



# Short- and long- term loss of preloading in slotted bolted connections

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## ABSTRACT

One recent solution to reduce the building repairing costs, in case of exceptional or destructive seismic events, is represented by the Sliding Hinge Joint (SHJ), initially proposed by the research group of the University of Auckland in 2005. This connection typology, using slotted bolted connections in beam-to-column joints of Moment Resisting Steel Frames (MRFs), ensures a large energy dissipation capacity with negligible damage. The slip resistance of the SHJ is usually provided by Asymmetrical or Symmetrical Friction Connections (AFCs or SFCs), whose response depends on the friction coefficient of the shims and on the bolt preloading. Since the bolt forces directly affect the resistance, the control of preloading during the life-time of the connection represents a key issue for the proper functioning of the device.

Within this framework, considering the lack of previous experimental works specifically devoted to the long-term response of SHJs, this paper presents the results of an experimental activity on subassemblies of friction dampers, assessing the loss of preload under service loading conditions, examining the possibility to limit the loss through different conical washer layouts (Belleville disk springs). Short-, mid- and long-term tests have been carried out in a joint experimental program carried out at the Universities of Liege and Salerno. The experimental results have been exploited to calibrate an analytical model able to predict the loss of preload over time, accounting for the influence of the external loads. The adoption of pre-set disk springs, reducing the stiffness of 1/10, shows a substantial reduction of the loss.

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## 1. Introduction

Moment Resisting Steel Frames (MRFs) are widely used in seismic areas due to their ability to accommodate large ductility demands providing a high energy dissipation capacity [1–4]. Currently, the recommendations given in Eurocode 8 [5] entail the formation of dissipative zones at the beam ends or in the joints depending on the calibration of the resistance thresholds of the beams and of the joints components. If the dissipative zones are located in the joints, namely partial-strength connections are used, the plastic resistance of the joint will be reached under severe earthquakes, activating ductile connection elements and leading to permanent damages at their level [2,6]. Even though these damages are not leading to the building collapse or casualties, they are the main source of economic losses, mainly associated with the direct costs for the repairs but also to indirect costs due to the interruption of the building functionality. It is for this reason that the problem related

to the post-events repair is becoming an important aspect to be considered in the design, especially in view of ensuring urban resilience through resilient engineering building systems.

One recent approach is related to the concept of low damage systems, which can dissipate the input energy suffering only negligible damage. Low damage semi-rigid beam-to-column connections have been recently investigated. In particular, slotted bolted connections have proved to be a promising alternative to the traditional connection typologies. Indeed, slotted bolted connections have been primarily investigated by Grigorian et al. [7] and, based on these studies, Sliding Hinge Joints (SHJs) with Asymmetric friction connections (AFCs) located at the bottom beam flange, have been developed by Clifton [8,9] and significant developments have been done in the last years [10]. Based on the same principle, the beam-to-column connection system with the weak-web-split-tee was developed in [11]. After these initial studies, other similar solutions have been proposed in the last years. In [12,13], the friction damper has been realized with angles and a haunch bolted both to the bottom beam flange and to the column. The main benefit of this configuration is the possibility of prefabricating the damper, assuring a better control of the friction material employed and of the correct application of the bolt tightening procedures.

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Moreover, the main difference with the solution proposed by Clifton [8] is the adoption of Symmetrical Friction Connections (SFCs) in place of Asymmetrical Friction Connections (AFCs). For both solutions, the presence of the slab concentrates plasticity at the bottom beam flange level, and, accordingly, the damage is confined in the device leaving the top part of the connection undamaged.

In Fig. 1, a connection with a friction damper located at the bottom beam flange is presented. In this connection, pre-stressed bolts are free to move in slotted holes. Between the haunch and the angles, friction shims, coated with a specific metallic coating [14], are developing the required friction coefficient to activate the dissipation through hysteretic loops. This aspect is important as the friction coefficient, and the bolt preloading are the two main parameters influencing the behaviour of the damper. Thus, assuming that the material chosen is able to assure an adequate friction coefficient [14,15], the monitoring of the preloading over time becomes the key issue to be addressed to guarantee the proper performance of the friction device in service and at ultimate limit state conditions. For these reasons, different techniques for preload monitoring in bolted connections have been developed, such as percussion-based approaches [16–18], procedures that use piezoelectric transducers [19] or more innovative solutions where the transducer is introduced directly in the washer (“smart washer” [20]). These techniques seem to be very promising to monitor the health conditions of bolted connections in real-time.

Preloaded bolts are widely used in connections, especially in seismic applications, where the cyclic action may cause the slip of the connection or the concentration of plasticity [21]. In the specific application of the SHJ, the connection is designed to slip only under severe earthquakes or exceptional events such as the loss of one of the main structural elements. Conversely, for all the other loading conditions, the connection must not slip, assuring a rigid behaviour during the whole life of the structure. This can be assured only by guaranteeing a certain minimum level of preloading. Several works have examined the influence of preloading techniques, relaxation phenomena, coatings creep, vibration, self-loosening showing that preloadable bolts always experience a loss of the initial preload [22–25]. In particular, these works have shown that the loss of preload is significant in the first 12 h after tightening, while a strong influence on the overall loss is also due to the magnitude of the external loads applied to the connections [26]. Additionally, long-term tests typically show that after the end of the initial effects, which are mainly related to the preloading technique, the loss of preload is continuous, obeying to a logarithmic evolution law [23]. In order to limit the effect of the loss of initial preload, in [27]–[30] the use of particular conical washers, called “Belleville”, has been investigated as a possible solution to reduce the loss of initial pretension of asymmetric friction dampers. Conical washers are able to reduce the

stiffness of the bolted assembly compensating some of the long-term effects, such as those related to the loss of the stiffness of the coatings.

Within this framework, this paper presents an experimental work aimed at estimating the loss of preload of bolted assemblies of friction dampers. The experimental work is based on short-, mid- and long-term tests examining possible alternative solutions to reduce the loss of preload. The experimental campaign is related to SFCs, also considering the possibility of applying to the connection an external load. The main results of this activity are hereinafter reported.

## 2. Experimental tests

The loss of initial bolt tension called “loss of preloading” is linked to different phenomena, among which the insufficient initial pretension in the bolts, the self-loosening, relaxation, creep, the use of a non-suitable material and the application of external loads are the most important [31]. Vibrations are another important phenomenon affecting the loss of preload. However, this work, which represents a first step towards a full understanding of the phenomena affecting the loss of initial pretension, the influence of vibrations on the loss evolution is not evaluated. In this paper, in order to characterize the single properties separately, the effect of creep and of the application of external loads are investigated, leaving to further works the study of vibrations over the loss of preload in friction dampers. Specifically, the objective of this paper is to provide a prediction of the bolt force evolution during time considering the effect of creep and of the application of external loads in the connection. To the authors' best knowledge, this correlation is difficult to obtain on a purely theoretical basis. However, a more theoretical contribution concerning the influence of washer details on the loss of preload was already presented in [32]. A schematic representation of the evolution of the bolt preloading over time is represented in Fig. 2, where three phases can be distinguished. Immediately after tightening, the bolt experiences an initial loss which is mainly associated with the installation process. This initial loss occurs just after tightening and increases with the magnitude of the applied preload, especially if the bolt is tightened beyond its yield limit [33]. After installation, a so-called mid-term loss appears; different aspects affect the amount of this loss, such as the temperature variations, problems of installation and influence of external loads. Lastly, a long-term loss occurs continuously during the life-time of the structure and, after a certain time, the loss-rate becomes stable. In order to characterize the response of preloadable bolts applied in friction devices, experimental tests have been conducted at the University of Salerno and at the University of Liège.

In particular, short-term (18 h) and mid-term (30 days) tests have been carried out at the STRENGTH (STRUCTURAL Engineering Testing Hall) laboratory of the University of Salerno. Conversely, long-term tests extended for a period of 5 months have been carried out at the University of Liège. All the tests had the goal of characterizing the different phases of the loss of preload following, as far as possible, the guidelines given by EN 1090-2 [34] for relaxation tests. In particular, in order to characterize the loss-of-preloading, assessing the methodologies to limit such a loss, four typologies of bolted assemblies equipped with different configurations of washers and disk springs have been examined. Additionally, in order to assess both the short-, mid- and long-term loss, for each configuration of the washer, tests extended for different periods of time have been executed. In order to assess the short- and mid-term relaxation, 20 short-term tests (extended up to 18 h) and four mid-term tests (30 days) have been performed. Additionally, for the four different washer configurations, five long-term relaxation tests have been performed monitoring the evolution of the bolt forces over 5 months.

### 2.1. Test layout

The tests have been performed on Symmetrical Friction Connections (SFCs) composed by shims (8 mm) coated with a friction material (the

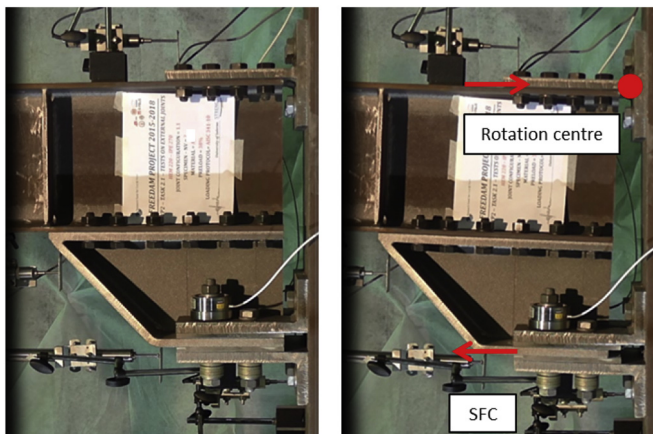


Fig. 1. Sliding Hinge Joint (SHJ) with a Symmetric Friction Connection (SFC).

