ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
DOI: 10.17559/TV-20150513090840

FAILURE ANALYSIS OF BOLTED JOINT FOR THE COLUMN OF AN AERIAL PLATFORM

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Original scientific paper
This paper focuses on the identification of failure causes of a bolted joint used for the bedding of a primary column of an aerial platform. The tests conducted to determine chemical composition and mechanical properties have confirmed the 12.9 grade of the bolts. Also, mechanical properties tests and metallographic examination did not indicate any hidden defects caused by heat treatment (e.g. decarburisation etc.). On the other hand, visual and metallographic examination of cross-section as well as electron microscope scanning confirmed fatigue fracture of the bolts. Therefore, further analyses were done to check the dimensioning and the installation of the bolts. The effects on stress states in the bolts are presented from the standpoint of rated operating regimes, stiffness of joined elements, lubrication conditions of thread surfaces and temperature incompatibility between the bolts and elements being joined. Pre-tightening torque value incompatible with lubrication conditions was found to be the main factor that led to high stress values that initiated and later intensified the fatigue process which ended in fatigue failure of the bolts.

Keywords: *bolted joint lubrication; failure of bolts with high mechanical properties*

Analiza otkaza vijčanog spoja stupa platforme za rad na visini

Izvorni znanstveni članak
U radu se razmatra problematika identifikacije uzroka otkaza vijčanog spoja uležištenja osnovnog stupa platforme za rad na visinama. Ispitivanja provedena kako bi se odredio kemijski sastav i mehanička svojstva, potvrdila su da se radi o vijcima kvalitete 12.9. Također, ispitivanja mehaničkih svojstava i metalografska ispitivanja nisu navodila ni na kakve skrivene kvarove uzrokovane toplinskom obradom (npr. razugljičenje itd.) S druge strane, visualno i metalografsko ispitivanje poprečnog presjeka kao i ispitivanje elektronskim mikroskopom potvrdili su lom vijaka uzrokovan zamorom. Zato su dalje analize bile usmjerene na utvrđivanje adekvatnosti dimenzioniranja i ugradnje predmetnih vijaka. U radu su predstavljeni utjecaji na naponsko stanje vijaka sa stanovišta nominalnih radnih režima, krutosti elemenata u spoju, uvjeta podmazanosti površina navoja i temperaturne nekompatibilnosti vijaka i elemenata koji se spajaju. Zaključeno je da je neusklađenost primijenjenog momenta prethodnog pritezanja vijaka s uvjetima podmazanosti površina navoja bila od dominantnog značaja za pojavu povišenih naponskih stanja u materijalu vijaka, koji su inicirali i intenzivirali zamorni proces, odnosno zamorni otkaz vijaka.

Ključne riječi: *podmazanost vijčanog spoja; otkaz vijaka visokih mehaničkih svojstava*

1 Introductory comments

Aerial platform operating conditions and working principle define operating regimes characterised by distinct stochastic nature regarding the level and the nature of loads on whole construction [1]. Fig. 1 shows subject platform and Fig. 2 shows problematic bolted joint.

Figure 1 Subject platform

Data from real life show that the subject platform was used for extremely low number of hours, during which failed bolts were replaced several times (Tab. 1).

Table 1 Bolt replacement chronology

Replacement date	Number of replaced bolts
04.08.2008	48 bolts (all)
21-23.06.2010	3 bolts
11-12.01.2011	3 bolts

Figure 2 Problematic bolted joint

Fig. 3 shows bolt failure positions after complete bolt replacement (Tab. 1).

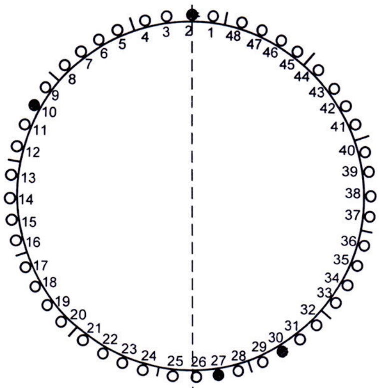


Figure 3 Bolt failure positions

Since failure of the bolts was not eliminated, the product was practically inoperable. In these circumstances, researches and analyses were simultaneously directed in two ways: to test the properties of bolt material and to conduct the fractographic and metallographic analysis on one side, as well as to check the dimensioning and the installation of the bolts in the critical joint on the other side [2, 3]. Also, identification of potential partial effects on load regimes and stress states of the bolts is conducted.

