numeričkim metodama, izvršena je uporedna analiza dobijenih rezultata.

5. UPOREDNA ANALIZA DOBIJENIH REZULTATA

Izmerene vrednosti napona na mestima mernih traka i rozeta upoređivane su sa vrednostima napona dobijenih MKE proračunom, za sve slučajeve opterećenja. Na celom vagonu postavljeno je 49 mernih mesta što u kombinaciji sa 15 različitih vrsta opterećenja daje oko 750 "kontrolnih tačaka" za uporednu analizu. Za potrebe proračuna statičke i dinamičke čvrstoće vagona namenjenog za prevoz naftnih derivate izvršena je uporedna analiza za svih 750 "kontrolnih tačaka", ali su za potrebe ovog rada prikazana samo neka karakteristična mesta.

Za potrebe uporedne analize na mestu gde su postavljene rozete razmatrane su vrednosti efektivnog napona. Za upoređivanje vrednosti napona očitanim na mestu mernih traka razmatrane su odgovarajuće komponente napona u pravcu mernih traka.

U Tabeli 3 su dati uporedni rezultati dobijeni na mestima rozeta i odgovarajući efektivni naponi dobijeni MKE analizom za odgovarajuće slučajeve opterećenja. U Tabeli 4 su dati uporedni rezultati dobijeni na mestima mernih traka i odgovarajući normalni naponi dobijeni MKE analizom za odgovarajuće slučajeve opterećenja.

Tabela 3: *Uporedni rezultati dobijeni na mestima rozeta i rezultati dobijeni MKE analizom [16]*

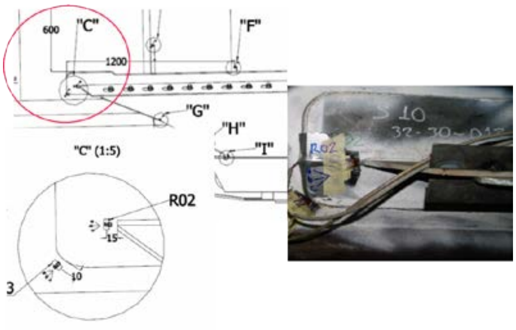
Oznaka rozete	Izmereni napon [MPa]	MKE rezultat [MPa]	Tip opterećenja
R01	282.7	259.9	Podizanje jednog kraja vagona
R02	221.3	218.1	Kombinacija vertikalno opterećenje i podužno opterećenje pritisna sila u nivou kvačila F=2000kN
R05	230.3	258.5	Podizanje jednog kraja vagona

Tabela 4: *Uporedni rezultati dobijeni na mestima mernih traka i rezultati dobijeni MKE analizom [16]*

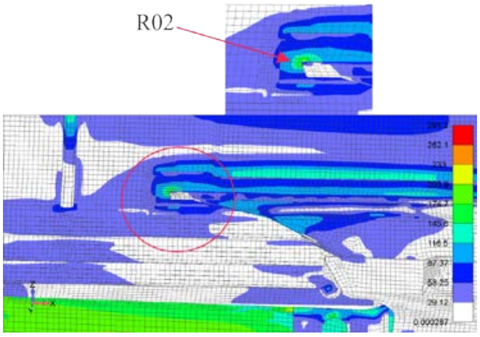
Oznaka merne trake	Izmereni napon [MPa]	MKE rezultat [MPa]	Tip opterećenja
T02	267.6	276.0	Podizanje jednog kraja vagona
T05	-279.7	-274.6	Podizanje jednog kraja vagona
T11	197.5	188.9	Podužno opterećenje vučna sila F=1500kN
T23	-202.3	-222.4	Podužno opterećenje pritisna sila F=1000kN po odbojiku
T27	-229.1	-215.3	Podužno opterećenje pritisna sila u nivou kvačila F=2000kN

Posebno je stavljen akcenat na merna mesta u blizini klizne vijčane veze koja predstavlja i primarni cilj istraživanja u ovom radu. Prikazani su rezultati samo za one slučajeve opterećenja koji su na kontrolnim mernim mestima pokazivali uvećane vrednosti napona (vrednosti napona iznad 200 MPa).

Na Slici 14 prikazan je položaj i izgled mernog mesta na kome se nalazi rozeta sa oznakom R02. Na Slici 15. prikazano je polje efektivnog napona na mestu rozete R02, za slučaj kombinacije opterećenja kada je vagon izložen vertikalnom opterećenju i horizontalnom opterećenju u podužnom pravcu u slučaju kada pritisna sila F=2000 kN deluje u nivou kvačila.

