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HIGH TEMPERATURE PUSH-OUT TESTS ON DEMOUNTABLE SHEAR CONNECTORS OF STEEL-CONCRETE COMPOSITE BEAMS

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Abstract

There is no denying that there is a growing need for reusable systems in the construction industry. This is not only a by-product of the increasing demand of materials, but also a necessity to reduce greenhouse gas emissions associated to the manufacturing process of construction components. Reusable systems aim to solidify the transition from a linear economy model to a circular economy model, where the lifecycle of materials is extended overtime. However, there are several factors that might hinder the reusability of structural components, ranging from regular use over a time period to accidental situations, such as earthquakes and fires.

This experimental study focuses its efforts on the analysis of demountable shear connectors for composite structural systems under the influence of high temperatures that resemble a situation of fire. The main idea behind this experimental campaign is to combine a standard push-out test, where a specimen composed by a HEB-260 steel profile with reinforced concrete slabs connected to its flanges via high strength bolts is subjected to a vertical force by utilizing a hydraulic jack with a simultaneous thermal action.

The tests reproduce a previous experimental campaign performed at the University of Luxembourg (cylinder and coupler systems), but subjected to 4 different temperatures (20, 300, 500 and 600 °C). The loss of strength of the connectors with the temperature, the failure mode and the reusability after a situation of fire are discussed in the present study.

Keywords

Reusable systems, push-out tests, circular economy, elevated temperature, fire resistance, shear connectors

1 Introduction

In steel-concrete composite structures, one of the most extended constructive systems is the one composed by reinforced concrete slabs connected to steel beams by welded studs in the top flange. This type of system is well known and it is present in a vast amount of constructions, especially in industrial and office buildings. However, this system has some drawbacks regarding its reusability. Once a building constructed with this system is demolished, the reinforced concrete slabs usually combined with steel sheeting profiles become non-reusable.

The problem exposed above leads to the design and study of demountable shear connectors, which aim to provide a reusable option as compared to the classic welded stud system. In a previous European RFCS research project (REDUCE), the University of Luxembourg proposed two new demountable systems: i.e 'Cylinder system', also denoted as 'P3.1' and the 'Coupler system' or 'P15.1', Figures 1 and 2.

It is important noting that these two system were mechanically tested with push-out tests at ambient temperature by Kozma et al. [1], obtaining favourable results about the reusability of both systems. However, temperature was not included as a variable in that study, therefore the behaviour of these systems under a fire situation remaining unknown. Other studies on the performance of the welded stud system for composite beams at several temperature thresholds were carried out by Chen et al. [2].

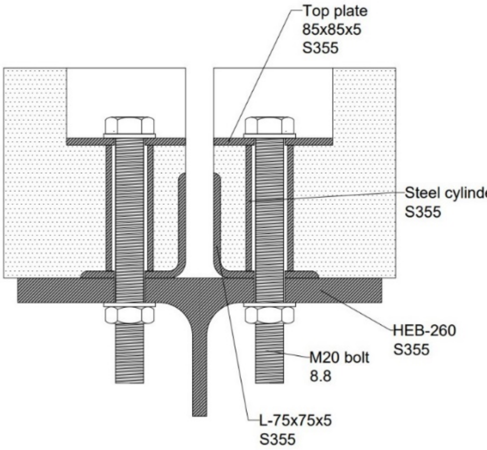

Figure 1 Demountable ‘Cylinder System’ P3.1.

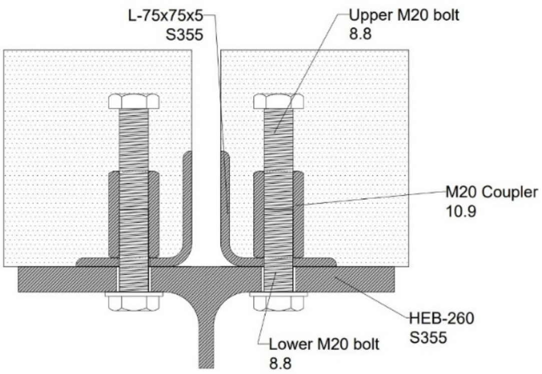

Figure 2 Demountable ‘Coupler System’, P15.1.