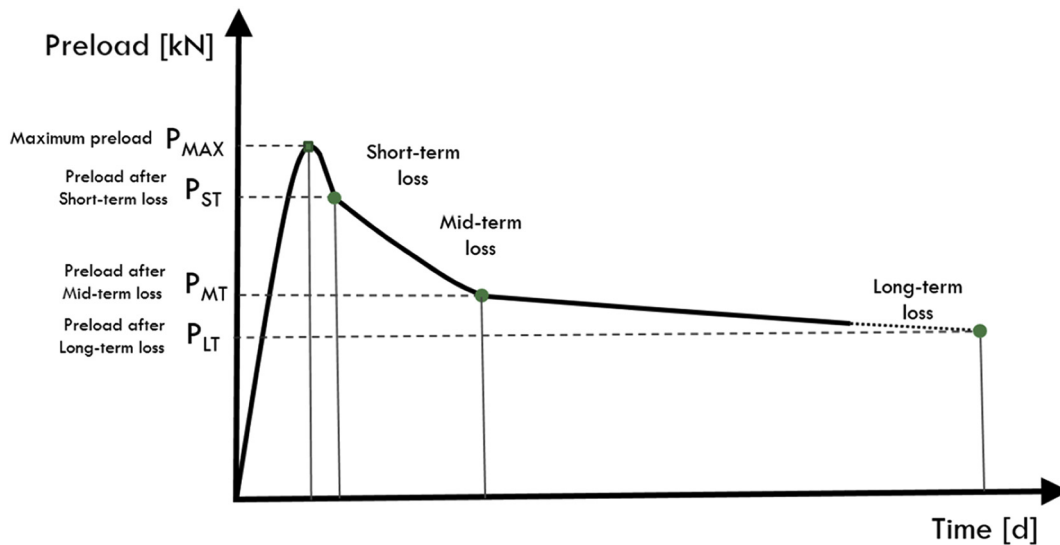


Fig. 2. Evolution of the preload in time:  $P_{ST}$  is the preload after the short-term loss,  $P_{MT}$  is the remaining preload after the mid-term loss and  $P_{LT}$  is the remaining preload after the long-term loss.

material M4 previously tested in [14]), two external hot-dip galvanized plates (15 mm) made of S275JR steel and a slotted internal plate made of AISI 304 stainless steel. The plates were fastened with M20 10.9 HV bolts. All the adopted bolts and their corresponding dimensions are reported in [35] (Table 2). The length of the bolts was properly selected according to the required clamping length. The tightening torque was applied using a calibrated torque wrench following the indications given in [34,36] for the torque method. The two-step procedure was applied for all the tested bolts, assuring a sufficient accuracy on the achievement of the minimum required preload. In particular, a hand torque wrench has been used applying in a first step the 75% of the target preloading and in a second step 110% of the preload, where the 1.1 coefficient covers randomness [30]. For M20 10.9 bolts according to the Eurocodes, the maximum preload is equal to  $F_{P,Cmax} = 171,5$  kN, however, in the specific case, the target preloading for the device was fixed equal to  $F_{P,C} = 120$  kN, since previous tests on SFCs have shown the beneficial effect provided by the reduction of the bolt stress to a working range limited to about the 30–70% of the proof preload [37]. For all the tests, the bolts were equipped with force measuring devices. In the short- and mid-term tests the evolution of the preload in the bolts was detected using a donut load cell (FUTEK LYH500 maximum capacity 222.4 kN). The calibration of the donut load cell is provided by the producer. However, the accuracy of the measurement is verified annually using a reference cell. For the long-term tests, strain gauges embedded in the bolt shank were used [29]; the two layouts are given in Fig. 3a-b. The tests performed at the University of Liège were placed in a temperature-controlled room with a constant temperature of 20 °C. Also, the tests at the University of Salerno were performed at an average temperature of 20 °C with a maximum excursion of  $\pm 3$  °C. The dimensions of bolt, nut and washer and the relative Standards are given in Fig. 3c.

## 2.2. Belleville washers

In order to maintain constant the required preload in the bolts, Belleville washers having the shape of a conical disks (Fig. 4a-b) can be employed. To assess the effectiveness of these springs on the loss-of-preload, two different types of conical-shaped disk springs have been examined in this work: the standardized European disk springs for M20 bolts (DS DIN 6796 [38]- Fig. 4b), and a customized type of Belleville washer (Big Washer, BW-Fig. 4a). The customized disk springs are pre-set in the shop. This means that they are fully flattened in the factory in order to harden the material, assuring a perfectly elastic force-displacement behavior. Conversely, the European typology of

standardized disk spring is typically produced without pre-setting. Therefore, it has been tested alternatively in the “as delivered” condition (not pre-set) and pre-setting it in the laboratory with a universal testing machine.

The main feature of the Belleville washers is their ability to reduce the loss of preload in bolted assemblies. Belleville springs are selected according to their flattening load, namely, the force needed to flatten the washer [39] completely. Compression tests on customized disk springs (BW) and on disk springs complying to DIN 6796 (DS) have been executed at the University of Liège (Fig. 4a-b). The latter tests evidence that the behaviour of the springs is linear until reaching the flattening load. Afterwards, a significant increase of the stiffness is evidenced. The customized springs carry a force equal to about 120 kN. Conversely, the European disk springs complying with DIN6796 have a flattening load of about 70 kN.

According to Davet [39], Belleville springs can reduce the loss of preload. In order to better understand how the spring influences the preload, the so-called “bolt diagram”, represented in Fig. 5a, can be used. This graph is the result of the union of two diagrams which represent: (i) the extension of the bolt and (ii) the compression of the joint (plates and washers). When a bolt is preloaded, the preloading force provides two effects: a bolt shank elongation, and a joint compression. The two cases examined in this paper are depicted in Fig. 5b and the relative bolt diagrams are given in Fig. 5c (flat washers) and 2.4d (Belleville washers). Belleville springs placed between the nut and the plates decrease the stiffness of the joint thus the total preloading loss [39]. When an external load is applied to the bolt (Fig. 5b), the bolt load increases and the clamping force in the joint decreases. In case c) the joint compression is smaller than the bolt elongation because the bolt is more elastic than the joint and, as a consequence, any externally applied load consistently reduces the clamp load of the plates [39]. When a Belleville washer is placed in a joint assembly, the joint will be more deformable than the bolt (case d). Thus, any externally applied load will result in a smaller change of the clamp load. As a consequence of this force repartition, a stiffer joint (Fig. 5c) loses much more preload than a deformable one (Fig. 5d).

As aforesaid, four different configurations of washers have been tested within the present study. The following layouts described in Fig. 7 have been tested: i) a configuration with flat washer (FW) complying with EN14399-6 [40]; ii) a configuration with a couple of pre-set customized Belleville Washers (BW) installed both under the bolt head and under the nut; iii) a stacking of 3 disk springs (3DS) in parallel complying with DIN6796; iv) a stacking of 3 disk springs in parallel

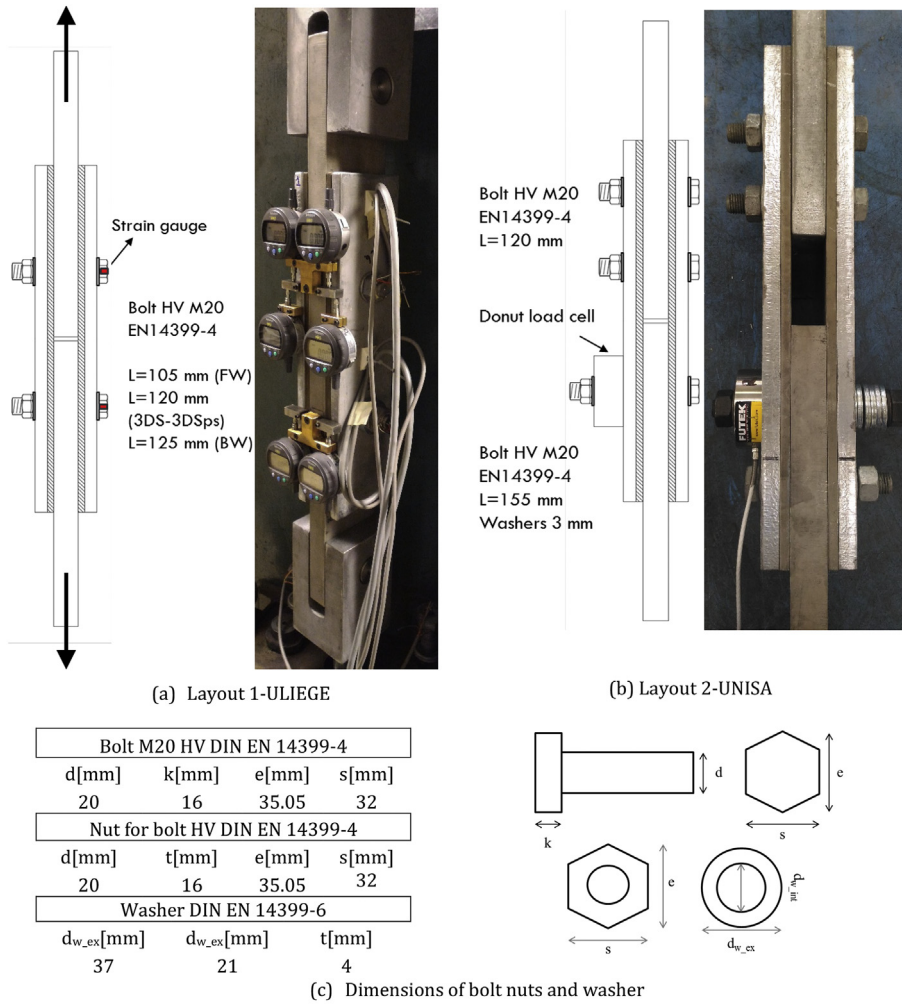


Fig. 3. Test layout in (a) Liège with bolt length for each washer configuration presented in the following and (b) Salerno; (c) bolt, nut and washer dimensions.

complying with DIN6796, pre-set in the laboratory by means of a Schenck Hydropuls universal machine (3DSps).