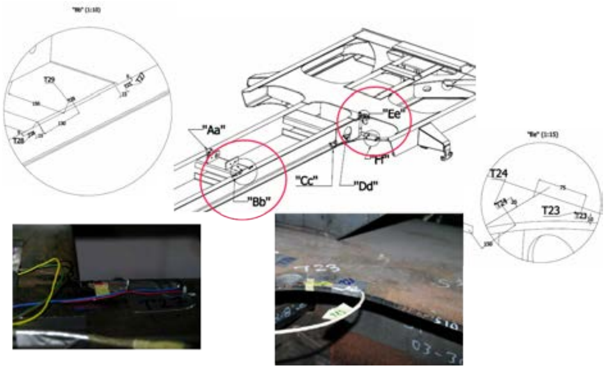


Sl. 14: *Rozeta R02 [16]*



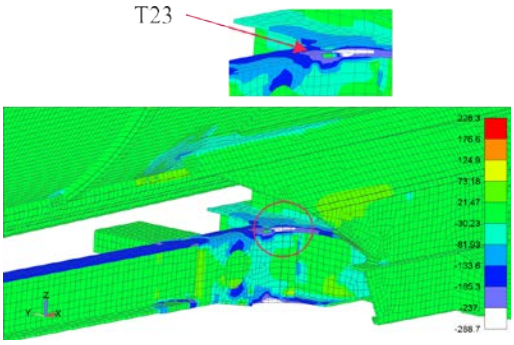
Sl. 15: *Polje efektivnog napona - Rozeta 02 - Kobinacija vertikalno opterećenje i podužno opterećenje pritisna sila u nivou kvačila F=2000kN*

Na Slici 16 prikazan je položaj i izgled mernih mesta na kojima se nalaze merne trake sa oznakama T23 i T27.



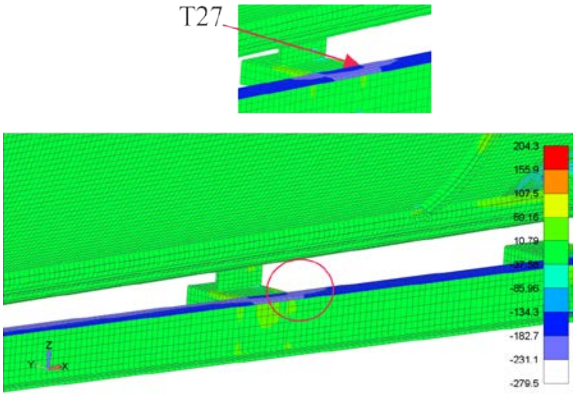
Sl. 16: *Merne trake T23 i T27 [16]*

Na Slici 17. prikazano je polje normalnog napona u x pravcu na mestu merne trake T23, za slučaj podužnog opterećenja pritisna sila F=1000 kN po odbojiku.



Sl. 17: *Polje normalnog napona u x pravcu – Merna traka T23 - Podužno opterećenje pritisna sila F=1000kN po odbojiku*

Na Slici 18. prikazano je polje normalnog napona u x pravcu na mestu merne trake T27, za slučaj podužnog opterećenja pritisna sila u nivou kvačila F=2000 kN.



Sl. 18*: Polje normalnog napona u x pravcu– Merna traka T27 - Podužno opterećenje pritisna sila u nivou kvačila F=2000kN*

6. ZAKLJUČAK

Cilj rada je bio da se na kompleksnom modelu vagona za prevoz naftnih derivata na što jednostavniji način, uzmu u obzir uticaji vijčanih veza, koje će u potpunosti odgovarati vezama na realnoj konstrukciji. Zbog činjenice da je vagon izložen termičkim dejstvima i da bi se omogućilo slobodno širenje delova konstrikcije dodatni problem predstavljao je način modeliranja klizne vijčane veze. Korišćenjem opcije “beam release” pri definisanju grednih elemenata kojima su modelirani vijci omogućeno klizanje u pravcu žljeba. Analizirano je ponašanje delova vagona spojenih fiksnom i kliznom vijčanom vezom, kao i sama funkcionalnost veza, za različite vrste opterećenja.

Upoređivanjem numeričkih rezultata sa rezultatima merenja potvrđeno je da MKE model daje rezultate koji imaju dobro poklapanje sa eksperimentalnim rezultatima. Na osnovu analize rezultata došlo se do zaključka da modelirane vijčane veze modelirane na način prikazan u radu realno prenose opterećenja između elementa vagonske konstrukcije i da se mogu koristiti za analizu kompleksnih konstrukcija izloženih različitim vrstama opterećenja.