Bolt crack as a cause of failure of various elements and machine parts has been frequently analysed [4÷9]. Various approaches have been proposed to identify the failure causes of bolted joint used for bedding of the primary column of an aerial platform. Some approaches assume the use of metallographic examination [6, 9] to indicate main causes of bolt failure. On the other hand, fracture morphology and spectral analysis [8] could give acceptable results in analysing the microstructure of cracked bolt. Also, in some cases, macro and micro observation on fracture surfaces [9] give reliable information "at first glance" that can speed up the process of failure analysis.

Identification of failure causes of subject bolts implies applying several methods, which will be separately presented and commented on.

2 Verification of the quality of used bolts with the analysis of fracture surface and structural state of the material

Practical procedure for identification of failure causes of bolts usually starts with checking the chemical composition and mechanical properties, i.e. with metallographic examination of specimens of failed bolts.

Visual examination of failed bolts indicates fatigue fracture under moderate stress levels due to a joining of several minor cracks initiated in places with low stress concentration at the bottom of the thread due to corrosion (Fig. 4).

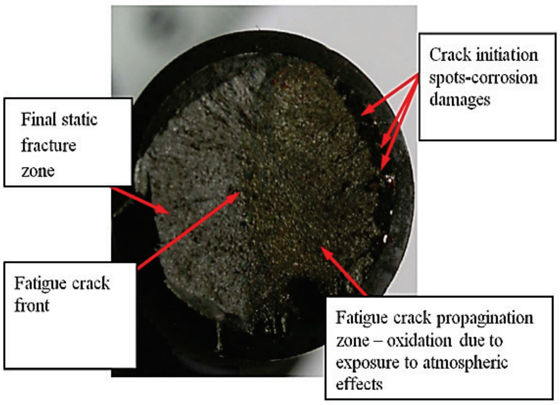


Figure 4 Fracture surface of the bolt (detail)

Results obtained by chemical composition tests (ISO 898-1:2009), Rockwell hardness tests (ISO 6508-1:2015), tensile property tests (ISO 6892-1:2009) and impact energy tests (ISO 148-1:2006) confirmed specifications of the subject bolts required by these standards.

Rockwell hardness was analyzed using tightening force of 1471 kN in compliance with SRPS EN ISO 6508-1:2011 on metallographic ground specimen taken from cross-section of the bolt, in the proximity of the crack. Average value of Rockwell hardness is 37,1 HRC. Hardness measured values are extremely balanced across the cross-section of the bolt. Rockwell hardness HRC is analyzed on a half-automatic hardness device WPM Leipzig.

Test results of bolt sample tensile property are presented in Tab. 2, and impact energy test results are presented in Tab. 3.

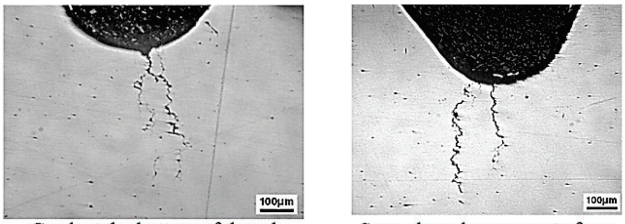
Table 2 Bolt sample tensile properties

Sample No.	Yield Strength $R_{p0,2}$ (MPa)*	Tensile Strength R_m (MPa)	Elongation A_5 (%)	Contraction Z (%)
1	1262	1326	14,00	51,00
ISO 898-1, Tab. 3	min 1100	min 1200	min 8	min 44