This study presents the results of an experimental campaign on push-out tests combined with high temperatures, allowing for a better understanding and characterization of these demountable shear connectors under the combined action of force and temperature.

2 Demountable shear connectors

2.1 The cylinder system

The first type of connection studied is known as cylinder system, also referred to as system ‘P3.1’ [1]. Its components are shown in Figure 1: an HEB-260 profile with steel grade S355; an L-75x75x5 profile with steel grade S355; a steel tube CHS 33.7x4x90 also with grade S355. This cylinder is the key component of the system, as it is the one that generates a cavity for a pre-tensioned M-20 through bolt of steel grade 8.8, with a ultimate tensile strength of 949 MPa, which connects the upper flange of the beam with a reinforced concrete slab, inside of which the cylinder is embedded and the reinforcement utilized for it is a two-layer reinforcement with ribbed bars ø8 mm B 500 S. Other components of this system are a plate with dimensions 85x85x5 and steel S355 welded on top of the cylinder, nuts and washer plates tightening the bolt and a square cavity over the top head of the bolt.

The main idea behind the design is connecting the frame to the slab in a way that ensures that, in case of failure, the only element that experiences non-reversible damage is the one that is easily replaceable, which in this case is the M20 bolt. The damages experienced by the beam and the slab would be minimal, therefore allowing for their reuse.

2.2 The coupler system

The second type of connection studied is known as the coupler system, also referred to as system ‘P15.1’ [1]. Its components are shown in Figure 2: an HEB-260 profile with steel grade S355; an L-75x75x5 profile with steel grade S355; a M20 coupler with steel grade 10.9. This coupler is the main element of the connection and its base is welded to the L profile. There are two M20 8.8 bolts in this connection, with a ultimate tensile strength of 1045 MPa. One of them is connected to the top of the coupler, while the other one connects the flange of the HEB-260 to the lower face of a reinforced concrete slab, and the reinforcement utilized for it is a two-layer reinforcement with ribbed bars ø8 mm B 500 S. Other components of this system are nuts and washer plates tightening the bolts.

The same idea that was explained for the cylinder system applies here. Only the replaceable elements of the system should fail in such a way that is no longer possible to reuse them. Therefore, only the lower bolt of the connection should fail. This is also the reason why the bolts have a lower steel grade than the coupler, since it is preferable that the failure mechanism damages the lower bolts, avoiding any significant damage to the steel profile and the concrete slab that could compromise their reusability.

3 Experimental campaign

3.1 Specimen and test design

The fabrication and assembling of the test specimens were carried out at the facilities of ICITECH, *Universitat Politècnica de València,* Spain.

The type of tests being performed in this experimental campaign are the classical push-out test adapted to demountable shear connectors simultaneously subjected to elevated temperatures (see Figure 3). A total of 8 tests were performed, 4 tests on the P.3-1 system (cylinder system) and another 4 on the P.15-1 system (coupler system), under 4 different temperature levels (20 ºC; 300 ºC; 500 ºC; 600 ºC). The features of these tests are presented in Table 1.

The initial phase of the campaign was the design of all the elements necessary to create one test specimen, which are composed by 4 reinforced concrete slabs (2 layers of reinforcement), 1 HEB-260 S355 profile with 8 holes that allow for the connectors to be bolted to it. The measured yield strength of steel was 394 MPa according to the material tests performed in accordance with EN 10025-1:2004.

Thermo-mechanical tests were performed, where the specimen was taken to a target temperature by using 2 lateral heating panels, and once the target temperature was reached at specific control points, the loading procedure with the hydraulic jack was started. It should be noted that the loading was performed in just one cycle.

Figure 3 shows a general view of the test setup.