ZAHVALNICA

Rad predstavlja deo istraživanja obavljen u okviru projekta TR 32036. Autori se zahvaljuju Ministarstvu prosvete, nauke i tehnološkog razvoja Republike Srbije

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IMK-14 – Research & Development in Heavy Machinery 24(2018)1, EN11-16
UDC 621 ISSN 0354-6829

Strength Analysis of the Freight Wagon for the Transport of Petroleum Products with a Sliding Bolted Connection

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This paper presents the strength analysis of the wagon for the transport of petroleum products with a sliding bolted connection according to TSI standard and norm EN 12663: 2010 standard. In order to optimize the number of elements of the FEA model and its complexity, the authors had a task to analyse the influence of bolted connections, which would completely correspond to the real connections. The primary objective of the analysis was to show a good agreement of the stress values obtained by FEM analysis with stress values obtained by strain gauges placed on a wagon prototype. According to comparative analysis of obtained and measured stress values, it has been concluded that the bolted connections modelled in the manner shown in this paper really transfer loads to other parts of the wagon construction and can be used to analyse complex structures exposed to different types of loads.

Keywords: Strength analysis of the wagon, FEA, Bolted connections, Experiment

1. INTRODUCTION

Numerical simulations have become a part of the standard engineering tools that find their application in a wide range of problems. Using numerical simulations at the design stage can prevent occurrence of possible errors that can lead to loss of the structures integrity. However, even in FEM modelling phase errors that will result in more or less deviations from the real behaviour of the structure could be made.

Although the widely used and widely known Finite Element Method (FEM) with new software versions is becoming more accessible and easier to use, there are still many specificities in the process of creating an FEA model that directly depend on the user. This problem can be even bigger if analysed structures have a large number of contact regions, different kinematic connections and other specially designed functional links. One of these problems is the correct way of modelling the bolted connection between different types of steel structures [1].

In the literature, one can find papers that present different ways to study this topic in order to find the best solution that would give the best agreement with experimental results [2]. Therefore, a large number of studies have been developed based on theoretical, experimental and numerical procedures [3]. The analysed bolted connections in literature were mainly exposed to tensile or bending loads, but a very small number of papers studied bolted connections subjected to shear loads [4]. In most papers, regardless of modelling way, type of load or type of procedure for bolted connection analysis, the authors mostly investigated the less complex structures [5]. In these cases, FEM models consisted of fewer number of elements and FEM analyses were not too complex.

The problem considered in this paper relates to the correct modelling of the sliding bolted connection in the static and fatigue strength analysis of the freight wagon for the transport of petroleum products in accordance to the relevant standards. Due to the complexity of the geometry and of the FEA model with large number of contact pairs and bolted connections, it is necessary to find the easiest way to model bolted connections, which will correspond to the bolted connections on the real model.

2. PROBLEM DESCRIPTION

The considered wagon - tank is intended for the transport of petroleum products, Figure 1. During exploitation the wagon is exposed to thermal effects. In order to allow free expansion and to avoid the occurrence of significant deformations, one side of the wagon is designed to allow the relative sliding of the tank along the longitudinal axis in relation to the underframe and side wing, on the opposite side of hand brake, for which tank is connected with sliding bolted connection. On the other side, side of the hand brake, the tank is connected with fixed bolted connection for the side wing.

***Fig. 1**: Freight wagon for the transport of petroleum products*

2.1. Description of the FEA model

Wagon is modelled using the FEMAP software with NX Nastran solver [6]. According to the construction type, shell elements of the appropriate thicknesses, 3D elements (for modelling of support plate, compensating ring, traction stop) and beam elements for modelling bolted connections were used for creating the finite element mesh. Structure is modelled in details with 236800 elements and 243846 nodes. General element side length is about 30 mm. The FEA model includes 14 contact pairs and 68 bolted connections.

Figure 2 shows the 3D FEA model of the whole wagon without bogies. Colours in Figure 2 match the

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various thicknesses of shell elements. Because of symmetry of the structure a half of the model was used almost for all load cases, taking in consideration the correspondent symmetry of the load cases. Full FEA model was used for unsymmetrical load cases.

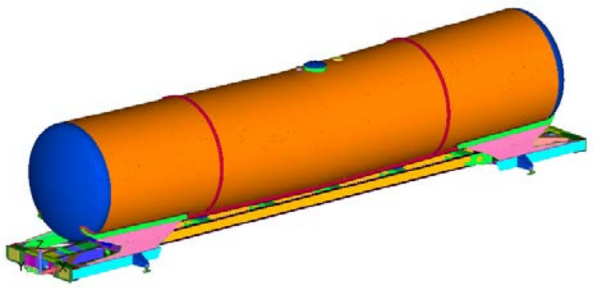


Fig. 2: *Finite element mesh – 3D vehicle model*

2.2. Description of contact pairs and bolted connections

The wagon structure is made in the way that there are three basic connections between its parts: connection between the tank and the saddle (contact pair), middle connection (combination – contact pair and sliding bolted connection) and side connections between chassis of wagon and tank (combination – contact pair and sliding bolted connection on the opposite side of hand brake; combination – contact pair and fixed bolted connection on the side of hand brake). For better understanding, the way of modelling and the details of all connections will be shown further in the text.

