Creep and Relaxation Behaviour of Stainless Steel Bolted Assemblies

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Abstract

Stainless steel material is a suitable choice for modern steel constructions as it has a high resistance to corrosion combined with high material strength and ductility. Furthermore, its use leads to significant reductions in maintenance. In this frame, bolted connections made of stainless steel components become more and more important to enhance the application of stainless steel not only to small parts of steel structures but also to complex structures. Whereas non preloaded stainless steel bolted connections are already widely used, according to EN 1090-2, the application of preloaded stainless steel bolting assemblies is not allowed unless otherwise specified. If they shall be used, they shall be treated as special fasteners and a procedure test is mandatory. Also EN 1993-1-4 requires that their acceptability in a particular application has to be demonstrated from test results. These restrictions are mainly caused by two facts: firstly, the viscoplastic deformation behaviour of stainless steel which might result in not negligible preload losses in the bolting assemblies themselves and secondly, the gap of knowledge regarding suitable tightening parameters and procedures for stainless steel bolting assemblies to secure a required preload in the bolting assemblies and to avoid galling. To solve these questions, research activities have been carried out in the frame of the European RFCS-research project "Execution and reliability of slip resistant connections for steel structures using CS and SS" SIROCO. The present contribution gives an initial insight into the viscoplastic deformation behaviour of stainless steel bolting assemblies which were achieved in SIROCO which shows that preloaded bolted stainless steel connections can be treated similar to those made of carbon steel.

Keywords

Loss of preload, stainless steel, creep, relaxation, preloaded bolted connections.

1 Introduction

Preloaded stainless steel bolting assemblies are desirable in such cases when either for ultimate limit state reasons the preload in the bolts is considered in the design process of structures to secure the bearing resistance of the bolted connection as in slip-resistant connections or in fatigue loaded bolted connections, or for serviceability reasons to limit slip and deformations of the joints. But: currently, according to EN 1090-2 [1], stainless steel bolting assemblies are not allowed to be preloaded, unless otherwise specified. Also EN 1993-1-4 [2] requires that their acceptability in a particular application has to be demonstrated from test results. These restrictions are mainly caused by two facts: firstly, the viscoplastic deformation behaviour of stainless steel is unknown, which might result in not negligible preload losses in the bolting assemblies themselves, and secondly, the gap of knowledge regarding suitable tightening parameters and procedures for stainless steel bolting assemblies to secure a required preload in the bolting assemblies as well as to avoid galling. To close these gaps of knowledge, both topics have been thoroughly investigated in the frame of the European RFCS research project "Execution and reliability of slip resistant connections for steel structures using CS and SS" (SIROCO) (RFSR-CT-2014-00024). Whereas the results regarding the latter topic are presented in [3], the results regarding the viscoplastic deformation behaviour are presented in the following.

2 Creep Behaviour of Stainless Steel Plates

The tested stainless steel materials were hot-rolled sheet EN 1.4404 (austenitic), hot-rolled sheet EN 1.4003 (ferritic), hot-rolled plate EN 1.4162 (lean duplex) and hot-rolled plate EN 1.4462 (duplex). The plate thicknesses were 8.0 mm for the austenitic, the ferritic and the duplex. The lean duplex plate thickness was 8.6 mm. The longitudinal 0.2 proof stress of the plates were 280 MPa for the austenitic, 304 MPa for the ferritic, 509 MPa for the lean duplex and 619 MPa for the duplex. The tested plates had continuous yielding behaviour.

The specimens were loaded to an initial tensile stress of 0.50, 0.65, 0.83 and 1.00 times the measured $R_{p0.2}$ and thereafter held at constant stress at room temperature conditions. The testing direction was longitudinal (rolling direction) and the specimens for the austenitic and ferritic plates were flat tensile specimens with cross-section of 10.0×8.0 mm^2 with 75 mm parallel length. For the duplex plates, flat tensile specimens with the cross-section 12.5×8.0(or 8.6) mm^2 with 110 mm parallel length was used.