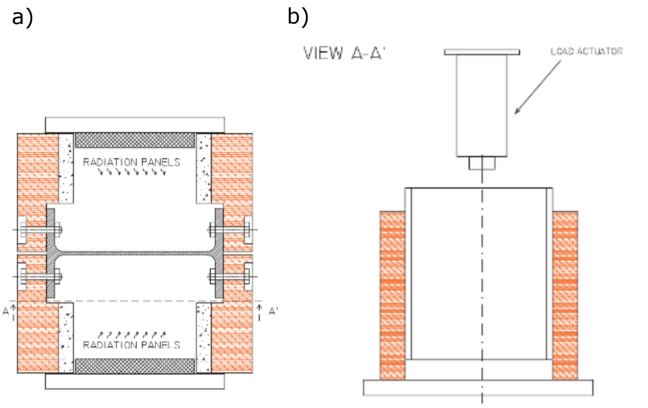

Figure 3 Configuration of the elevated temperature push-out tests: a) top view, b) lateral view.

3.2 Specimen preparation

The fabrication of the reinforced concrete slabs was accomplished by utilizing a custom formwork. This formwork allowed for fabricating a total of 16 slabs at once, therefore utilizing the same concrete for a complete family of specimens, since each specimen was composed by 4 slabs connected to the HEB-260 steel profile, and a total of 4 tests, each one with a target temperature.

In order to obtain the desired data, two types of measuring devices were utilized, being these linear variable differential transducers (LVDTs) and thermocouples. For each specimen studied, a total of 4 LVDTs were installed in order to measure the vertical displacement experienced by the system. The distribution of thermocouples was designed with the intention of acquiring temperature data at the points considered as the most relevant, such as the shear plane where the failure of the bolts is prone to occur. Figure 4 shows the distribution of thermocouples.

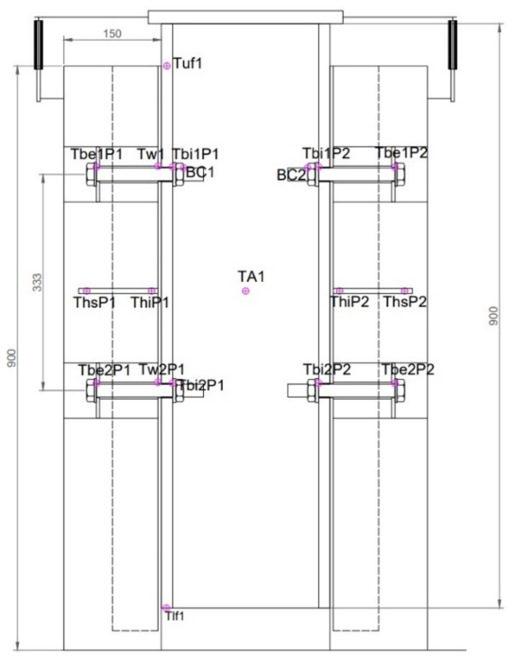

Figure 4 Thermocouple arrangement. Lateral view.

An explanation of the acronyms used for the thermocouples is given here. 'Tbi' is the reference name for the thermocouples installed at the shear plane of the bolt, while 'Tbe' is used for the thermocouples installed at the exterior head of the bolt. Number 1 refers to those thermocouples located at the upper row, while number 2 is used for those located at the lower row. 'TA' is a thermocouple located at mid-height of the HEB-260's web, 'Tlf' is located at the lower plane of the flange, while 'Tuf' is located at the upper plane of the flange. Thermocouples 'Thi' are embedded inside the concrete slab: 'Thi' at the level of the lower reinforcement layer and 'Ths' at the level of the upper reinforcement layer. Finally, thermocouples 'BC' are the bolt control thermocouples, which are located at the thread of the bolt, right after the nut.

3.3 Test setup

The testing procedure followed the next sequence:

- Specimens were assembled and the bolts were pretensioned until the required force was achieved by using a dynamometric torque wrench.
- The specimen was positioned under the hydraulic jack, over a stable base that guaranteed its proper support.
- Heating panels were adhered to the corresponding sides of the specimen by a previously designed fixation method.
- The heating panels were turned on and a target temperature was set up. The process of heating had a duration as long as needed in order to reach the goal temperature on the element that was considered as the control component.
- Once the test temperature was reached, the hydraulic jack started acting on the specimen. The load increased until shear failure of the connector occurred.

Figures 5 and 6 show different phases of the test setup.

Figure 5 Test specimen at ambient temperature located under the hydraulic jack before being loaded.