Table 3 Bolt sample impact energy

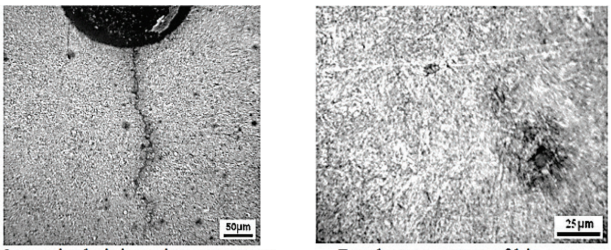
Test temperature T (°C)	No.	Impact Energy $KU_{300/2}$ (J)	Average (J)
+20	1	24,5	25.2
	2	26,5	
	3	24,5	
ISO 898-1, Tab. 3			min 15

Bolt material microstructure was analysed by testing the embedded metallographic ground specimen taken from the cross-section of the supplied bolts, with and without etching [10]. Figs. 5 and 6 show characteristic illustrations, as well as necessary comments and notes. Metallographic analysis of the microstructure was performed by using metallographic microscope METAVAL (Carl Zeiss Jena, Germany) and by using bright field technique.



Crack at the bottom of thread propagates from corrosion pit and branches off. Several cracks propagate from the bottom of thread.

Figure 5 Inter-crystal cracks on longitudinal section of the bolt, without etching



Martensite-bainite microstructure; No decarburisation of bolt surface case; Measured hardness around 400 HV1; 3% Nital. Random presence of big non-metallic inclusions; 3% Nital.

Figure 6 Microstructures on longitudinal section of the bolt, with etching

More detailed analysis of fracture surfaces required additional testing using scanning electron microscope

JEOL JSM 6460 [8]. Fig. 7 clearly shows corrosion pits at the bottom of thread as crack initiation spots, whereas Fig. 8 clearly shows oxidised surface in fatigue crack propagation zone (see Fig. 4).

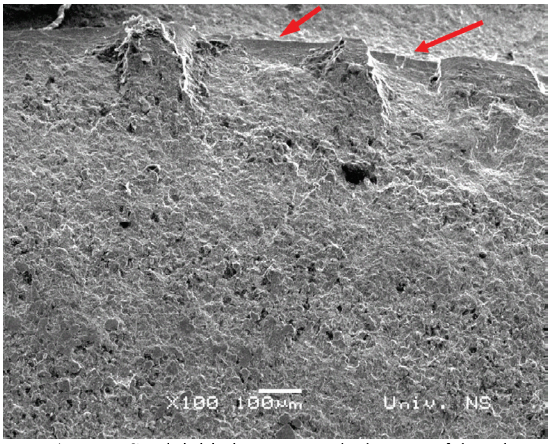


Figure 7 Crack initiation spots at the bottom of thread

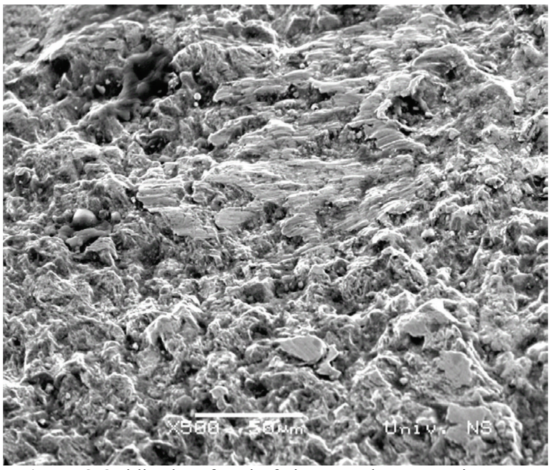


Figure 8 Oxidised surface in fatigue crack propagation zone

Based on aforementioned, it is possible to formulate conclusive comment on the quality of the bolts from several aspects. Regarding their chemical composition and mechanical properties, subject bolts are 12.9 grade bolts (ISO 898-1:2009). Mechanical properties and metallographic examination have not indicated any hidden defects caused by heat treatment (e.g. decarburisation etc.), that may have had considerable effect on the fracture of the bolts. Visual examination indicates fatigue fracture of the bolts with crack initiation spots occurring due to corrosion. Results obtained using metallographic examination of cross-section as well as scanning electron microscope confirm that fatigue cracks were initiated in corrosion pits at the bottom of the thread. Fracture of subject 12.9 grade bolts took place due to fatigue, after further inter-crystal propagation of fatigue cracks and at the moment when remaining bolt ligaments lost their carrying capacity.