The testing system for the duplex plates consisted of an electromechanical servo controlled machine. The load cell used was a 250 kN class 0.5 and the extensometer used was a class 0.5 macro extensometer. The initial loading rates used were constant crosshead speed equivalent to a strain rate of 10^{-5} 1/s and 10^{-4} 1/s. For the $0.50{\times}R_{p0.2}$ stress level for the austenitic and ferritic grade a similar electromechanical servo controlled machine was used. The load cell used was a

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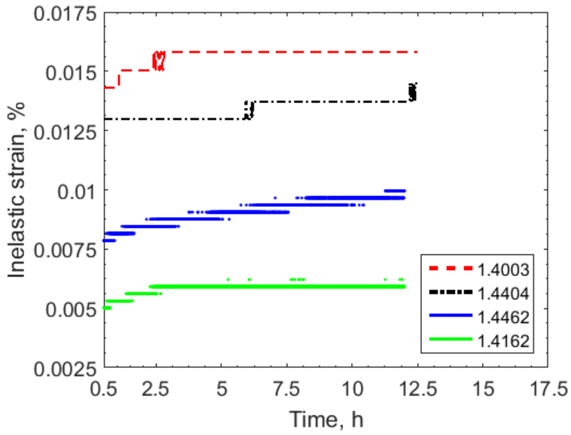
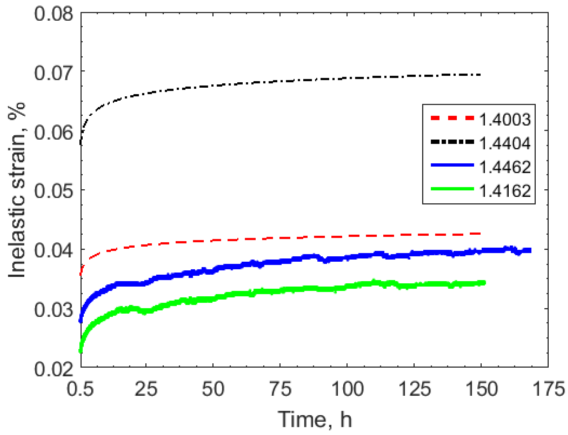
250 kN class 1.0 and the extensometer used was a class 1.0 macro extensometer. The initial loading rate used was constant crosshead speed equivalent to a strain rate of $2.5 \cdot 10^{-4}$ 1/s. For the other stress levels for the austenitic and ferritic plates a dead weight creep testing machine was used. Strain gages were used for measuring the strain during testing. The specimens were loaded manually to the specified initial tensile stress. The investigations have been carried out at Outokumpu Avesta R&D Center and Outokumpu Tornio R&D Center.

Fig. 1 shows the uniaxial tensile creep results for the stainless steel plates at room temperature condition. The inelastic strain was defined as the total strain minus the elastic strain. Therefore, any plastic strain that occur during the initial loading were included in the inelastic strain. Thus, the viscoplastic strain (i.e. the creep strain) may be less than showed in Fig. 1. The reason for showing the inelastic strain was to be able to compare the creep results from the dead weight testing system (where it was difficult to distinguish between the initial loading and early creep) with the creep testing with the electromechanical servo controlled machines.

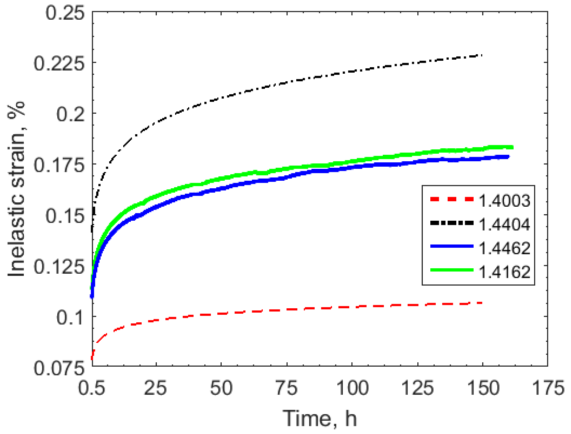
At the $0.50 \times R_{p0.2}$ stress level creep was observed for all the tested stainless steel grades. After 2.5 h of testing, the inelastic strain became constant indicating that the creep rate was below the resolution of the testing systems. At the $0.65 \times R_{p0.2}$ stress level continuously increasing inelastic strain was observed. With increasing stress level the amount of inelastic strain increased.