The load-carrying capacity of a single DIN6796, M20, not pre-set Belleville spring (DS), is around 70 kN. Thus, parallel stacking is needed to increase the loading capacity of the washers. In the tested configurations, 3 springs in parallel have been used (as indicated in the code of the configuration 3DS) to have a safety margin when compared to the nominal preload, which is equal to 120kN. Conversely, the pre-set Belleville washers (BW) have a load-carrying capacity of 163 kN. Therefore, only one washer under the head and one under the nut have been adopted.

The stiffness of the considered configurations (Fig. 7) has been calculated according to the Agerskov formulation [41], which accounts for the different contribution of the threaded and unthreaded part of the bolt shank to determine the stiffness of the bolt ( $k_b$ ), as reported in Eq. 2-1. Fig. 6

$$k_b = \left( \frac{k_1 + 2k_2}{2EA_s} \right)^{-1} \quad (2-1)$$

where:

$$k_1 = l_s + 1.43l_t + 0.71l_n$$

$$k_2 = 0.1l_n + 0.4l_w$$

$A_s$  is Nominal cross-section of the bolt.

$E$  is the Young modulus of the steel.

The Belleville washer can be considered as an additional spring ( $k_w$ ) to be added in series to the bolt with a stiffness given by:

$$k_w = \frac{Et_w^2}{0.65r^2} \quad (2-2)$$

Where the value of  $r$  and the geometry of the disk spring are indicated in Fig. 6. Therefore, the deformability of the assembly (Bolt + Belleville spring,  $k_{bw}$ ) can be calculated as follow:

$$k_{bw} = \left( \frac{k_1 + 2k_2}{2EA_s} + \frac{1}{k_w} \right)^{-1} \quad (2-3)$$

The stiffness of the four configurations studied in this work is given in Fig. 7. It is worth emphasizing that the stiffer the assembly, the higher is the expected loss of preload and the use of Belleville pre-set springs (BW) reduced of almost 1/10 the stiffness of the assembly when compared with normal washer (FW).

### 3. Experimental results

Three experimental test campaigns to investigate the short- mid- and long-term tests are presented in this chapter. All the performed tests have been named with acronym strings as "ST-FW-TEST #"; where the first two letters indicate the type of test, ST = Short-Term, MT = Mid-term, and LT = Long-term; a second couple of

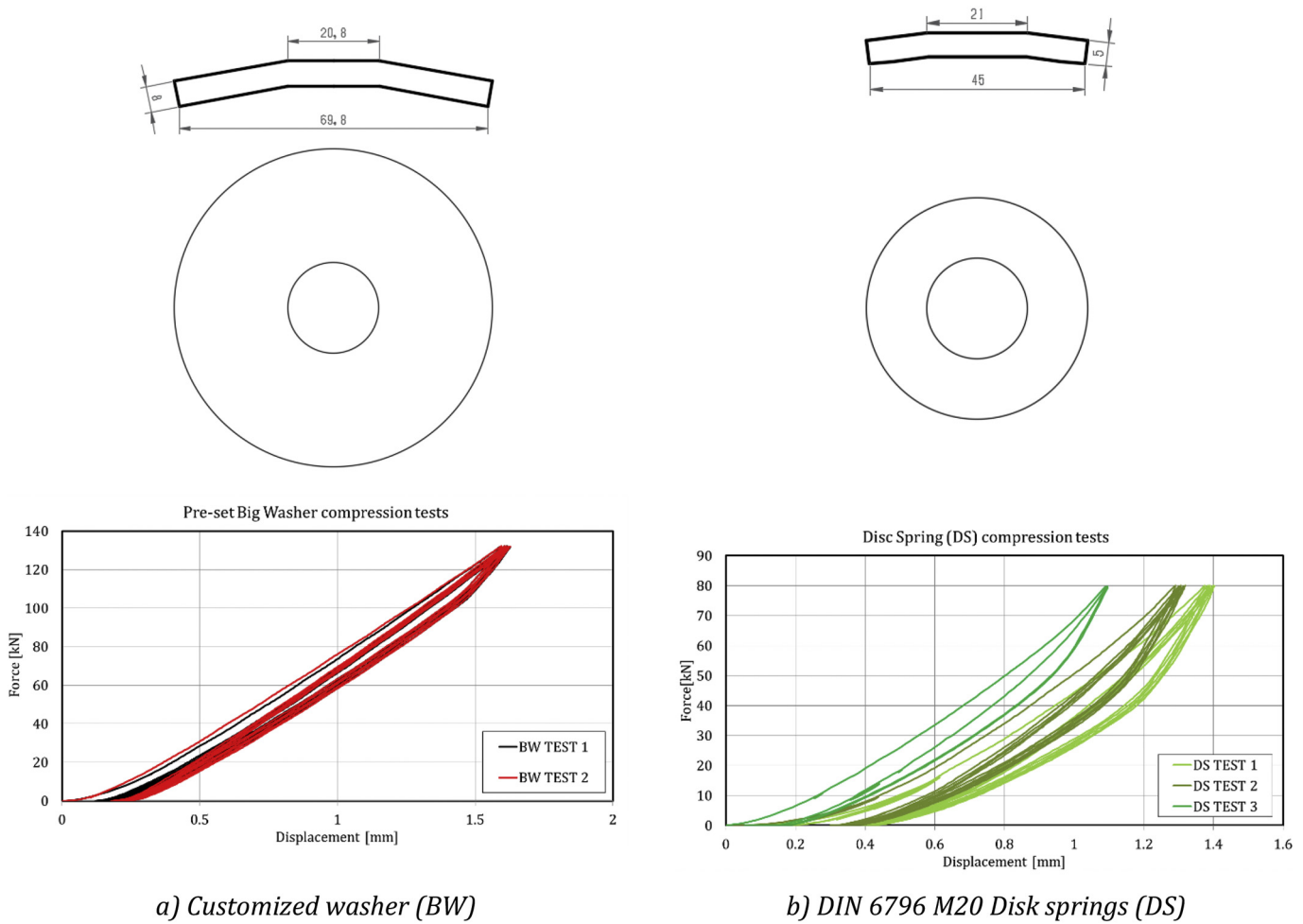


Fig. 4. Tested configurations and labelling: a) BW- Big Washer (dimension in mm); b) DIN 6796 Disk Springs (DS)-(dimensions in mm).

letters individuates the bolt configurations, FW = Flat Washer, BW = Big Washer, 3DS = 3 Disk Springs and 3DSps = 3 Disk Springs Pre-Set and the last number indicates the test number (1, 2, 3...). The same string has been used for the test with the applied external load adding the string EXLOAD (EXternal LOAD) after the bolt configuration. For example, the label "ST-BW-EXLOAD-TEST1" indicates the Short-term (ST) Test 1 (TEST1) on the Big Washer configuration (BW) with an externally applied load (EXLOAD). The external load is determined according to EN1090-2 for extended creep tests, where it is stated that the specimens have to be loaded with "a specific load equal to the 90% of the mean slip load" (90% of  $F_{slip}$  in Eq. 3-1):

$$F_{s,Rd} = 0.9 F_{slip}$$

$$F_{slip} = n_b n_s \mu_m F_p \quad (3-1)$$

$n_b$  is the number of bolts - equal to 1 for the tested specimens;  $n_s$  is the number of slip surfaces - equal to 2 for the tested specimens;  $\mu_m$  is the mean value of the slip factor for the given material;  $F_p$  is the bolt preload.

This load is the same in all the tests, and it is equal to 120 kN.

### 3.1. Short-term loss of preloading without load (ST tests)

In order to assess the short-term relaxation in the proposed bolted connection, 20 tests (extended up to 18 h) have been performed on Layout 2 (Fig. 3). For each configuration, five tests have

been performed. The examined configurations of washers are the following: a) the EN14399-6 standard washers without disk springs; b) customized disk spring (BS); c) DIN 6796 washers without pre-setting (3DS); d) DIN 6796 washers with pre-setting (3DSps) and (Fig. 8).

Four of the five tests have been executed without external loads in the connection (ST-##-TEST#), and the fifth has been executed applying an external load equal to 120 kN (ST-##-EXLOAD-TEST#) to the elementary friction damper. This to estimate, separately, the influence of the external tensile load over the loss of preload. All the test results are summarized in Fig. 9a-d.

When a tensile load is applied to the damper (ST-##-EXLOAD-TEST#), an instantaneous loss of preload occurs. This is due to the settlement of the coatings between the bolt head and nut and of the bolt threads. Mostly, the externally applied load results in a concentrated loss at the end of the loading process. All the tests, in fact, show a shifting of the loss-time curves proportional to the applied load. In Tables 1 to 4, the loss of preloading occurring in the bolted assemblies is reported in terms of statistical parameters (mean value 5% and 95% fractiles) for time steps 1 h, 6 h, 12 h and 18 h. The loss is estimated as a percentage of the initial peak value (120kN). Additionally, the expected loss in 50 years is calculated at each time step with a logarithmic extrapolation of the data up to that time step, according to the procedure given in EN 1090-2. The last two columns of each table report the loss of preload and the 50 years loss estimation for the test with an applied tensile load; in this case, due to the limited sample tested, statistical evaluation was not possible.