Considering residual stress generated during the manufacturing of bolt itself, it is important to emphasise that procedure of installation of subject 12.9 grade bolts includes sample bolts tightening to the point of cracking before the installation itself.

This verifies the recommended value of the pre-tightening torque in a way that takes into consideration the overall influences, including the aspect of residual stress in bolts production. Data on sample bolts tightening in this particular case were not available, as in the case of factory installation, and when it comes to replacing bolts in service.

Considering extremely low number of hours the platform was used as well as the frequency of bolt replacements, activities of other part of the research were simultaneously performed, with the aim to evaluate correct dimensioning of the subject bolted joint [11]. These researches and analyses were directed towards recognising the potential partial effects on load regimes and stress states of the bolts in the critical joint from the perspective of lubrication conditions of thread surfaces while forming the bolted joint, bolt pre-tightening, temperature incompatibility between the bolts and the elements being joined, platform rated operating regimes, as well as the stiffness of the elements in the critical joint regarding load distribution within the bolts.

3 Effect of lubricant on bolt stress regimes during installation

The effect of thread surface lubrication on pre-tightening force, i.e. stress within the bolt, while applying relevant tightening torque, was determined experimentally. Fig. 9 shows applied testing procedure, acquisition system, as well as necessary comments and notes. Bolted joint was formed by using adapters and washers made of original bushes, so that testing conditions of bolts could be identical to real conditions of bolted joints on the platform.

Fig. 10 shows the comparative overview of tightening forces obtained by applying the same tightening torque of 150 N·m. Tightening force of lubricated bolted joint is 8,5 % greater than that of non-lubricated bolted joint.

Based on the obtained values and known geometry of the bolt, it is possible to define k coefficient in both cases. For non-lubricated joint k = 0,144, whereas for lubricated joint k = 0,132. Tightening torque recommended by the platform manufacturer is M_p = 460 N·m. Based on experimentally determined value of k coefficient, it is possible to evaluate bolt forces and stresses when applying recommended tightening torque. In case of non-lubricated joint, bolt tightening force is 178 kN, whereas stress is 930 MPa. By applying rated tightening torque in case of lubricated joint, bolt force increases to 193 kN, whereas stress increases to 1007 MPa. Difference between bolt stress state of 77 MPa is very important because it represents 6,4 % of material performance regarding strength (R_e = 1,200 MPa).This effect is especially interesting because of frequent partial bolt replacements in this specific case, in which it is difficult to precisely determine the state of the bolted joint regarding presence of lubricant.

4 Effect of platform operating regimes and stiffness of elements in the bolted joint

Rated operating conditions of the subject platform were determined by using bending moment M = 530 kN·m, whereas basic properties of formed discrete computational model can be seen in Fig. 11.

Structure of the bodywork base on vehicle chassis, design of platform column and flange were modelled by using surface finite elements, whereas bolts were modelled using linear elements, transferring axial loads only. Rated operating bending moment of the platform is provided by force acting from the appropriate distance (arm). Since the platform rotates around its vertical axis, critical zone regarding the bolt load is always opposite to the acting arm of rated load which can be positioned randomly all over the circle. In this manner and for accepted random position, results important for the subject analysis refer only to the zone with tensile bolts opposite to the acting arm of external load.