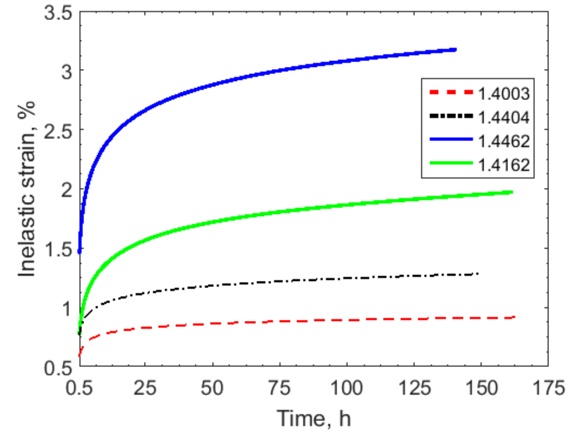
(a) $0.50 \times R_{p0.2}$ stress level



(b) $0.65 \times R_{p0.2}$ stress level



(c) $0.83 \times R_{p0.2}$ stress level



(d) $1.00 \times R_{p0.2}$ stress level

Fig. 1 Uniaxial tensile creep results. The initial loading rate for the EN 1.4404 and EN 1.4003 at the $0.50 \times R_{p0.2}$ stress level was $2.5 \cdot 10^{-4}$ 1/s. The initial loading rate for the EN 1.4462 and EN 1.4162 was 10^{-5} 1/s

The ferritic grade, except at the $0.50 \times R_{p0.2}$ stress level, exhibit lower inelastic strain than the austenitic grade. The two duplex grades exhibited the lowest amount of inelastic strain for the two lowest stress levels. At the $0.83 \times R_{p0.2}$ stress level the two duplex grades shows increased inelastic strain compared to the austenitic and ferritic grades. At the $1.00 \times R_{p0.2}$ stress level the two duplex grades exhibited the highest inelastic strain. One part of the explanation was likely that the duplex grades had higher proof strength compared to the austenitic and ferritic grades. This resulted in higher amount of strain during the initial loading which consequently resulted in larger contribution of plastic strain to the inelastic strain. The mean contribution of plastic strain to the inelastic strain was 33 % for the duplex grades where the 1.4462 had the highest contribution of plastic strain from the initial loading.

For the austenitic stainless steel grades it has been reported [4], [5] that the creep rate at room temperature can be described by the following generalised equation:

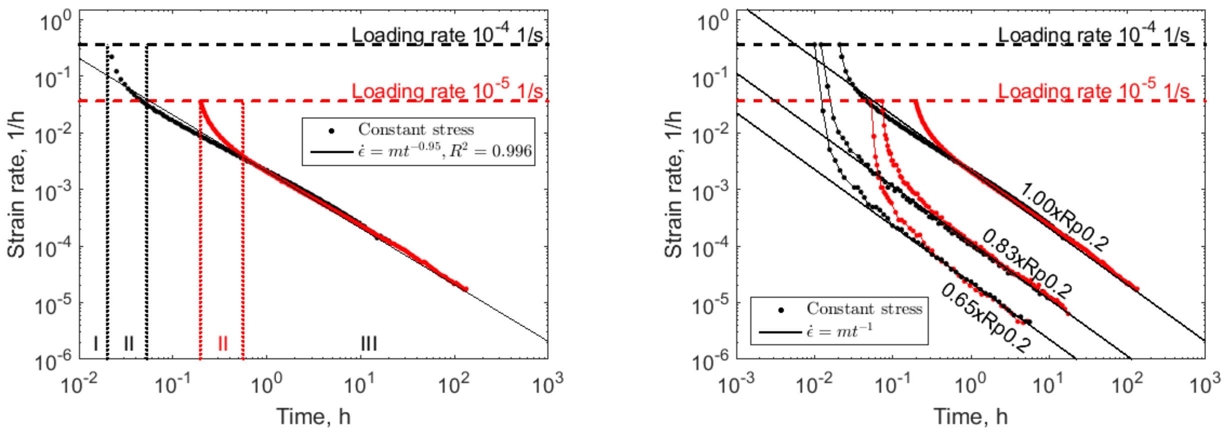
$$\dot{\varepsilon}(t) = f_1(\sigma)t^{-1} \quad (1)$$