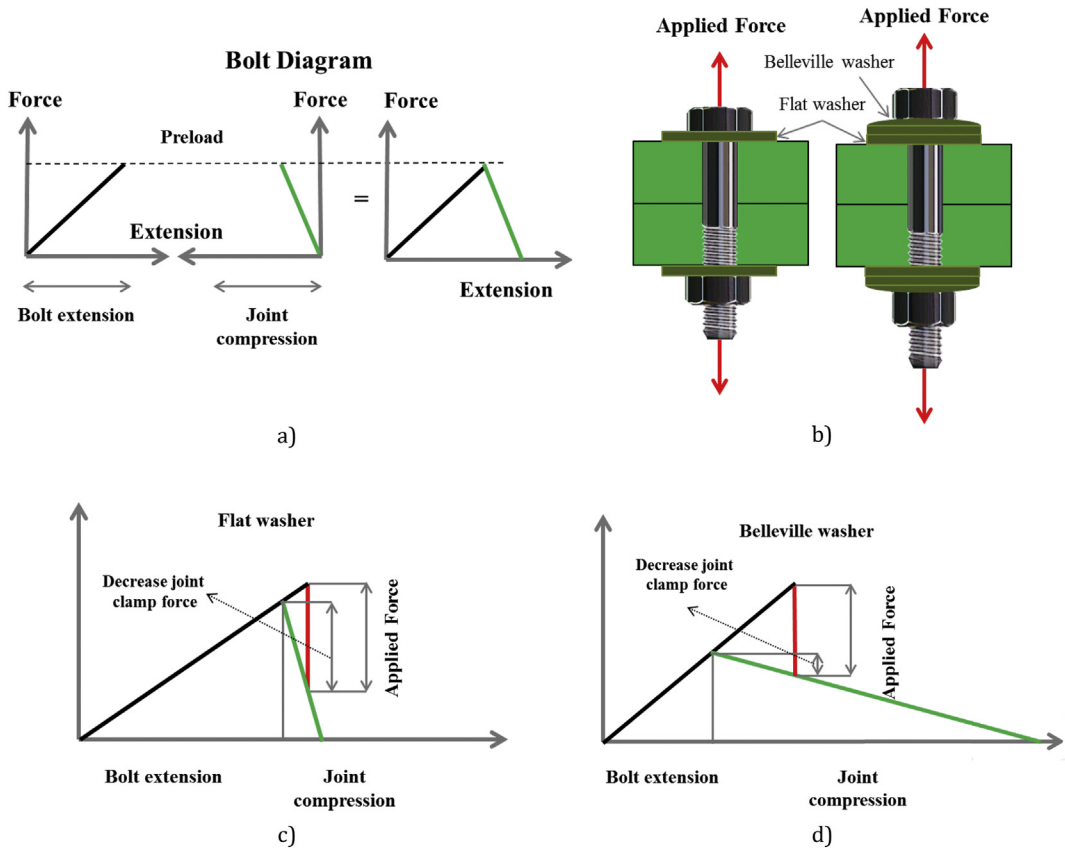


Fig. 5. Bolt diagram: a) Joint stiffer than the bolt (without Belleville spring); b) Deformable assembly (with Belleville spring).

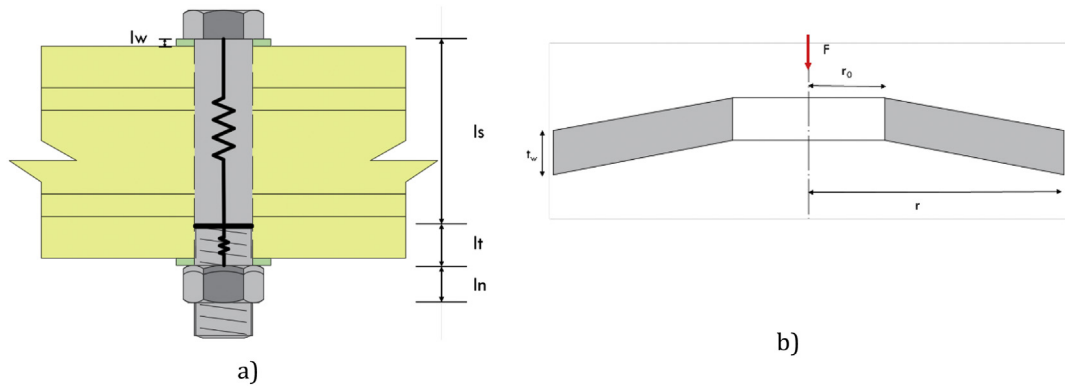


Fig. 6. a) spring model of the Bolt; b) Geometry of the Belleville washers.

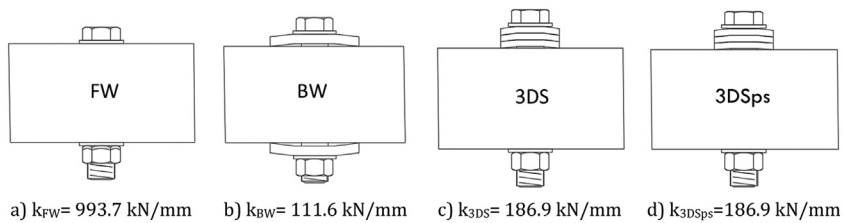


Fig. 7. Tested configurations and nomenclature: FW-Flat Washer; BW- Big Washer; 3DS- stuck of 3 Disk Spring; 3FDS- Stuck of 3 Flattened Disk Spring.

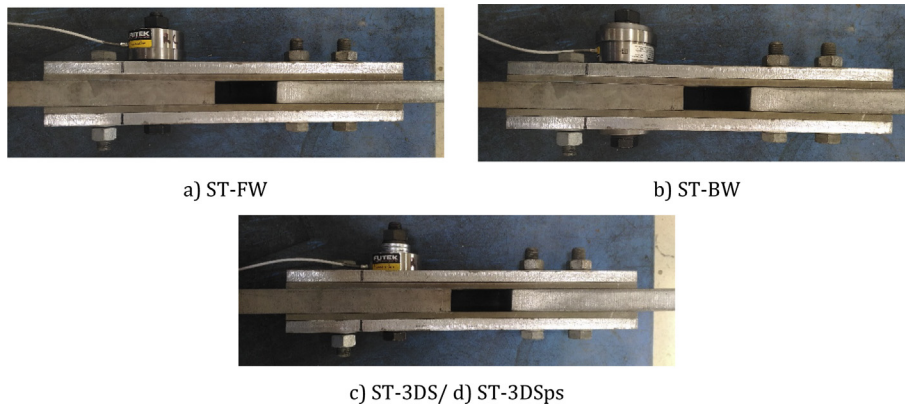


Fig. 8. Tested short-term configurations UNISA layout 2: a) ST-FW-Flat Washer; b) ST-BW- Big Washer; c) ST-3DS /ST-3FDps.

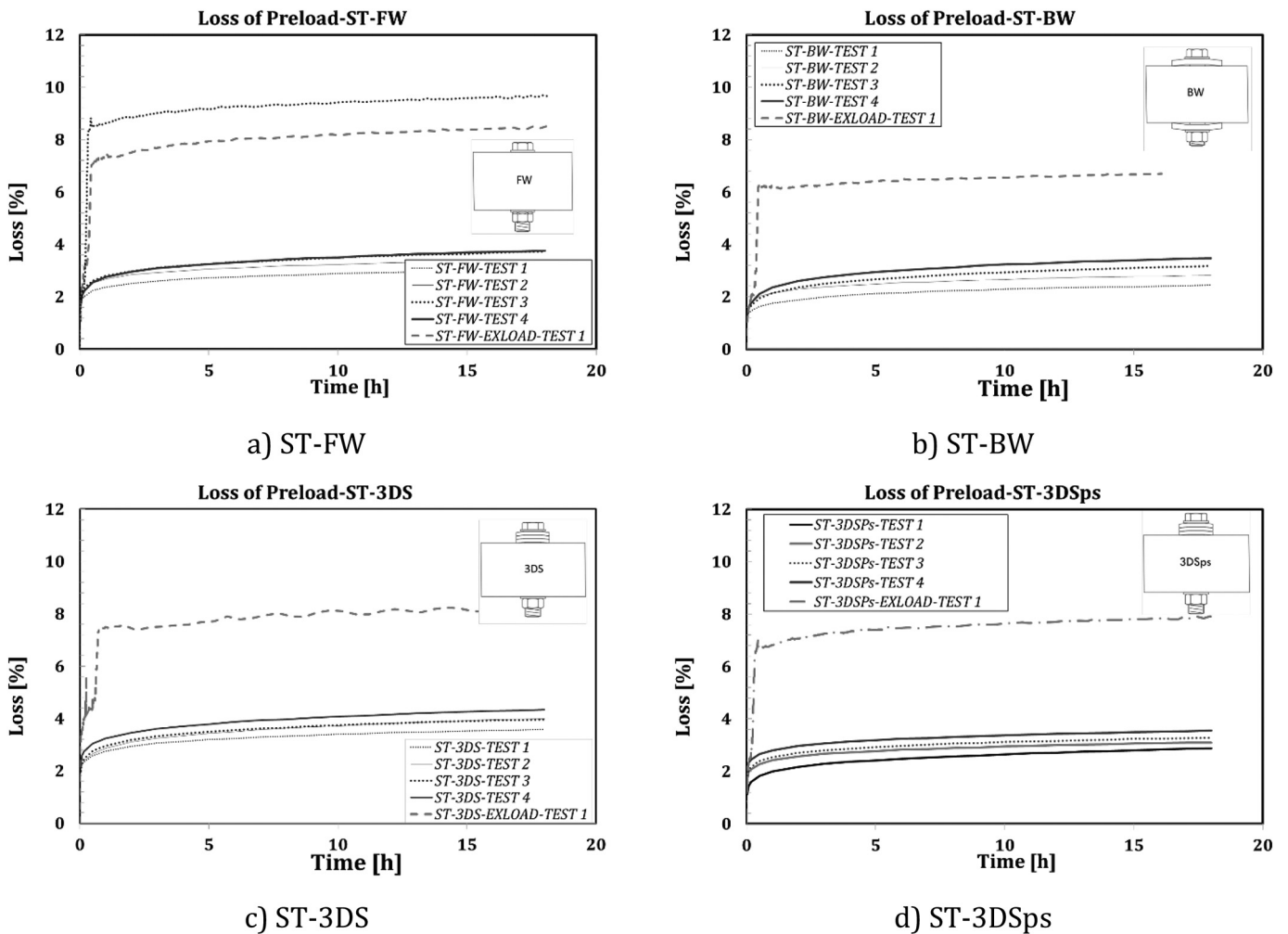


Fig. 9. Tested configurations and nomenclature: FW-Flat Washer; BW- Big Washer; 3DS- Stuck of 3 Disk Spring not pre-set; 3DPS- Stuck of 3 pre-set Disk Spring.