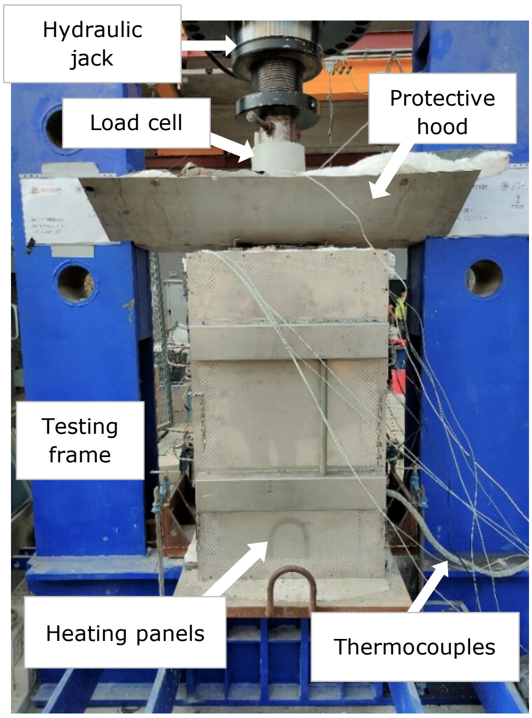

Figure 6 Test specimen with heating panels assembled to it.

4 Results

4.1 Temperature results

The measured temperature-time curves at the different locations were the thermocouples had been installed are presented in this section. Curves of temperature-time are provided in Figures 7 and 8. The temperature selected for being represented is 500 ºC, since it is the threshold where the mechanical properties of the bolts experience a significant reduction. As it can be seen, although the temperature was set to reach the target of 500 ºC at the bolt control points, there was a noticeable temperature difference between the different points which were monitored along the bolt.

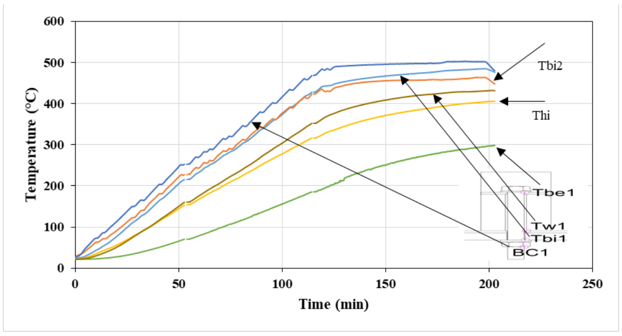

Figure 7 Temperature evolution for P3.1-T500 at the thermocouple locations.

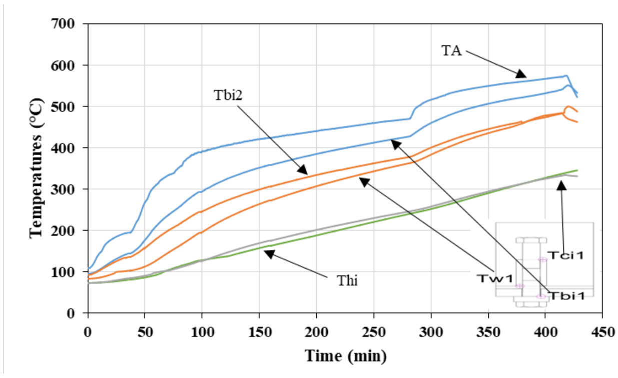

Figure 8 Temperature evolution for P15.1-T500 at the thermocouple locations.

The relevant temperatures-at the shear plane (Tbi) of the 8 bolts are collected in Table 1. The average value has been computed for each test, which will be used as a reference for the calculations of the shear failure at elevated temperature that will be presented in Section 5.

Table 1 Summary of relevant temperatures obtained at the shear plane (Tbi) in the push-out tests.