where $f_1(\sigma)$ is a function of the applied stress and t is the time. This is usually referred to as logarithmic creep behaviour as the integral of equation (1) becomes the natural logarithmic function of t. Fig. 2a shows the strain rate during uniaxial tensile creep testing of the lean duplex grade for the two different loading rates. Three distinct regions could be found: the first region (I) was the initial loading which in this case was constant strain rate of 10^{-5} 1/s or 10^{-4} 1/s, the second region (II) was the initial creep region where the creep rate rapidly decreases and the third region (III) was the creep rate region where the creep rate could be described by equation (1). Apparently equation (1) does not describe the initial creep behaviour.

One can also observe that the logarithmic creep rate region was independent of the initial loading rate. The initial loading rate determines the strain at the specified stress and the maximum creep rate obtained during testing. Higher loading rates result in lower initial strain and higher viscoplastic strain.

Fig. 2b shows the influence of the stress level on the creep rate. The rapid decrease in creep rate during the initial creep region (II) was observed to depend on the stress level where a high stress level had lower creep rate drop which resulted in an elevated logarithmic creep rate (higher m value) which results in higher amount of inelastic strain as seen in Fig. 1.

The creep rate for the austenitic and ferritic grade in the present work was also found to be logarithmic.



(a) The influence of the loading rate on the creep rate

(b) The influence of the stress level on the creep rate

Fig. 2 The strain rate during uniaxial tensile creep testing of EN 1.4162

3 Stress Relaxation Behaviour of Austenitic Stainless Steel Bars

The material was 12 mm cold drawn bar of EN 1.4436. The cold drawn was to represent cold headed bolts with high amount of cold work. Cold drawn bar was chosen over actual bolts due to practical limitations in testing. The measured $R_{p0.2}$ and R_m was 823 MPa and 966 MPa respectively.

The same electromechanical servo controlled machine as for the creep testing of the duplex plates was used with the addition of a class 1 clip-on extensometer with 60 mm gauge length. The specimens were loaded to an initial stress of 0.6, 0.8 or 1.0 times the measured $R_{p0.2}$ and thereafter held at constant strain for 12 h at room temperature conditions and then unloaded. The initial loading rate was 10 MPa/s. The investigation has been carried out at Outokumpu Avesta R&D Center.

Fig. 3a shows the stress relaxation obtained during 12 hours of testing. The stress relaxation was defined as:

$$\sigma_{relax.} = \left(1 - \frac{\sigma_i}{\sigma_0}\right) * 100 \quad (2)$$

where σ_i was the measured stress under constant strain and σ_0 the initial stress. The time was adjusted for removing the difference in time due to initial loading times. The stress relaxation was high in the beginning but quickly slowed down with increasing time. Most of the stress relaxation occurred within the first minutes. Fig. 3b shows the stress relaxation rate during testing. Similar viscoplastic deformation behaviour was observed as for the creep rate, recall Fig. 2. The time dependent stress relaxation after the initial stress relaxation was however not found to be logarithmic but instead had a power-law function of time ($t^{1.16}$).

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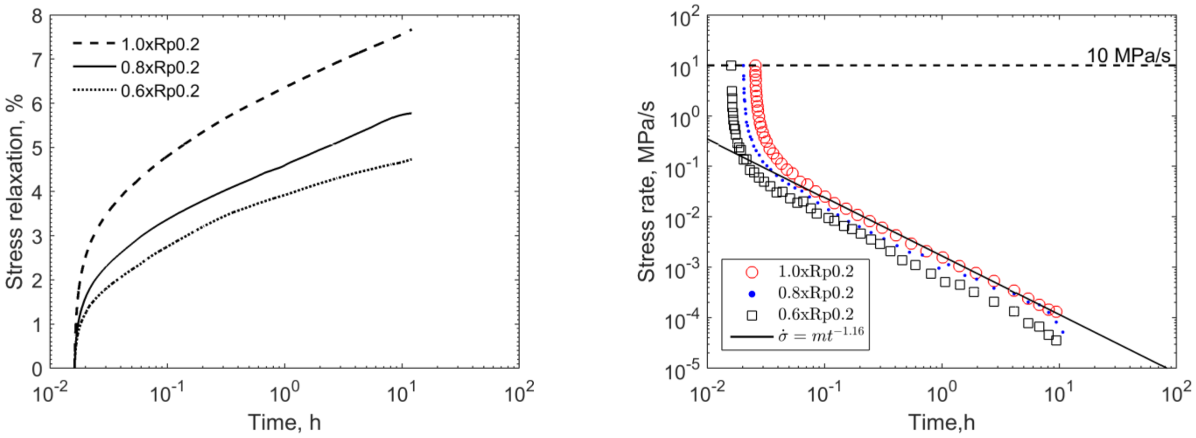