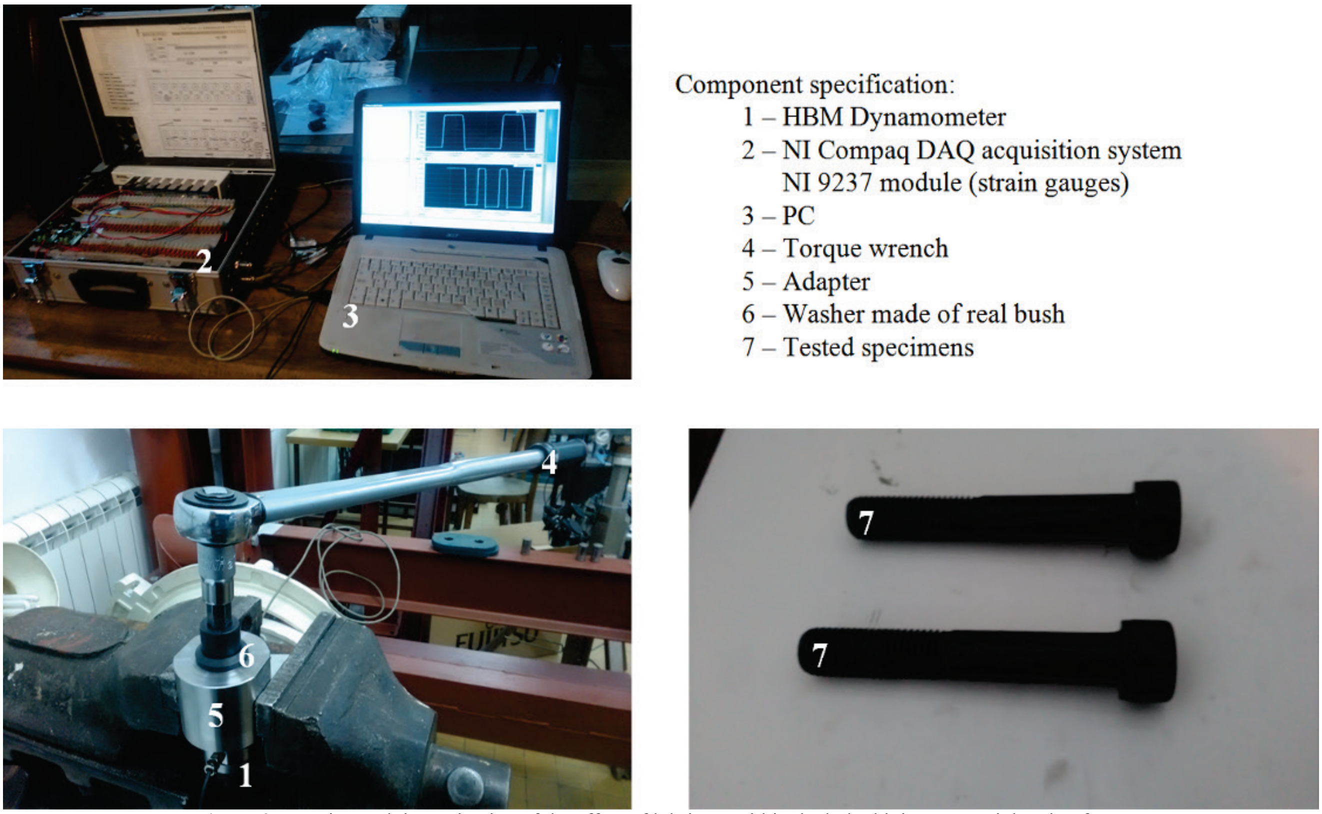


Figure 9 Experimental determination of the effect of lubricant within the bolted joint on pre-tightening force

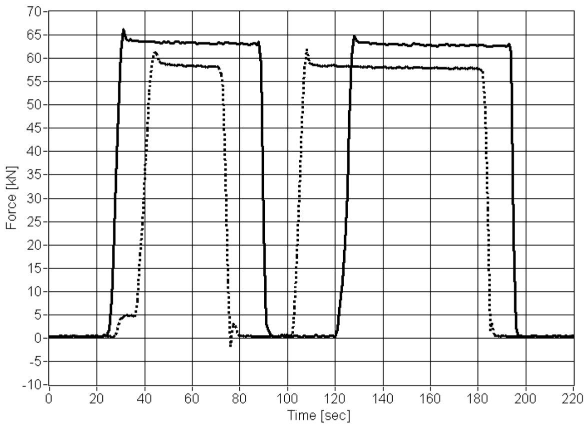


Figure 10 Tightening forces obtained by applying tightening torque of 150 N·m (Full line - lubricant present on thread surface; Dashed line - dry non-lubricated thread surface)