The tank is leaning on the saddle, which is in the direction of the wagon bogie, ie., the main transversal girders. For purpose of relative sliding, between the tank and the saddle a layer of polytetrafluoroethylene (PTFE) is placed in order to reduce the friction between the steel plates. The detail on the FEA model of this connection with contact pair is shown in Figure 3. Contact pair between the tank and the saddle is used as a contact steel-PTFE with the friction coeficient according to [7].

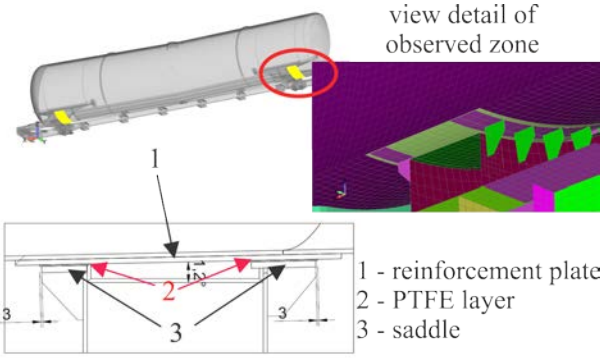


Fig. 3: *Contact pair steel-PTFE between the tank and the saddle*

As already mentioned, during the exploitation wagon is exposed to thermal loads. In order to allow the free expansion and to avoid the occurrence of significant deformations, one side of the wagon is designed to allow relative sliding of the tank in relation to the wagon chassis. For this reason, the middle connection between the tank and the wagon chassis (Figure 4), as well as one side connection between the tank and the wagon chassis, is modelled with a sliding bolted connection (Figure 5), while on the other side connection between the tank and the wagon chassis is modelled with the fixed bolted connection. Beside modelling of the appropriate bolted connections, contact pairs as steel-steel contact are modelled with the corresponding friction coefficient according to [7]. These contact pairs modelled in the FEA model are given in Figure 6.

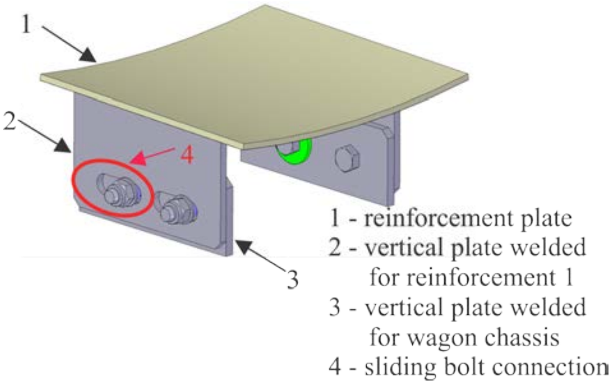


Fig. 4: *CAD model of middle connection between tank and wagon chassis*

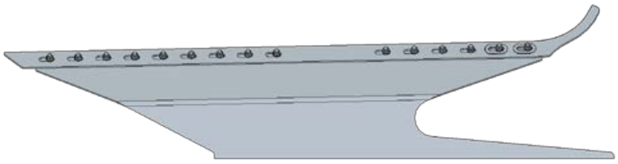
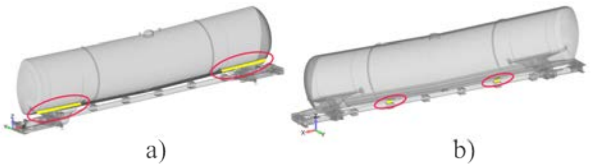


Fig. 5: *CAD model of side connection between tank and wagon chassis – sliding bolted connection*



a) b)

Fig. 6: *a) Contact pairs steel-steel between side wings and tank; b) Contact pairs steel-steel between tank and middle part of wagon chassis*

The tank is connected to the side wings with 60 bolts, 15 per one connection, while the middle connection is achieved by the 8 bolts, which means that there are 30 fixed and 38 sliding bolted connections in the FEA model. The fixed side represents a classical bolted connection. The perpendicular cross-section of the sliding bolted connection is shown in Figure 7.