(a) 12 hours stress relaxation results

(b) The stress relaxation rate

Fig. 3 Stress relaxation of austenitic stainless steel cold drawn bar (EN 1.4436)

4 Relaxation Behaviour of Preloaded Stainless Steel Bolted Assemblies

4.1 Experimental investigations

Within the project, austenitic, ferritic, duplex and lean duplex stainless steel components and austenitic stainless steel bolting assemblies with M16 and M20 bolts according to EN ISO 4017 [6] were used for experimental testing of the loss of preload of stainless steel bolted connections. The test matrix and the test results are summarized in Table 1.

The investigations have been carried out at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen.

All stainless steel plates were used in the as delivered 1D surface condition without any other surface treatment. The relaxation tests presented within this contribution were performed by eleven different series of bolted assemblies in the short clamping length range of $\sum t/d = 3.7$ in order to take account of the fact that shorter clamping lengths lead to greater preload losses. Furthermore, the influence on the loss of preload in bolted connections with more than one bolt has been investigated. For this reason, two specimen configurations were developed: (1) one-bolt-specimen (75 mm × 75 mm plates) and (2) eight-bolt-specimen (150 mm × 150 mm plates), see Fig. 4. For comparison reasons, one test series was performed with carbon steel HV bolts according to EN 14399-4 [7] in combination with carbon steel plates for the one-bolt-specimen configuration. All carbon steel plates were shot blasted to clean the surfaces from rust.

The bolts used were A4 austenitic stainless steel M16 Bumax 109 and Bumax 88 as well as M20 Bumax 88 bolts acc. to EN ISO 4017. All stainless steel bolts were supplied by BUAMX AB, which produces stainless steel bolts of these property classes deviating to EN ISO 3506-1. Herein, Bumax 88 and 109 relates to property classes 8.8 and 10.9 according to EN ISO 898-1 [8] comparable to those of carbon steel bolts, see [3].

In a first step, two different methods were selected to measure the preload in the bolting assemblies: (1) instrumented bolts (SG) and (2) load cells (LC), see Fig. 5. It could be shown that the accuracy of the instrumented bolts with implanted strain gauges for measuring the preload inside the bolts is in principle acceptable, see also[9] and [10], but it has also to be pointed out that viscoplasticity occurs already during the preloading process of the stainless steel which means that these changes in the strain were measured by the strain gauges as well. This yielded to deviating values in comparison to the real preload level. This phenomenon is not usually observed in carbon steel bolts due to the dynamic strain aging that occurs at room temperature [11].

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Table 1 Text matrix for the relaxation tests of bolted assemblies made of carbon and stainless steel