Fig. 12 gives graphical display of bolt loads as a function of stiffness of the platform structure in zone of bolted joint (varied thickness of platform column wall $t = 5$ / 10 / 15 / 20 mm). Fig. 13 illustrates bolt load in relevant zone with tensile bolts opposite to the acting arm of external load, whereas Tab. 4 gives relevant numerical values of bolt forces.

Based on obtained loads, stress caused by rated functional operating loads equals 156 MPa, which is 13 % of bolt material yield strength (R_e = 1200 MPa). Besides, the effect of stiffness of elements in the bolted joint on stress states of the bolts is practically negligible and equals 2 % of the effect of maximum operating load, which is about 0,2 % compared to material performance.

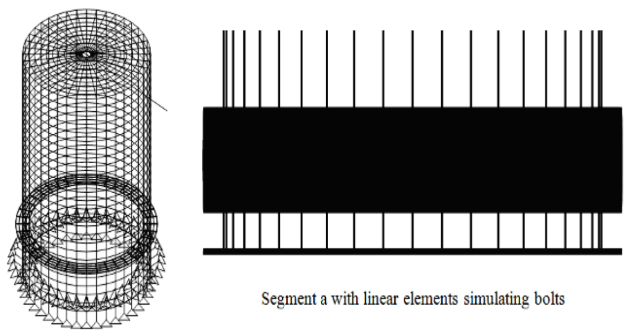


Figure 11 Formed discrete computational model

The procedure of forming relationship with subject 12.9 grade bolts means securing of temperature compatibility of bolt materials and elements that are combined (24 hours bolts must be implemented with a structure in which it is applied). Reliable information about this requirement is not available. Bearing in mind the obligatory bolts replacement interval (Tab. 1), this influence on bolts stress state, with the necessary notes are represented in Tab. 5.

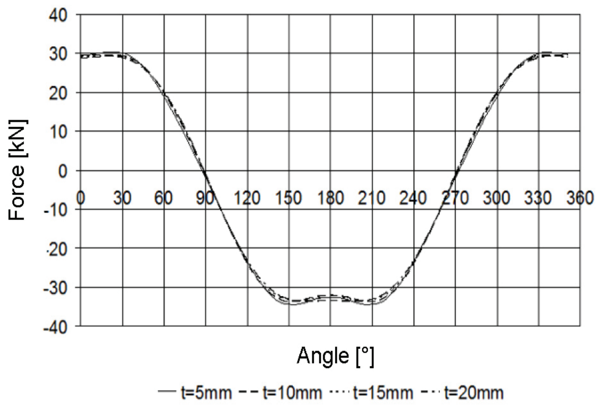


Figure 12 Bolt loads in zone of bolted joint

In order to consider the effect of determined potential differences between tightening forces obtained during forming of bolted joint, it is necessary to analyse bolt stress states due to consolidated effects including platform rated operating regime. Tab. 5 indicates effects of some considered influential factors on the stress of the subject bolts.

Tab. 5 includes necessary comments and explanations, for easier perception of specific importance of each considered influential factor regarding the available resource, i.e. bolt carrying capacity (R_e = 1200 MPa).