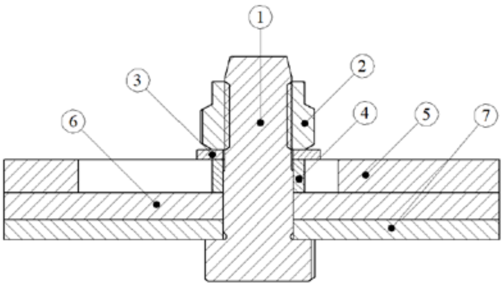


Fig. 7: *Perpendicular cross-section of the sliding bolted connection*

Parts of the sliding screw connection (Figure 7) are:

1. Bolt M20 – 10.9
2. Nut
3. Washer
4. Spacer
5. T – plate welded for the tank

6. Side wing
7. Reinforcement

Function of the spacer (position 4), together with the profiled hole, is to provide a gap between the washer and T plate (position 5) to allow the free sliding along the hole on the T plate and at the same time to limit other displacements.

Because of the large number of nodes and elements in the FEA model, all bolted connections are modelled using the beam element. At the place of fixed bolted connection, all degrees of freedom are disabled, while the sliding bolted connection using the "beam release" option allows sliding in the direction of the slot (Figure 8). The initial bolt preloads of all bolts in the bolted connections are in accordance with [8].

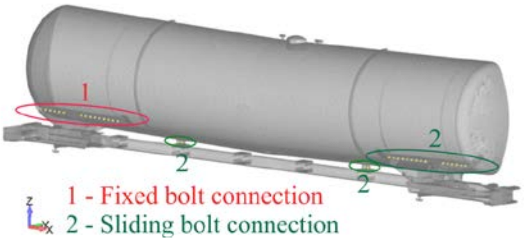


Fig. 8: *Bolted connections in FEA model*

3. SAFETY FACTOR, PERMISSIBLE STRESS, LOAD CASES AND REQUIREMENTS

3.1. Safety factor and permissible stress

According to BS EN 12663-2:2010 [9], Clause 6.2.2.1, Table 18 and Table 19, and in dependence of the material properties of the wagon (medium structural steel S355J2+N [10] and steel for pressure purposes P355GH [11]), permissible stresses in parent material and in parent material in the immediate vicinity of welds can be calculated under the static load cases. The ratio of yield stress R_e to calculated stress σ_c must be greater than or equal to S_1, Table 1.

Table 1: *Safety factor and permissible stress for static loads – parent material and welded joints*

Material	Safety factor S_1	Maximum permissible stress σ_{cmax}[MPa]
S355J2+N	1.0	355
P355GH	1.0	355
Welded joints	1.1	323

According to the source of fatigue loading, load used in design is in range of ± 30% of vertical static load. Limit values of different type of welded joints are determined in dependence of the referent fatigue value for 2 million cycles of constant amplitude [12-13].

Table 2 shows limit values for static test to verify the fatigue strength in accordance to the Eurocode 3, Part 1.9 [14], using Figure 7.1 and Table 3.1

3.2. Load cases and requirements

According to TSI standard [15] and BS EN 12663-2:2010 [9], it is necessary to calculate static and fatigue strength of wagon in relation to different types of load.

Exceptional loads, which cover: longitudinal design loads, maximum vertical load, load combinations, lifting and jacking and other exceptional loads are defined according to TSI [15] Clause 4.2.2.3.2 and BS EN 12663-2:2010 [9], Clause 5.2.2-5.2.3. For all exceptional loads maximum value of permissible stress must be lower than the permissible stress shown in the Table 1. Service (fatigue) loads are specified in TSI [15], Clause 4.2.2.3.3 and BS EN 12663-2:2010 [9], Clause 5.2.5. For service (fatigue) loads maximum value of calculated stress in welded joints must be lower than the limit stress for safe life in the Table 2.

Table 2: *Limit stress values for static test to verify fatigue strength for steels S355J2+N and P355GH*

Category detail - Direct stress range $\Delta\sigma_c$[MPa]	Permissible max. fatigue stress $\Delta\sigma_{doz}$[MPa]	Limit stress for safe life [MPa] – bezbedan	
		Low consequence γ_{Mf}=1.15	High consequence γ_{Mf}=1.35
160	347	301	257
140	303	264	225
125	271	236	201
100	217	188	160
90	195	170	144
80	173	151	128
71	154	134	114
63	136	119	101
56	121	106	90
50	108	94	80
45	98	85	72
40	97	75	64
36	78	68	58

4. FUNCTIONALITY OF MODELLED BOLTED CONNECTIONS

As already mentioned, all bolted connections are modelled with the beam element. At the place of fixed bolted connection, all degrees of freedom are disabled, while sliding bolted connection using the "beam release" option allows sliding in the direction of the slot. In order to verify the correct method of modelling and functionality of bolted connections, calculation results are shown to demonstrate the behaviour of the FEA model for different types of loads. Due to the fact that the sliding, or relative displacement of the tank in relation to the wagons chassis, is the most dominant in case of horizontal loads, Figure 9, the longitudinal displacement field of the wagon is shown for the load case - compressive force at buffer level; F=1000kN at each buffer.