	Specimen ID 1)	Number of tests	Σt 2) [mm]	Σt/d [-]	Bolt material	Clamped plates: Type of material	Clamped plates: Thickness [mm]	Surface condition	Loss of preload: measured after days - min / max [%]	Loss of preload: after 50 years (extrapolated) min / max [%]
Carbon steel	HV-bolts - M20 × 75									
	CS	2	48	2.4	HV-bolt Class 3) 10.9	Carbon steel	20	Shot blasted	68 – 5.2 / 8.1	7.8 / 10.5
Stainless steel	Bumax 88 - M20 × 100									
	SS01	12				Austenitic EN 1.4404			14 – 3.7 / 6.0	6.0 / 8.7
	SS02	12	75	3.75	Bumax 88	Ferritic EN 1.4003	16	1D	14 – 3.4 / 4.7	5.3 / 7.5
	SS03	8				Duplex EN 1.4462			55 – 3.9 / 5.0	5.4 / 7.2
	SS04	3				Lean Duplex EN 1.4162			14 – 4.0 / 4.5	6.4 / 7.1
	Bumax 88 – M16 × 100									
	SS21	12				Austenitic EN 1.4404			14 – 3.9 / 5.5	6.1 / 8.5
	SS22	12			Bumax 88	Ferritic EN 1.4003			14 – 3.5 / 5.0	5.6 / 7.7
	SS23	12				Duplex EN 1.4462			14 – 3.9 / 5.8	6.1 / 8.7
	SS24	3	59	3.70		Lean Duplex EN 1.4162	8	1D	14 – 4.9 / 5.5	7.3 / 8.5
	SS26	2				Austenitic EN 1.4404			14 – 5.7 / 6.6	9.2 / 10.3
	SS27	2			Bumax 109	Ferritic EN 1.4003			14 – 4.2 / 4.9	6.2 / 7.4
	SS28	12				Duplex EN 1.4462			55 – 4.2 / 5.6	6.4 / 8.6

1) all bolts were preloaded to the $F_{p,C}$ level | 2) clamping length | 3) property class

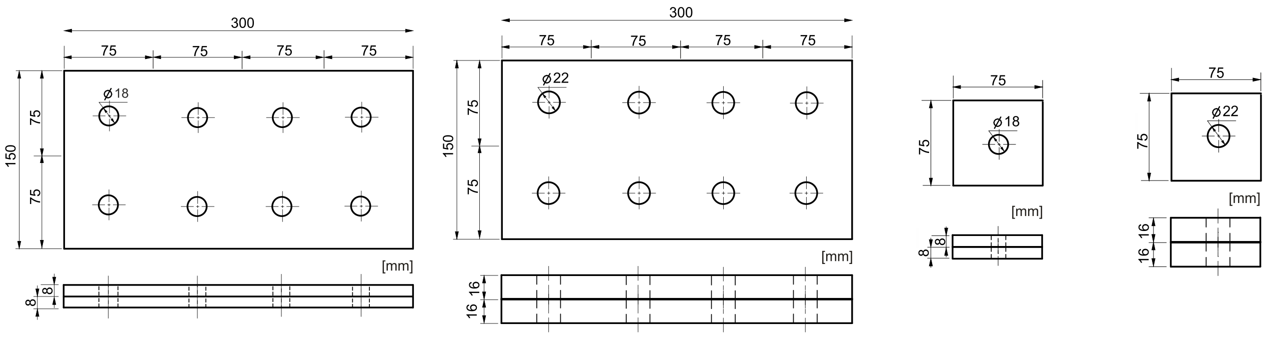

Fig. 4 The test specimen geometry for relaxation test (test specimens for M16 and M20 bolts)

For this reason, it was decided to prepare small load cells for stainless steel bolts and instrument additional carbon steel M20 HV bolts with strain gauges for the measurement of the preload. The advantage of using load cells for stainless steel bolts is that viscoplastic deformation has no influence any more on the measured preload level. All load cells were prepared and calibrated under stepwise tensile loading. The calibration procedure confirmed the expected robustness and accuracy of the instruments with an error < 1% of the full scale used in combination with M16 and M20 bolts.

(a) eight-bolt-specimen (150 mm × 150 mm plates) (b) one-bolt-specimen (75 mm × 75 mm plates)

Fig. 5 Production phases of load cells and test setup of relaxation test

For all tests, the same preload level of $F_{p,C} = 0.7\, f_{ub}\, A_s$ acc. to EN 1090-2 (with f_{ub}: tensile strength of the bolt and A_s: tensile stress area of the bolt) was considered to compare the influence of different types of stainless steel and bolt sizes. Herewith, the preload level for M16 Bumax 109 and Bumax 88 yielded to about 110 kN and 88 kN respectively. Both M20 Bumax 88 and HV-bolts were preloaded to 137 and 172 kN respectively.