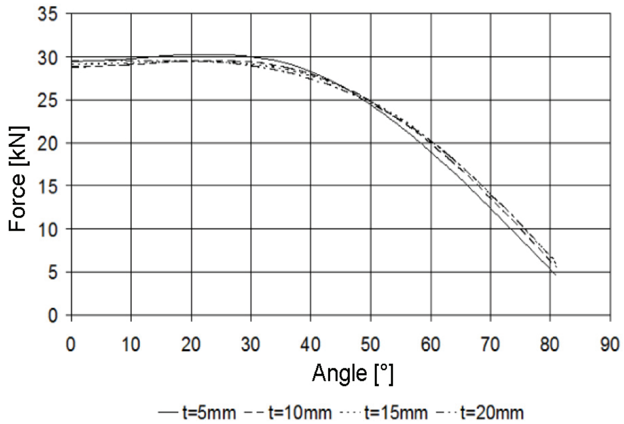


Figure 13 Bolt loads in relevant zone with tensile bolts opposite to the acting arm of external load

Based on values from Tab. 5, it can be concluded that consolidated stress response, including all partial effects, equals 1186,4 MPa, which practically corresponds to bolt material yield strength (R_e = 1200 MPa). Such a high value superimposes all considered effects and represents the most unfavourable case. Designed operating regimes with included effect of considered influential factors practically bring bolts in observed bolted joint into the zone of material performance regarding carrying capacity, i.e. strength.

According to guidelines and recommendations of standard for joints formed by bolts with high strength grades DIN 912 (SRPS U.E7.140), pre-tightening of bolts is determined in a way not to exceed 80 % of bolt material yield strength, which is 864 MPa in this case.

Table 4 Relevant numerical values of bolt forces

Bolt force in tensile zone (kN)				
Ordinal no.	*t* = 5 mm	*t* = 10 mm	*t* = 15 mm	*t* = 20 mm
1	29,4	28,8	29,1	29,5
2	29,7	29	29,2	29,5
3	30,2	29,4	29,4	29,5
4	30,2	29,5	29,3	29,2
5	29,2	28,7	28,5	28,2

Pre-tightening force has dominant effect on complete stress state of bolts. And in case of standard defined stress values due to bolt pre-tightening, consolidated stress state, including all considered partial effects, equals 1120,4 MPa, which is 93,4 % compared to bolt material yield strength (R_e = 1200 MPa). This is also high stress value that will boost initiation of fatigue cracks and contribute to their intensive propagation.

5 Conclusion

The paper identifies participating levels of some influential factors within consolidated stress state of high strength grade bolts forming considered bolted joint. Pre-tightening torque value incompatible with lubrication conditions was found to be the main factor that led to high stress values that initiated and later intensified the fatigue process which ended in fatigue failure of the bolts. That means that the human factor is the cause of the problems in considered bolt juncture, by noncompliance of procedures defined for installation of bolts with high mechanical properties.

Human factor can also be important in identification of platform rated operating regime and temperature incompatibility effects. In the present problem, those two factors induce low values of stress (compared to bolt material mechanical properties), but, when superposed with stresses induced by pre-tightening force incompatible with lubrication conditions, they can further intensify the present problem.

Table 5 The effects of some considered influential factors on the stress of the subject bolts

Stresses due to relevant partial influential factors (MPa)				
Pre-tightening*	Functional operating load	Lubrication of bolted joint	Temperature incompatibility**	Stiffness of element structures in the joint
Based on experimentally defined k coefficient applied to recommended M_p = 460 kN				
930 (77,5 %) ***	156 (13 %) ***	77 (6,4 %) ***	23,4 (2 %) ***	0,2
* Values defined on the basis of experimental data (item 3) ** Effect defined analytically for temperature difference of 10 °C between the elements being joined *** Percentage stress value compared to material yield strength (R_e= 1200 MPa)				

It can, also, be concluded that extreme bolts hardness "wearing" by pre-tightening is unnecessary, especially when it comes to connections where tightness is not required, but only hardness as consequence of applicable operating loads distribution. That causes lower stress an order of magnitude below hardness characteristics of the bolts material.

Acknowledgement

This paper is a part of a project of The Ministry of Science and Technological Development of Serbia (project number TR035045 – "Scientific-Technological Support to Enhancing the Safety of Special Road and Rail Vehicles").

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