Following the procedure given in Eurocode 0, the methodology adopted to estimate the loss of preload, calculating the 5% and the 95% percentile (respectively  $l_{5\%}$  and  $l_{95\%}$ ) and assuming a normal distribution of the loss (equal to the mean value  $\mu$ ), is described by Eqs. 3-2. Since the number of tests is limited, the methodology suggested by ECO is applied considering that the Coefficient of Variation ( $CV$ ) of the distribution as “unknown” and fixed equal to 10%. All the values in Tables 1 and 4 are calculated assuming the value of  $\gamma$  in Eq. 3-2 equal to 2.63:

$$l_{5\%} [\%] = \mu (1 - \gamma CV)$$

$$l_{95\%} [\%] = \mu (1 + \gamma CV) \tag{3-2}$$

The short-term loss appears to have a similar magnitude for each studied configuration when external loads are not applied to the assembly (3.4% on average). When the external load is considered, the

**Table 1**  
Short-term relaxation configuration FW.

ST-FW TEST 1-4						ST-FW-EXLOAD-TEST1-2				
Time	$\mu$ [%]	$\sigma$ [%]	CV	Fractile 5% [kN]	Fractile 95% [kN]	Loss after 50 years			Loss [%]	Loss in 50 years [%]
						Fractile 5%	$\mu$ [%]	Fractile 95%		
1 h	2.65%	0.17%	6.39%	2.29%	3.01%	5.24%	6.93%	6.90%	8.15%	12.80%
6 h	3.12%	0.15%	4.71%	2.81%	3.44%	5.46%	6.57%	6.68%	8.71%	13.16%
12 h	3.34%	0.26%	7.91%	2.78%	3.91%	5.05%	6.45%	7.10%	8.97%	13.13%
18 h	3.49%	0.29%	8.40%	2.86%	4.11%	4.98%	6.42%	7.16%	9.16%	13.23%

**Table 2**  
Short-term relaxation configuration BW.

ST-BW TEST 1-4						ST-BW-EXLOAD-TEST 1				
Time	$\mu$ [%]	$\sigma$ [%]	CV	Fractile 5% [kN]	Fractile 95% [kN]	Loss in 50 years			Loss [%]	Loss in 50 years [%]
						Fractile 5%	$\mu$ [%]	Fractile 95%		
1 h	2.10%	0.22%	10.35%	1.64%	2.56%	4.28%	5.49%	6.70%	6.17%	6.31%
6 h	2.61%	0.31%	12.06%	1.94%	3.28%	4.08%	5.49%	6.90%	6.48%	7.07%
12 h	2.84%	0.36%	12.55%	2.08%	3.60%	4.02%	5.49%	6.96%	6.60%	9.91%
18 h	2.98%	0.39%	12.96%	2.16%	3.80%	3.97%	5.49%	7.00%	6.76%	9.22%

**Table 3**  
Short-term relaxation configuration 3DS.

ST-3DS TEST 1-4						ST-3DS-EXLOAD-TEST 1				
Time	$\mu$ [%]	$\sigma$ [%]	CV	Fractile 5% [kN]	Fractile 95% [kN]	Loss after 50 years			Loss [%]	Loss in 50 years [%]
						Fractile 5%	$\mu$ [%]	Fractile 95%		
1 h	2.96%	0.18%	6.08%	2.57%	3.34%	6.05%	6.95%	7.85%	7.55%	15.23%
6 h	3.54%	0.22%	6.30%	3.07%	4.02%	6.01%	6.94%	7.88%	7.95%	13.38%
12 h	3.81%	0.24%	6.39%	3.29%	4.33%	6.00%	6.95%	7.89%	8.12%	12.83%
18 h	3.97%	0.27%	6.69%	3.40%	4.54%	5.96%	6.95%	7.94%	8.29%	12.59%

**Table 4**  
Short-term relaxation configuration 3DSps.

ST-3DSps TEST 1-4						ST-3DSps-EXLOAD-TEST 1				
Time	$\mu$ [%]	$\sigma$ [%]	CV	Fractile 5% [kN]	Fractile 95% [kN]	Loss after 50 years			Loss [%]	Loss in 50 years [%]
						Fractile 5%	$\mu$ [%]	Fractile 95%		
1 h	2.44%	0.29%	11.98%	1.82%	3.07%	4.13%	5.55%	6.97%	6.87%	12.28%
6 h	2.88%	0.28%	9.56%	2.30%	3.47%	2.22%	5.52%	6.65%	7.47%	11.16%
12 h	3.07%	0.26%	8.49%	2.52%	3.63%	4.51%	5.51%	6.51%	7.72%	11.18%
18 h	3.20%	0.25%	7.76%	2.67%	3.73%	4.59%	5.50%	6.41%	7.85%	11.21%

configuration FW, 3DS, and 3DSps show a comparable level of loss (9.16%, 8.29%, and 7.85% respectively), while the configuration BW shows a slightly smaller loss 6.76%.

### 3.2. Mid-term loss of preload without load (MT tests)

Following the same approach adopted for the short-term tests and the same layout given in Fig. 8, four mid-term relaxation tests have been performed, monitoring the evolution of the bolt force up to 30 days (720 h). The mid-term tests have the main goal of identifying the loss appearing in the first hours/days after tightening. However, the tests were extended much longer to have an idea about the stabilizing time of the loss. The results given in Fig. 10a-d are always compared with the case in which an external tensile load is applied in the specimen (MT-##-EXLOAD-TEST#).

When the external loads are not considered, only one test per configuration is available. Thus, it is not possible to have a statistic evaluation of the results. In Table 5 results are given for the tests with and

without the external loads. For the assembly with FW, with an externally applied load (Fig. 10a), two tests are available. Hence, the values are referring to the average. Using a regression study gives the expected losses in 50 years based on the 30-days relaxation tests are also reported. The table is reporting both cases, the one with external load (MT-##-EXLOAD-TEST#) and the one without (MT-##-TEST#).

Globally there is not a significant difference between the loss for the assemblies FW, BW, and 3DSps when no external loads are applied. On the contrary, a higher loss appears for the assembly 3DS (9.21%), which is also rather close to the loss experienced when an external load is applied for the same assembly (9.87%). Due to the limited number of tests, it is rather difficult to generalize the mid-term behaviour for this test.

### 3.3. Long-term loss under SLS loads (LT)

The long-term tests on the four configurations of Fig. 7 have been performed at the "Laboratoire de Mécanique des Matériaux et Structures" at the University of Liège on Layout 1 in Fig. 3. The tests were