Test ID	Tbi1P1 (ºC)	Tbi2P1 (ºC)	Tbi1P2 (ºC)	Tbi2P2 (ºC)	Tbi1P3 (ºC)	Tbi2P3 (ºC)	Tbi1P4 (ºC)	Tbi2P4 (ºC)	Average temperature at shear plane Tbi (ºC)
P3.1-T20	-	-	-	-	-	-	-	-	20
P3.1-T300	293,4	291,2	289,3	264,5	293,4	266,3	291,5	278,4	283,5
P3.1-T500	483,2	444,8	484,7	463,7	484,9	465,7	485,3	436,7	468,6
P3.1-T600	549,7	521,2	558,6	530,2	561,8	533,3	544,7	516,2	539,5
P15.1-T20	-	-	-	-	-	-	-	-	20
P15.1-T300	329,10	309,6	327,5	307,4	328,2	308,3	327,1	306,9	318
P15.1-T500	546,01	499,2	551,3	500,1	558,2	507,5	554,5	506,2	527,8
P15.1-T600	629,7	573,2	627,7	571,2	623,1	567,7	620,3	567,3	597,5

4.2 Shear tests results

From the performed push-out tests, it is possible to obtain the corresponding load-displacement curves, as well as to work out the degradation of the shear load resistance depending on temperature.

Figure 9 shows the load-displacement curves for system 'P3.1'. As it was expected, the curve that reached a higher load value was the one corresponding to P3.1-T20, which is the test performed at ambient temperature. The value of the highest load reached for this curve is 148,22 kN. All bolts failed by shear in this test, see Figure 10a). However, the failure for other tests was different. For test P3.1-T300, only two bolts (of the same concrete slab) experienced shear failure, which happened in a brittle way. Tests P3.1-T500 and P3.1-T600 showed a significant decrease in the maximum load per bolt, as a consequence of temperature thresholds reached, where the properties of the steel are severely affected. In test P3.1-T500, only one bolt of the lower row experienced shear failure, while the other bolts needed to be removed with a wrench after the test was finished. It is important to note that, during this test, the lower heating panel of the side where the bolt failed was heating at a lower rate that the other panels, leading to a situation where one bolt was less affected by temperature, conserving more rigidity and absorbing more force than the other bolts.

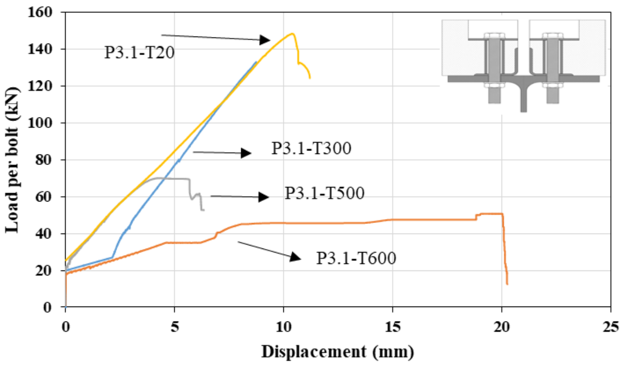

Figure 9 Load-displacement curves at each temperature for series 'P3.1'.

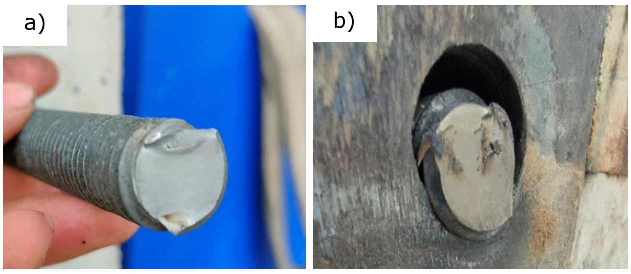

Figure 10 a) Bolt after shear failure for test P3.1-T20; b) Upper row bolt after shear failure for test P3.1-T300

Figure 10b) shows the failure at the shear plane for test P3.1-T300 (300ºC target temperature), where it is visible how the L profile penetrated into the bolt's thread.

Figure 11 shows the load-displacement curves for system 'P15.1'. For this group, the behaviour and failure mode for each pair of curves (below and above 500ºC) was clearly more similar than those observed for group 'P3.1'. A decrease in maximum load reached and an increase in the maximum displacement occurred as a result of the higher temperature reached, which is the expected behaviour for the connectors. For this series, all bolts failed by shear on every test. As it was explained previously in section 2.2, the connection was designed in a way that only the bolts that connect the slab to the HEB profile failed. This is what happened on every test of this series.