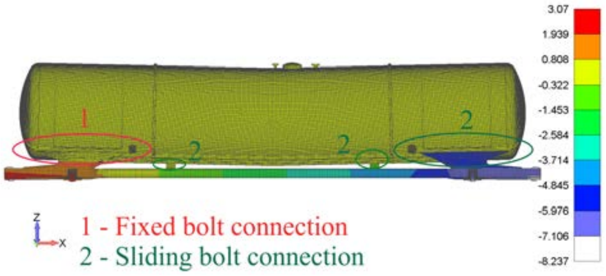


Fig. 9: *Longitudinal displacement field – compressive force at buffer level; F=1000kN at each buffer*

Based on the displacement field shown in Figure 9, the character of the behaviour of bolted connections can be seen. At the place of the fixed bolted connection, it can be clearly seen that there is no relative displacement of the tank in relation to the wagon chassis. The modelled fixed bolted connection with beam element does not allow the relative displacement of the tank and the side wings of the wagon. A diagram with the values of the longitudinal displacement of the tank and the side wing at the bolt positions (15 bolt) on side of hand brake where the fixed bolted connection is located is shown in Figure 10.

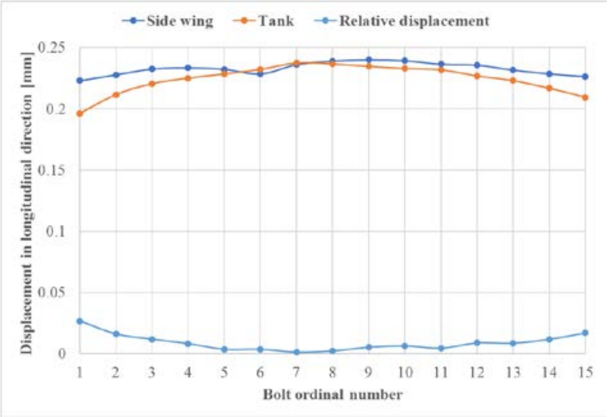


Fig. 10: *Displacement in longitudinal direction – fixed bolted connection*

Based on the displacement field shown in Figure 9, it can be seen that there is a difference in the values of the tank displacement and displacement of the wagon chassis at the place of the sliding bolted connection. The modelled sliding bolted connection with beam element using the "beam release" option allows the relative displacement of the tank and side wings of the wagon in the direction of the slot. A diagram with the values of the longitudinal displacement of the tank and side wing at the bolt positions (15 bolt) on opposite side of hand brake where the sliding bolted connection is located is shown in Figure 11.

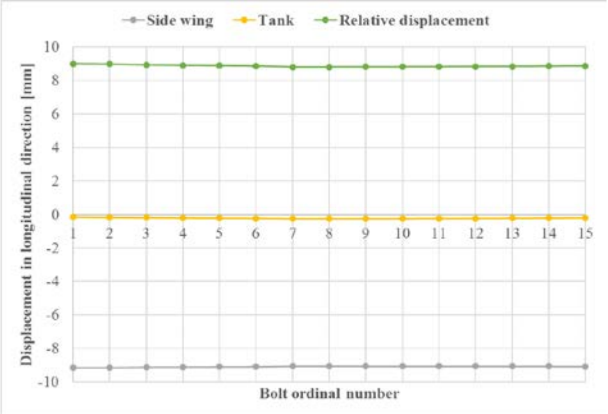


Fig. 11: *Displacement in longitudinal direction – sliding bolted connection*

5. MEASURING AND POSITION OF STRAIN GAUGES

Based on technical documentation, a prototype of the wagon for the transport of petroleum products was made and measurements for all load cases defined in accordance with the relevant standards in the field of the wagon industry [9] and [15] were done. Strain gauges were set up on the wagon prototype and measurements were carried out in order to compare the values of the stress obtained by the experimental and by numerical FEA analysis.

Positions of strain gauges are selected in the way to cover all the places on the wagon where the numerical calculations showed the stress concentration. For testing purposes, 32 strain gauges and 17 rosettes were placed on the wagon. Wagon prototype prepared for experimental tests, as well as positions of strain gauges and rosettes are shown in Figures 12 and 13 respectively [16].