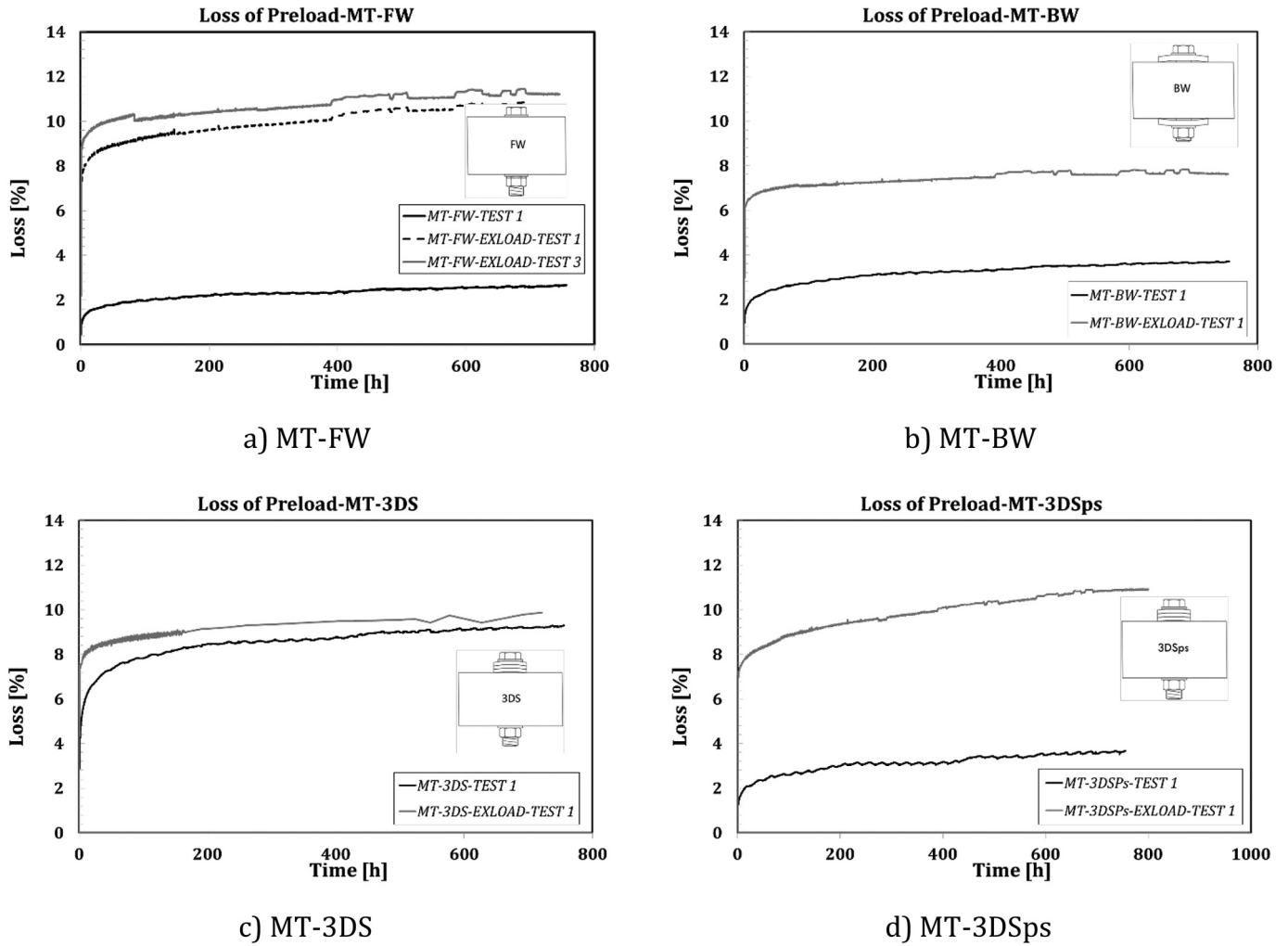


Fig. 10. Medium-term relaxation tests: a) MT-FW flat washer; b) MT-BW Belleville big washer; c) MT-3DS 3 disk springs non pre-set; d) MT-3DSps 3 pre-set disk springs.

Table 5  
Medium-term relaxation tests.

Time	MT-FW		MT-FW-EXLOAD		MT-BW		MT-BW-EXLOAD		MT-3DS		MT-3DS-EXLOAD		MT-3DSps		MT-3DSps-EXLOAD	
	Loss [%]	50y Loss [%]	Loss [%]	50y Loss [%]	Loss [%]	50y Loss [%]	Loss [%]	50y Loss [%]	Loss [%]	50y Loss [%]	Loss [%]	50y Loss [%]	Loss [%]	50y Loss [%]	Loss [%]	50y Loss [%]
1 h	0.89	0.9	8.62	12.54	1.22	4.18	6.17	6.31	3.8	13.99	7.55	16.23	1.17	4.12	6.82	12.28
6 h	1.31	2.77	9.27	12.82	1.76	4.75	6.48	7.07	5.54	15.81	7.95	13.38	1.69	4.68	7.48	11.17
12 h	1.48	3.17	9.49	12.85	1.99	5.00	6.60	9.19	6.17	15.94	8.12	12.84	1.92	4.94	7.73	11.17
18 h	1.56	3.43	9.64	12.93	2.13	5.13	6.76	9.22	6.72	15.94	8.29	12.59	2.08	5.18	7.85	11.22
24 h	1.6	4.18	9.77	13.00	2.2	5.13	6.81	7.75	6.72	15.82	8.41	12.19	2.10	5.18	8.00	11.48
7d	2.15	4.01	10.31	12.93	2.45	5.78	7.21	8.61	8.27	14.84	9.00	11.73	2.44	5.49	9.22	12.44
15d	2.32	4.19	10.70	12.97	3.29	6.06	7.47	9.11	8.65	14.28	9.35	11.78	3.10	5.87	9.90	15.92
30d	2.59	4.35	11.22	13.61	3.67	6.33	7.65	9.08	9.21	13.92	9.87	11.88	3.60	6.12	10.84	15.97

carried out monitoring the loss of preload over a period of five months. The tests have been executed following the protocol for extended creep tests according to EN 1090 [34]. The aim of the codified approach is to individuate the slope of the displacement - log time curve, defining, by extrapolation, the loss occurring in the target time. In the tests presented in this work, the stabilization occurred after about 2–3 months. This result is consistent with the findings of other authors which, on similar details, found that the stabilization occurs usually before 4 months [22,23]. The tests were performed in a temperature-

controlled room with a constant temperature of 20 °C for the whole test duration (Fig. 11a). The objective was to measure the change in strain experienced by the bolts in order to quantify the amount of loss in a long-term period of time accounting for the influence of the service load given in Eq. 3-1. Each bolt was instrumented with a strain gauge placed in the bolt shank (Fig. 11b). These devices can measure the strain gradient with a change in electrical resistance. The changes of strains in the bolt shank are very small, implying the use of a Wheatstone bridge configuration able to catch micro-strain variations. The strain gauges

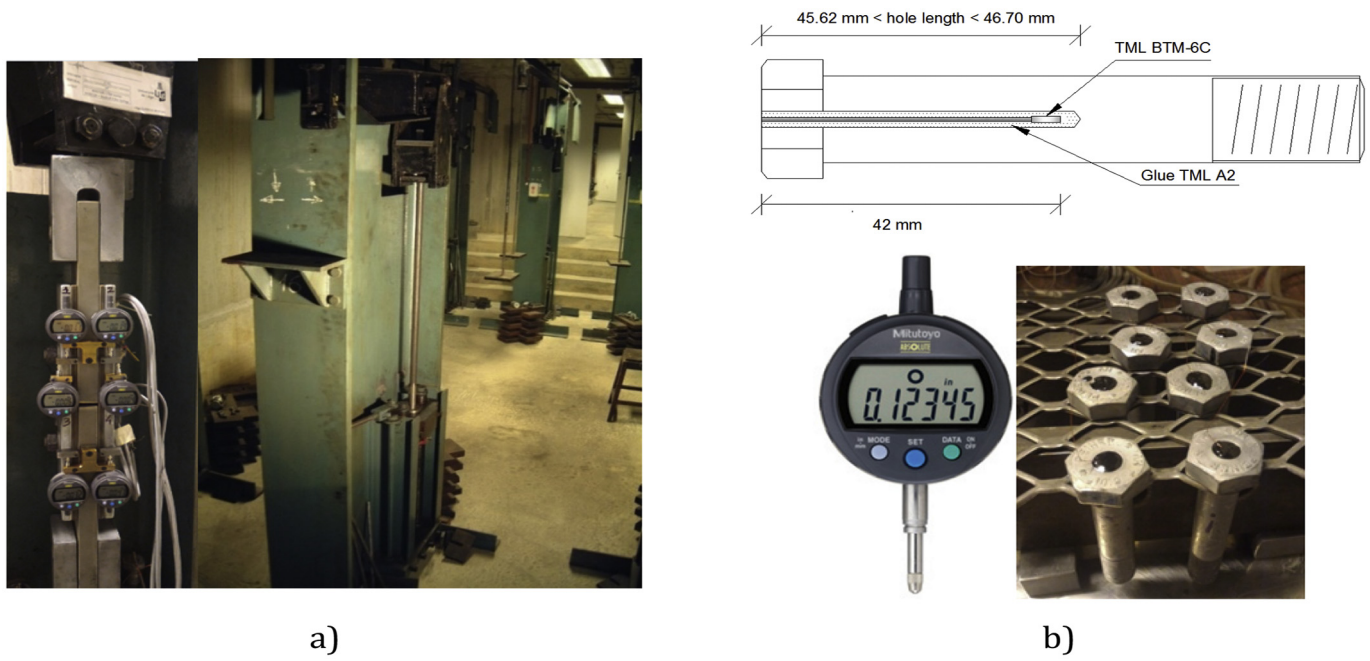


Fig. 11. a) Relaxation test machine; b) Bolt gauges and Digimatic indicator ID-C112X/1012×.

were calibrated testing the instrumented bolts through a tensile test; such a test allows controlling if the strain gauges are well capturing the evolution of the strains while applying a tensile load directly to the bolts. The gauges measurements were recorded continuously for five months before and after the tensile load application. In order to track the displacements of the plate due to creep, six indicators (Digimatic indicator ID-C112X/1012× Fig. 11b) with an accuracy of 0.0025 mm were placed on the specimens. The devices are measuring the relative displacements between the internal plate and the friction pad and the relative displacements between the external plate and the friction pads, which are way below the limitation given in EN1090-2. Six devices were adopted to control both relative and total displacements.

Immediately after tightening of the bolts, the assemblies were placed into the machine (Fig. 11a), and a tensile axial load  $F_{s,Rd}$  (Eq. 3-1) was applied.

The losses of preloading during five months, expressed as a percentage of the initial bolt preloading, are reported in Fig. 12a-d.

Overall, there is not a remarkable difference between the results for the FW, 3DS, and 3DSps, which is confirming the results already discussed for short- and mid-term tests.

The higher bolt loss can be detected for the configuration with Flat Washers C2-C4 (FW-Fig. 12a), which are losing 11.9%–12.3%. This is in line with the expected results since there is no possibility for the standard washer to compensate the loss in the bolt. 3DS assembly is showing a loss of 11.3%, which is still similar to the FW assembly, in this case, the lack of pre-setting of the disc springs makes them less suitable for the current application. However, also the 3DSps configuration shows similar results (11.6% in 5 months); indeed, a similar preloading loss was registered for this configuration. The result obtained for the 3DSps (Belleville DIN6796) indicates that, for this case, the loss of pre-load is not influenced by the pre-setting procedure.