The resulting preload losses of the bolting assemblies after testing were extrapolated to 50 years, see Table 1. In order to have a rational evaluation of the measurements, the first three seconds of the measurements were not taken into account. After tightening of the bolts, a considerable drop in the measured preload curve between the maximum peak and the first seconds after the tightening can be observed. This instance drop is not entirely related to relaxation behaviour of the bolted assemblies. However, this phenomenon is explained by turning back of the nut and elastic recovery of the bolt threads when the wrench is removed; it is the so called overshoot effect. For this reason, this overshoot has to be extracted. By removing the first three seconds and by considering the linear behaviour of the loss of preload in logarithmic scale, it is possible to derive the exact starting point of the relaxation test. Fig. 6 shows exemplary the preload losses-log (time) diagrams for SS28 test series.

4.2 Results and discussion

The results show that the highest loss of preload was observed for M16 Bumax 109 austenitic bolted assemblies by about 10 %. It can also be seen from Table 1 that the amount of loss of preload between M16 and M20 stainless steel bolting assemblies with same clamping length ratio for different type of stainless steel are comparable.

For the austenitic stainless steel bolted assemblies (austenitic bolts and plates), the maximum preload losses were approximately 10 % for Bumax 109 and for Bumax 88 approximately 7 %. However, this phenomenon cannot be seen for the combination of austenitic bolts and ferritic/duplex plates for which preload losses result of maximum 8 % for ferritic and maximum 9 % for duplex stainless steel plates independent from the preload level of the bolts. The reason for this may be the following. The stress in the plates due to the preload was estimated by means of a simple axisymmetric finite element model. The bolt was modelled as an elastic body. The plate material was elastic-plastic with isotropic hardening. The maximum though-thickness stress levels were $0.71 \times R_{p0.2}$ for the austenitic plates,

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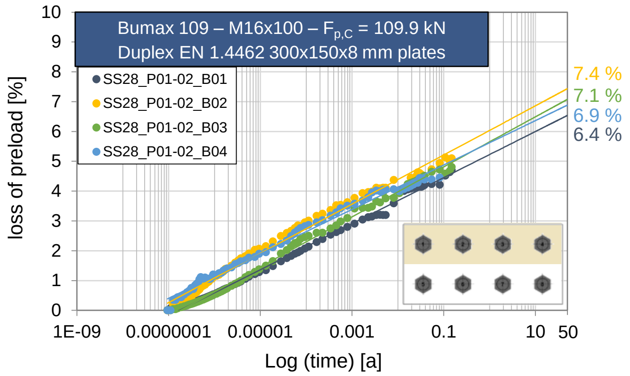
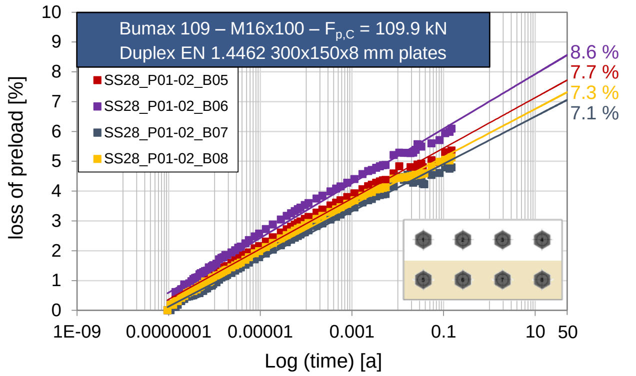
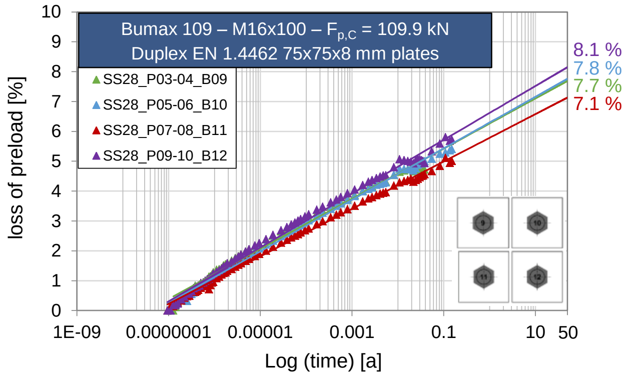
$0.66{\times}R_{p0.2}$ for the ferritic plates, $0.49{\times}R_{p0.2}$ for the lean duplex plates and $0.40{\times}R_{p0.2}$ for the duplex plates. As seen in Fig. 1 the amount of inelastic strain in the ferritic grade was roughly 8 times higher at $0.65{\times}R_{p0.2}$ compare to $0.50{\times}R_{p0.2}$ for the lean duplex grade. The austenitic grade was approximately 30 times higher at $0.71{\times}R_{p0.2}$ (mean of the 0.65 and $0.83{\times}R_{p0.2}$ case) compare to the lean duplex grade at $0.50{\times}R_{p0.2}$.