Fig. 12: *Prototype of a wagon prepared for experimental tests [16]*

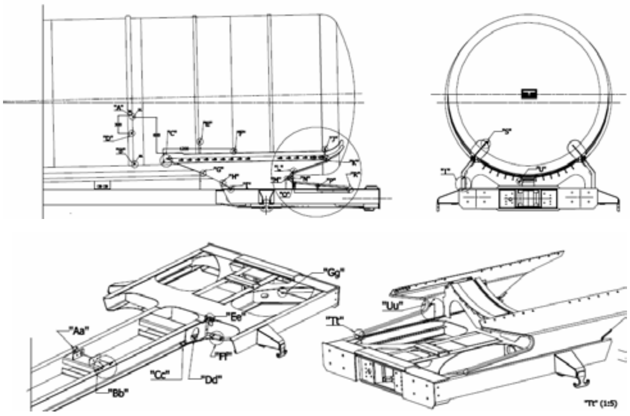


Fig. 13: *Position of strain gauges*

Based on the obtained stress values at the appropriate measuring points, by experimental and numerical methods, a comparative analysis of the obtained results was performed

6. COMPARATIVE ANALYSIS OF OBTAINED RESULTS

The measured values of stress at the positions of the strain gauges and rosettes were compared with the values of the stresses obtained by the FEA, for all load cases. There were 49 measuring points on the wagon prototype, that, in combination with 15 different types of loads, give about 750 "control points" for comparative analysis. For the strength calculation of the wagon for the transport of petroleum products, a comparative analysis was carried out for all 750 "control points", but only some characteristic points were presented for the purposes of this paper.

For the purposes of a comparative analysis at the place where the rosettes were placed, the values of the Von Mises equivalent stress were considered. For the purposes of a comparative analysis at the place where the strain gauges were placed, the values of the normal stresses in direction of strain gauge were considered.

Table 3 shows comparative results of stress obtained by rosettes and Von Mises equivalent stress obtained by FEA for corresponding load cases. In the Table 4 shows comparative results of stress obtained by strain gauges and normal stress obtained by FEA for corresponding load cases.

Table 3: *Comparative results obtained by rosettes and FEA [16]*

Rosette mark	Measured stress [MPa]	FEA [MPa]	Load case
R01	282.7	259.9	Lifting at one end of the vehicle
R02	221.3	218.1	Combination vertical load and compressive force at coupler level; F=2000kN
R05	230.3	258.5	Lifting at one end of the vehicle

Table 4: *Comparative results obtained by strain gauges and FEA [16]*

Strain gauge mark	Measured stress [MPa]	FEA [MPa]	Load case
T02	267.6	276.0	Lifting at one end of the vehicle
T05	-279.7	-274.6	Lifting at one end of the vehicle
T11	197.5	188.9	Tensile force applied on the support plates “a”; F=1500kN
T23	-202.3	-222.4	Compressive force at buffer level; F=1000kN at each buffer
T27	-229.1	-215.3	Compressive force at coupler level; F=2000kN

A special attention was paid to measuring points near the sliding bolted connection, which is also the primary goal of the research in this paper. The results are presented only for those load cases that showed higher stress values at control measuring points (stress values higher than 200 MPa).

Figure 14 shows the position and measuring place of rosette R02.

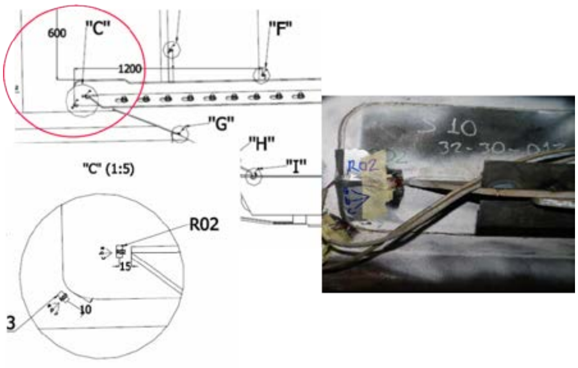


Fig. 14: *Rosette R02 [16]*

Figure 15 show field of von Mises equivalent stress on the model at the place of rosette R02 for combination load case, vertical load and compressive force at coupler level; F=2000kN.