An efficient reduction of the loss of preloading is observed with the BW configuration. In fact, the BW assembly shows a smaller loss of pre-load in 5 months (7.4%). This result is in line with the short-term and mid-term loss presented in the previous paragraphs. However, for this case, the evolution of the loss is slightly different from the other cases. In fact, the slope of the loss (BW-Fig. 12b) is not always positive. This can be the result of relaxation, leading to slow unloading of the washer

which compensates the tension loss in the bolt. This may require the bolt tension to drop until the slide of the big washers' edge over the underneath plate is allowed. More details on the influence of this kind of washer on the preload can be found in [28].

It has to be highlighted that the experimental tests presented, although in a limited number, are confirming and extending the results obtained in previous tests on similar details executed by the same authors [29,30].

#### 4. Analytical model

A simplified analytical model able to predict the loss of preload over time in friction bolted connection has been derived based on the experimental campaign herein presented. The proposed model is a useful tool to ensure an adequate preloading in the friction devices during their life. Moreover, knowing in advance the loss that the connection will experience, it is possible to account for it in the preloading procedure or to program a re-tightening of the bolts during the life of the structure. The model is composed of two parts: the first part is describing the loss of preload not influenced by any externally applied load, which has a linear evolution in a logarithmic scale and needs the calibration of two parameters ( $c_1$  and  $c_2$ ). The second part is a constant which accounts for the loss due to the settlement occurring initially due to the external load applied in the connection. It is based on the calibration of a third parameter ( $c_3$ ). The complete analytical model proposed in this paper is defined by Eq. 4-1:

$$l_t[\%] = c_1 \ln(t) + c_2 + c_3 \frac{F_i}{F_{slip}} \quad (4-1)$$

The parameters of this equation ( $c_1$ ,  $c_2$ ,  $c_3$ ) have been calibrated on the base of the previous experimental data, as described in the following paragraphs. In particular, the coefficients describing the time-dependency of the loss-of-preload ( $c_1$  and  $c_2$ ) have been calculated, starting from regression studies of the mid-term tests. Conversely, the coefficient describing the force-dependency ( $c_3$ ) has been calibrated starting from the results of tests in which external loads have been applied to the connection incrementally.

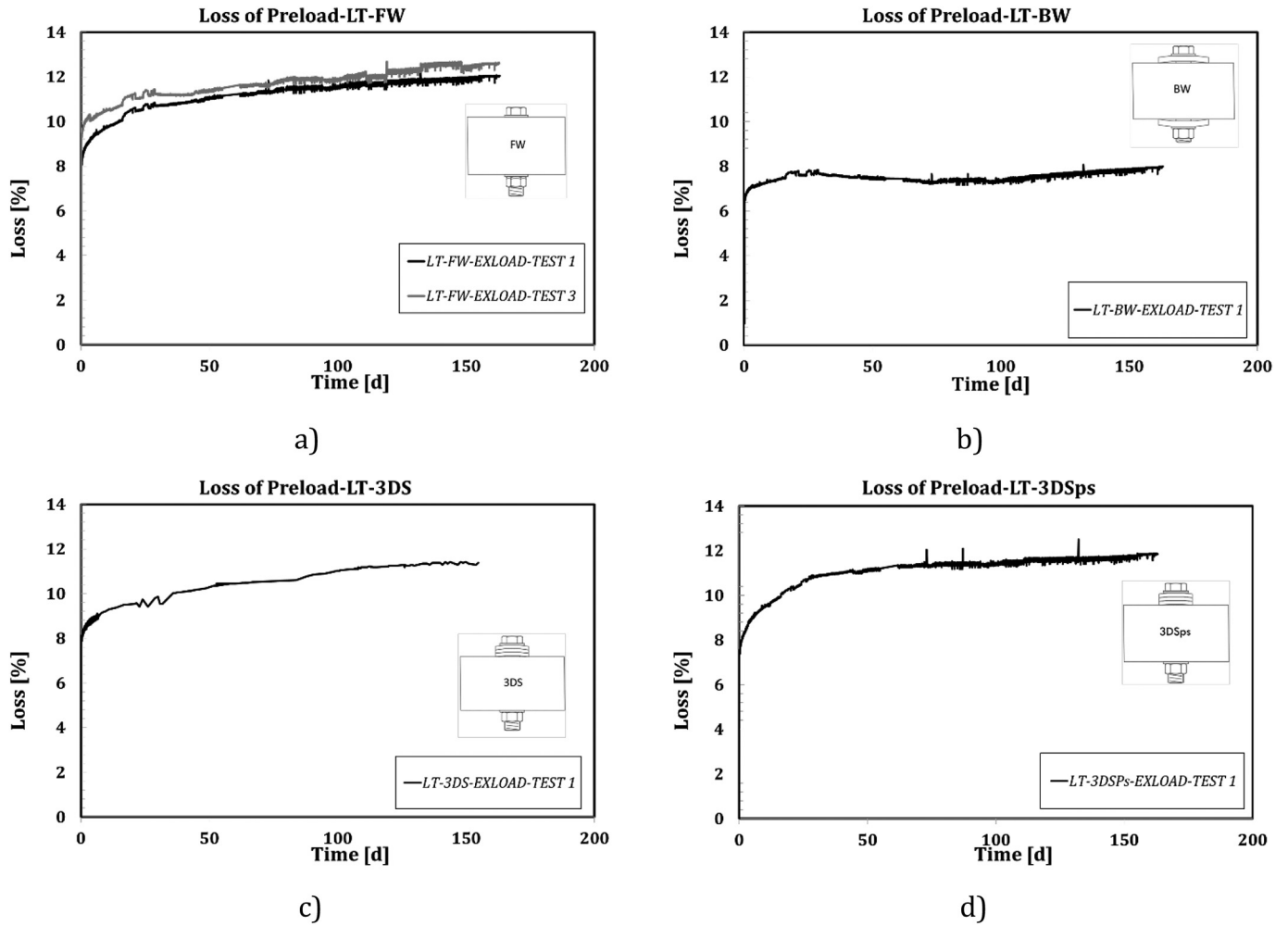


Fig. 12. Loss of preload in Long-term Tests (LT): a) FW-Flat Washer; b) BW- Big Washer; c) 3DS- stuck of 3 Disk Spring; d) 3DSps- Stuck of 3 pre-set Disk Spring.

4.1. Loss of preload without external loads: Calibration of  $c_1$  and  $c_2$

Following the approach given in [22,29,30], where a logarithmic evolution for the loss of preloading in time was recognized, the evolution of the loss without externally applied loads can be predicted using Eq. 4-2. The parameters  $c_1$  and  $c_2$  are calibrated on the short-term loss presented in Fig. 9;

$$l[\%] = c_1 \ln(t) + c_2 \tag{4 - 2}$$

The values reported in Table 6 of  $c_1$  and  $c_2$  are calibrated with a logarithmic regression on the short-term tests, not accounting for any external load at each time step (1, 6, 12 and 18 h). From the data reported in this table, it is clear that after 6 h, the regression study gives almost stable values of the parameters. This means that the loss of pretension is stabilized, leading to a constant gradient over time. Moreover, in Table 7, the same coefficients  $c_1$  and  $c_2$  are calculated at

Table 6  
Logarithmic regression coefficients at different time steps for short-term tests.

Time	ST-FW		ST-BW		ST-3DS		ST-3DSps	
	$c_1$	$c_2$	$c_1$	$c_2$	$c_1$	$c_2$	$c_1$	$c_2$
1 h	0.0024	0.0266	0.002	0.0207	0.0025	0.0295	0.002	0.0244
6 h	0.0025	0.266	0.0023	0.0214	0.0028	0.0301	0.0021	0.0247
12 h	0.0025	0.0268	0.0025	0.0217	0.0029	0.0303	0.0022	0.0248
18 h	0.0026	0.0268	0.0026	0.0218	0.003	0.0304	0.0023	0.0249

the last step of the short-term test (18 h) using the average loss, the 5% and the 95% percentile.

4.2. Loss of preload with the effects of an external load: Calibration of  $c_3$

As a result of the application of an external load, considering as an example the LT tests for BW and FW in Fig. 13, the initial part of curve describing the evolution of the loss of preload can be divided into two phases: the first phase is linked to the loss experienced by the bolt when no external loads are applied; the second phase of the loss is related to the application of the tensile load to the specimen. In fact, focusing on the first part of the long-term tests presented in the previous paragraph and enlarging the diagram in the time frame of the loading procedure, it is rather clear that the losses are directly linked to the application of the loads. The external load applied to the specimen in the long-term tests is applied in six steps, as shown in Fig. 13. In correspondence of each step, an instantaneous loss of bolt preload is observed.

Table 7  
Logarithmic regression coefficients for Short-term Test (18 h).

	ST-FW		ST-BW		ST-3DS		ST-3DSps	
	$c_1$	$c_2$	$c_1$	$c_2$	$c_1$	$c_2$	$c_1$	$c_2$
Mean value	0.0026	0.0268	0.0026	0.0218	0.003	0.0304	0.0023	0.0249
5% Fractile	0.0019	0.0198	0.0019	0.016	0.0022	0.0224	0.0017	0.0184
95% Fractile	0.0033	0.0339	0.0033	0.0275	0.0038	0.0384	0.0029	0.0315

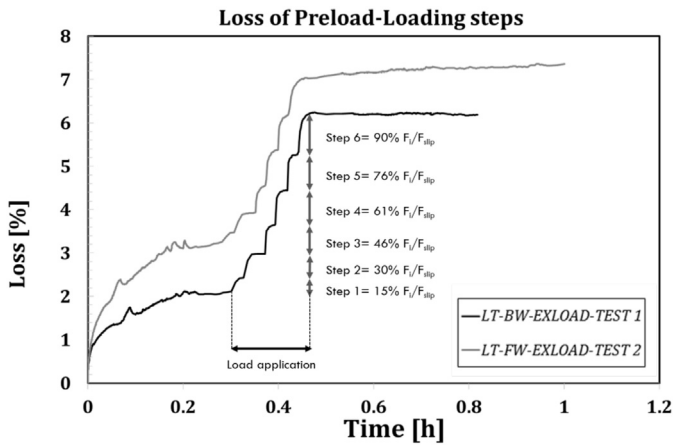


Fig. 13. Loading steps in LT tests, where  $F_i$  is  $i$ -th step out of 6 in total until 90% of  $F_{slip}$ .