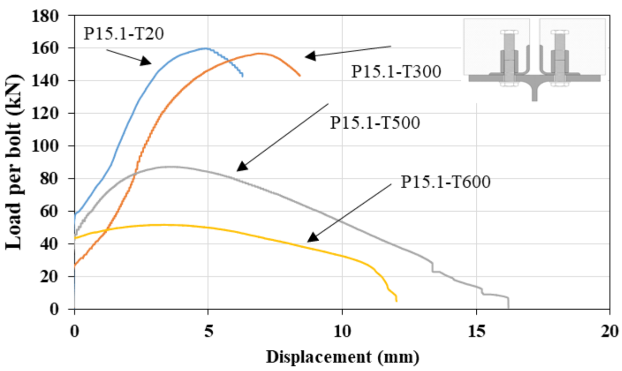

Figure 11 Load-displacement curves at each temperature for series 'P15.1'.

As a reference, a comparison between the results obtained for both systems at the room temperature push-out tests carried out in this project and those previously obtained in project REDUCE [1] is shown in Figure 12.

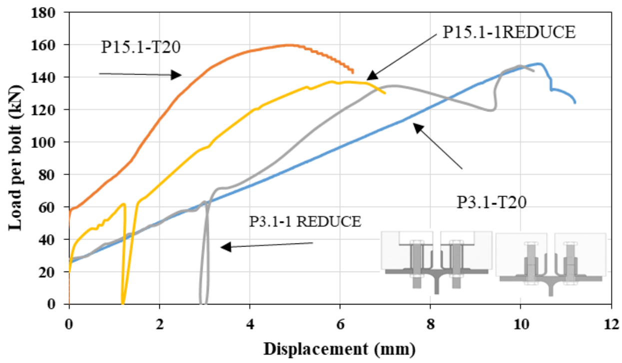

Figure 12 Comparison of ambient temperature push-out tests from projects FIREDUCE and REDUCE.

The degradation of the shear capacity in relation to the temperature was also obtained as a relevant result from the tests. Figure 13 shows the shear capacity loss curves for groups 'P3.1' and 'P15.1', where the decrease in terms of maximum load per bolt as the temperature increases can be observed.

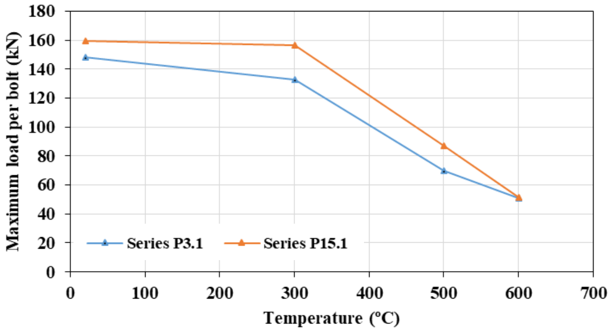

Figure 13 Shear degradation with temperature for series 'P3.1' and 'P15.1'.

It can be seen that the deterioration of system P3 with temperature is more pronounced than that of P15 system, although for the 600ºC target temperature, the ultimate load values are similar. The ultimate load and maximum displacement values obtained from the shear tests are presented in Table 2.

5 Discussion

The shear resistance values obtained through the experimental testing are compared in this section with the theoretical values, in order to assess their accuracy and how they correlate with temperature. EN 1993-1-8 [3] provides in Section 3.6.1 an expression for the calculation of the shear resistance of bolts per shear plane (equation 1). The terms in this equation are α_v, with a value of 0.6 for a class of bolt 8.8, A_s which is the tensile stress area of the bolt, with a value of 245 mm² for an M20 bolt, and f_{ub} is the ultimate tensile strength of the bolt, with a nominal value of 800 MPa for 8.8 bolts. The available data of the real strength of the bolts obtained from the tensile tests, with a value f_{ub} equal to 948.7 MPa [1], has been used in the calculations instead of the nominal value. Therefore, the expression provided in the design code has been adapted accordingly and the material safety factor γ_{M2} has been removed from this expression.

$$F_{v,Rd} = \alpha_v \, f_{ub} \, A \qquad (1)$$

Table 2 provides the values of the ultimate loads (F_u) obtained in the push-out tests, friction resistance, reduction factor ($k_{b,\theta}$), which is calculated as the quotient between the ultimate load (F_u) obtained for a certain temperature divided by the value of the ultimate load of the test performed at 20ºC ($F_{u,20}$). The corresponding reduction factors for bolts from Table D.1 of EN 1993-1-2 [4] corresponding to the average temperature of the bolts at the shear plane are also added in this table for comparison.