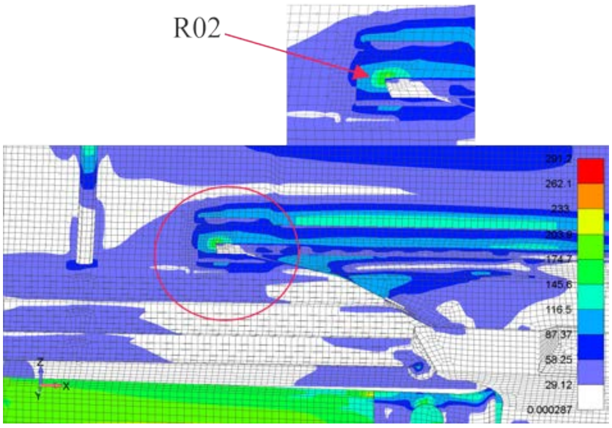


Fig. 15: *Von Mises equivalent stress field - Rosette 02 - Combination - vertical load and compressive force at coupler level; F=2000kN*

Figure 16 shows the position and place of strain gauges T23 and T27.

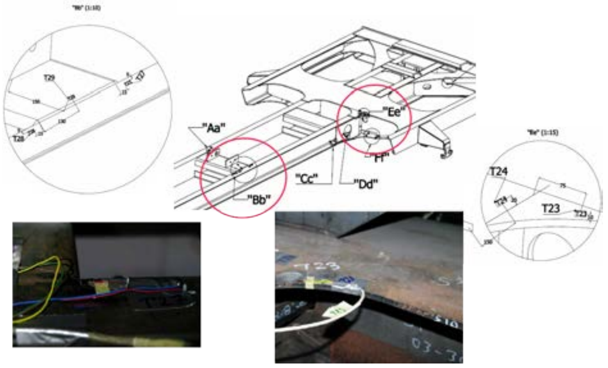


Fig. 16: *Strain gauges T23 and T27 [16]*

Figure 17 show X Normal stress field on the model at the place of strain gauge T23 for load case compressive force at buffer level; F=1000kN at each buffer.

Figure 18 show X Normal stress field on the model at the place of strain gauge T27 for load case compressive force at coupler level; F=2000kN.

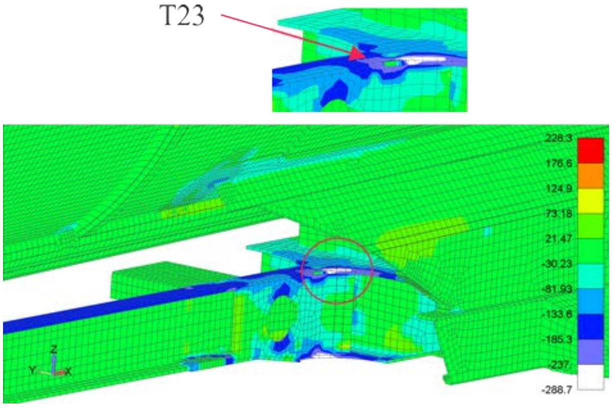


Fig. 17: *X Normal stress field – Strain gauge T23 - Compressive force at coupler level; F=1000kN*

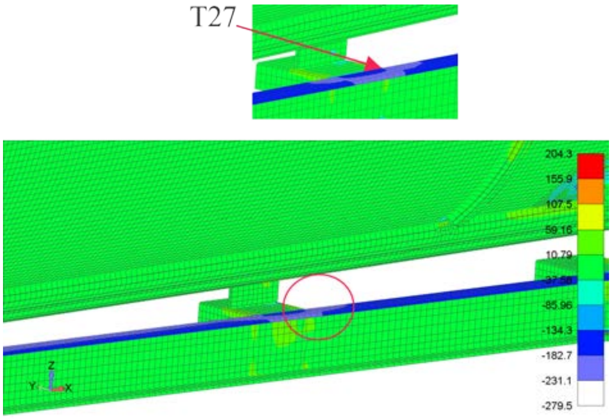


Fig. 18: *X Normal stress field – Strain gauge T27 - Compressive force at coupler level; F=2000kN*

7. CONCLUSION

The aim of this paper was to take into account the effects of bolted connections on the complex model of wagon for the transport of petroleum products, that will completely correspond to the connections on the real structure. Due to the fact that the wagon is exposed to the thermal loads it is necessary to allow the free expansion of the tank to avoid the thermally induced stresses in the material and because of that the sliding bolted connection was created which demanded special attention in the process of model creation. Using the "beam release" option, sliding along the direction of the slot is enabled in appropriate bolted connections. The behaviour of wagon parts connected with fixed and sliding bolted connections was analysed, as well as the functionality of connections for different types of loads.

Comparing the numerical results with the results of experimental measuring, it is verified that FEA model gives good agreement with the experimental results. Based on analysis of results, it has been concluded that bolted connections modelled in the manner shown in the paper realistically transfer loads between parts of the wagon structure and can be used to analyse complex structures exposed to different types of loads.

ACKNOWLEDGEMENTS

The part of this research is supported with the Project TR32036 of Ministry of Education, Science and Technical Development, Republic of Serbia.

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