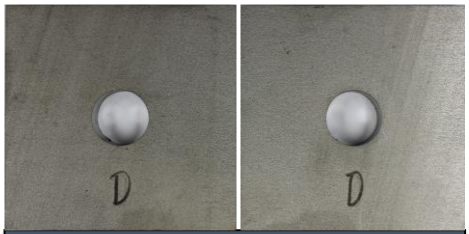
(a) preload losses-log (time) diagrams for eight-bolts specimens – first raw



(b) preload losses-log (time) diagrams for eight bolts specimens – second raw



(c) preload losses-log (time) diagrams for four one-bolts specimens



Loss of preload min / max [%]	
measured after 55 days	after 50 years (extrapolated)
4.2 / 5.6	6.4 / 8.6

(d) loss of preload 55 days / 50 years

Fig. 6 Preload losses exemplary for Bumax 109 – M16 bolts and Duplex EN 1.4462 plates

One may therefore assume that the creep in the plates in the two types of Bumax 88 connections was not significant in regard to the loss of preload. Therefore it seems that one cannot directly relate uniaxial creep to the creep in plates in preloaded bolted connections.

The austenitic grade had the lowest proof stress (and consequently the highest stress level) and also the highest susceptibility to creep at stress levels below $1.00{\times}R_{p0.2}$. The increased loss of preload in the austenitic Bumax 109 connection may therefore been attributed to increased creep in the plates due to the higher preload. For the ferritic and duplex connections that increase in stress in the plates did not result in any observable loss of preload.

Short term measurements of the loss of preload of the austenitic plates with different plate surfaces shows 40 % reduction in extrapolated loss of preload when using grit blasted surface instead of the as delivered 1D surface [12]. The conclusion drawn then was that the loss of preload in the preloaded connections in this work (1D surface) was mainly attributed to the setting effects and the stress relaxation in the bolts while the gross creep in the plates was negligible.

The present relaxation experiments show that the loss of preload in preloaded carbon steel bolting assemblies and preloaded stainless steel bolting assemblies are comparable, see Table 1, as the preload loss for the carbon steel bolting assembly yield to approximately the same value of maximum 10.5 % as the maximum value achieved over all stainless steel test samples.

5 Summary

The loss of preload in stainless steel bolting assemblies has been investigated in the form as isolated elements (uniaxial tensile creep testing of plates and uniaxial stress relaxation of cold drawn bars) and as instrumented stainless steel preloaded bolted connections.

The result from the creep testing shows observable room temperature creep at stress levels larger than $0.50{\times}R_{p0.2}$. The creep rate could, except from the initial creep rate, be described by logarithmic creep. The logarithmic creep rate was dependent on the initial stress level but not on the initial loading rate.

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However, the results from the measured loss of preload in instrumented bolting connections indicated that the loss of preload was mainly due to the initial setting effects and stress relaxation of the bolts. The loss of preload due to creep in the plates seems to be negligible for the preloads used in this study. For the preloaded stainless steel connections, the loss of preload was similar to the loss of preload in preloaded carbon steel connection. Thus, the high concern about the loss of preload due to relaxation and creep seems to be unreasonable and preloaded bolted stainless steel connections can be treated similar to those made of carbon steel. Further investigations are currently in progress to precisely investigate the relaxation behaviour of bolting assemblies made of stainless steel.

Acknowledgements

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