Evaluating equation (1), the value of shear resistance of the bolts per shear plane is 139.35 kN. If the ultimate loads at ambient temperature (20ºC) are compared with the shear resistance per plane obtained through this equation, then $F_{v,Rd}$ accounts for a 94% of P3.1-T20 (148.22 kN) and for a 87% of P15.1-T20 (159.68 kN). Therefore, the theoretical values calculated with the modified equation are similar to the values obtained through the experimental tests. As it can be seen in Table 2, for both series the ultimate load experiences a significant decrease as the temperature at the shear plane rises, especially when the 500ºC threshold is reached. This decrease in ultimate load is frequently associated with an increase in the displacement, which translates into a more ductile failure.

According to Section 3.9.1 in EN 1993-1-8 [3], the design slip resistance (or "friction resistance") of a pre-tensioned class 8.8 bolt can be calculated by means of equation (2), where k_s is a factor dependent on the type of hole - with a value of 1 for a regular hole -; n is the number of shear planes, equalling 1; μ is the slip factor at the friction plane depending on the surface treatment, which is taken as 0.3 for steel-brushed surfaces; and $F_{p,C}$ is the preloading force, equal to 100 kN for series P3.1 and 175 kN for series P15.1. Again, the material safety factor γ_{M3} has been neglected when applying the design equation, as the real value of the preload force has been used.

$$F_{s,Rd} = k_s \, n \, \mu \, F_{p,C} \qquad (2)$$

Evaluating equation (2), a value of 30 kN is obtained for the P3.1 system, while a value of 52.5 kN corresponds to the P15.1 system. These are the values of the friction resistance that each of the bolts offers to the applied load due to pre-tensioning, before any slip can occur. Once these threshold values are exceeded, the pre-tensioning effect at the bolts is lost and slip at the shear plane starts. These values are comparable to the measured ones for the 20ºC tests (24.5 kN in P3.1-T20 test and 59.7 kN in P15.1-T20 test), but its decreasing variation with temperature tends to indicate that the friction resistance progressively reduces as temperature increases, as reflected in Table 2.

Table 2 Ultimate loads and reduction factors.

Test ID	Ultimate load F_u (kN)	Max. displacement (mm)	Friction resistance (kN)	Experimental reduction factor $k_{b,\theta}$ (F_u / $F_{u,20}$)	Reduction factor according to EC3
P3.1-T20	148,22	11,23	24,5	1	1
P3.1-T300	132,84	8,73	20	0,89	0,91
P3.1-T500	70,01	6,33	22,19	0,47	0,58
P3.1-T600	50,65	20,24	19	0,34	0,42
P15.1-T20	159,68	6,27	59,7	1	1
P15.1-T300	156,68	8,41	29,6	0,98	0,88
P15.1-T500	87,21	16,204	42,3	0,55	0,46
P15.1-T600	51,68	12,03	43,6	0,32	0,23

6 Conclusions

In this work, an experimental study was carried out to analyse the behaviour of two types of demountable shear connectors at elevated temperatures: the cylinder system and the coupler system. A total of 8 push-out tests in combination with a thermal load applied by means of electric heating panels were performed - 4 tests for each system -, corresponding to 4 different temperature levels, ranging from ambient temperature to 600 ºC.

Reduction factors for each test series were calculated, allowing for a comparison with those proposed for bolts by EN 1993-1-2. It was found that temperature severely impacted the shear resistance of the connectors, especially above a threshold of 500 ºC, with a reduction of almost 50 % for both systems. The type of failure was also affected by temperature, producing a more ductile failure with larger displacements than those measured at the ambient temperature tests.

Both systems proved to be adequate for reuse, since the elements that experienced most damage were the demountable shear connectors. However, after a fire situation, the integrity of the other components of the systems, such as the primary steel beams and the concrete of the slabs should be checked in order to verify their reusability.

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