Neglecting the initial loss, which took place between the bolt tightening and Step 1 of the loading sequence, the loss associated with the application of the tensile load can be easily isolated. To each loading step, a relative loss is registered; it is observed that this relative loss increases linearly with the applied load. This is reflected in Fig. 14, where the loss of preloading for each loading step is given for the four studied configurations. In this figure, the loading steps are given as a percentage of the slipping resistance of the tested device ( $F_{slip}$  in Eq. 3-1), thus, varying from zero to 90% of  $F_{slip}$ , which corresponds to the final tensile load  $F_{s,Rd}$  applied to the tested device.

Since the loss associated with the tensile loading ( $l_{lt}$ ) in the specimen has a linear evolution, it can be represented using the following form:

$$l_{lt}[\%] = c_3 \frac{F_i}{F_{slip}} \quad (4-3)$$

Where  $F_i$  is the loading step, which will be equal to 90% of  $F_{slip}$  at the end of the loading steps, and  $F_{slip}$  is given in Eq. 3-1. The value of the loss  $l_{lt}$  at the end of the loading sequence and the associated value of parameter  $c_3$  for each test are given in Table 8. It is worth noting that, from the point of view of the instantaneous losses due to the tensile force applied in the specimen, the most sensitive configuration is that with flat washers, while both configurations with pre-set disk springs lead to a significant improvement of the devices' response.

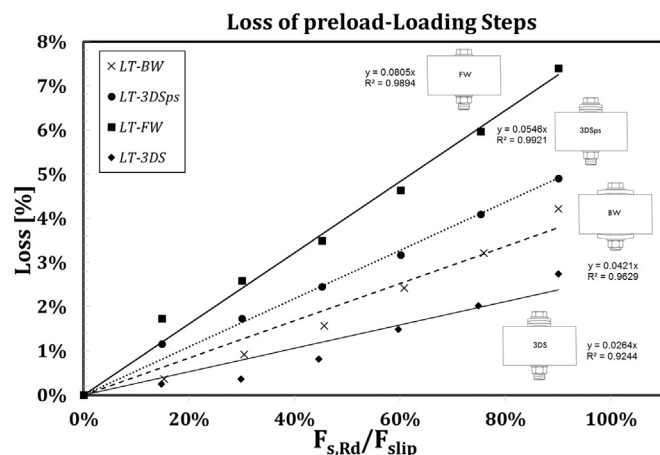


Fig. 14. Loss associated to the loading step in LT tests.

Table 8

Loss of preloading at the end of the loading sequence.

Test	$c_3$	$l_{lt}$
LT-FW	0.0805	7.25
LT-BW	0.0421	3.79
LT-3DS	0.0264	2.38
LT-3DSps	0.0546	4.91

#### 4.3. Model verification

Starting from the values of the parameters  $c_1$ ,  $c_2$ , and  $c_3$  calibrated in the previous sections, the accuracy of the suggested analytical model has been assessed considering the results of the long-term tests previously described. Since the loss of preloading is affected by statistical variability, the model has been applied using the mean value and the upper and lower fractiles (5% and 95%) of the parameters  $c_1$  and  $c_2$  (see Table 7 and Table 6), while the values of parameter  $c_3$  are given in Table 8. The obtained results are presented in Fig. 15 where the analytical prediction (AP) is compared with the experimental results of the long-term tests (LT).

The prediction of the loss of preloading with the proposed formulation seems in substantial agreement with the experimental results.

For the case in Fig. 15a-b, the prediction with the average value of the coefficient is catching the actual behaviour of the tested configurations (FW-BW). For the case with 3DS, the real behaviour is closer to the upper bound of the solution, while for the configuration 3DSps, some discrepancies are individuated. Nevertheless, these provide errors of only about 20%. Probably the difference between the analytical model and experimental results, in this case, is due to the limited number of available experimental data on which the proposed regression model has been calibrated.

## 5. Conclusions

The work presented in this paper deals with the loss of preloading of Sliding Hinge Joint (SHJ) with a Symmetric Friction Connection (SFC). The developed experimental campaign has been carried out characterizing the loss of preloading occurring in bolted connections of SHJs. In particular, the study of the short and mid-term loss of preloading was first addressed. Then, in order to investigate the long-term loss and the influence of the application of an external load to the connection, five months long-term tests were performed. The main outcomes of the presented study can be summarized as follow:

- Different bolt configurations using different washer solutions have been investigated (FW, BW, 3DS, 3DSps) and overall the configuration using the pre-set customized Belleville Washers (BW) has provided the best results reducing the loss of preload;
- A logarithmic evolution of the loss in time is found, which is in line with the findings in the literature. Additionally, an influence of the external load applied in the connection on the loss of preloading has been recognized;
- With the collected data, regression laws have been statistically calibrated on the experimental evidence accounting both for the sensitivity to time-dependent variables and external loads. A complete analytical model to predict the loss of preloading has been derived;
- Finally, the results obtained from the analytical model have been compared with the long-term tests. Overall, the model is quite accurate in reproducing the response. The maximum error in the prediction is for the configuration with not pre-set disk springs (around 20%). For all the other tests, the error is lower than 7%. However, the proposed model should be further validated in future investigations on a larger set of cases. Nevertheless, the test results collected so far confirm the accuracy of the proposed calibrated coefficients.

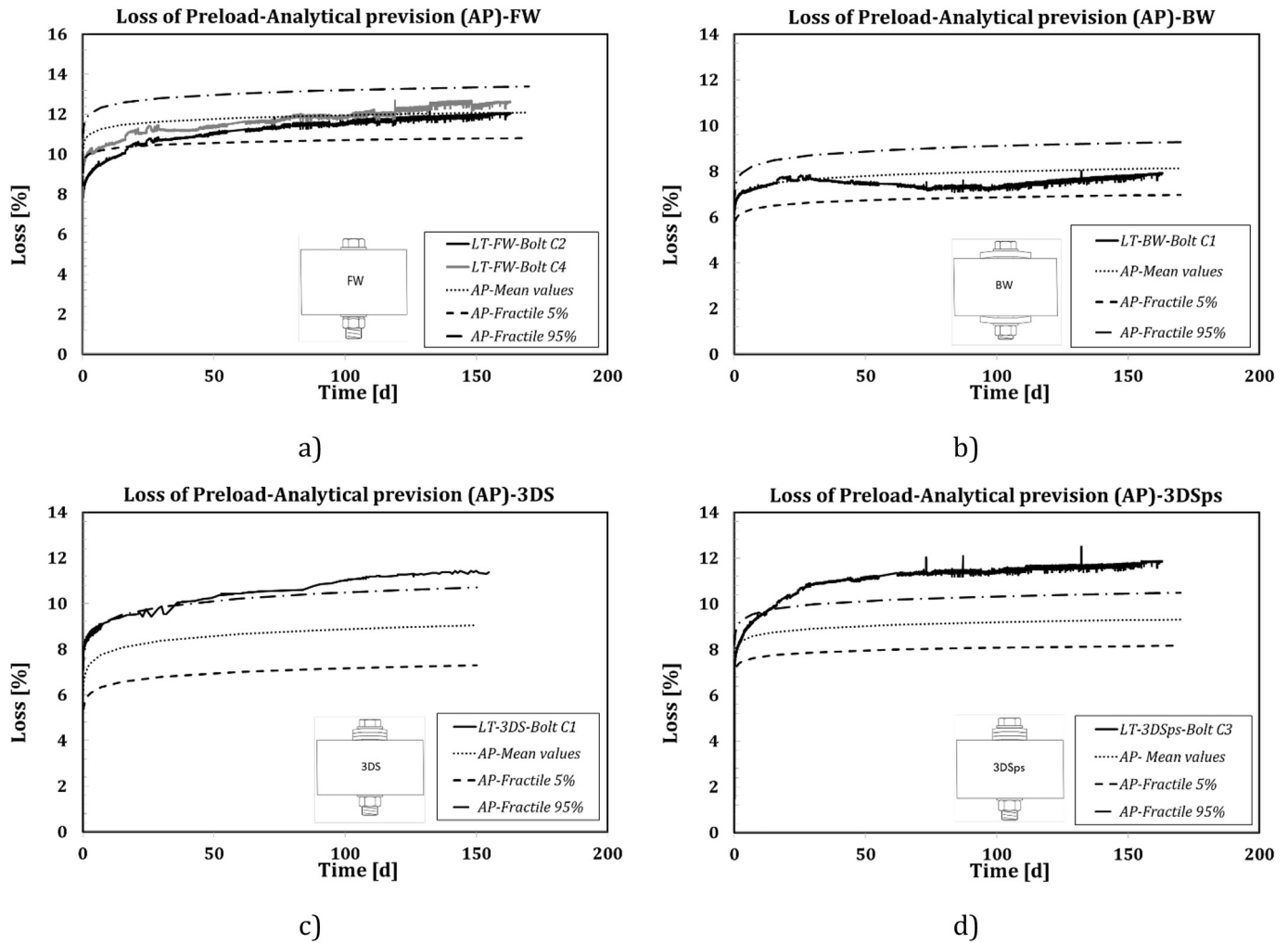


Fig. 15. Loss of preloading - Analytical Prevision (AP): a) FW-Flat Washer; b) BW- Big Washer; c) 3DS- stuck of 3 Disk Spring; d) 3DSps- Stuck of 3 pre-set Disk Spring.

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## Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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