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EXPERIMENTAL BEHAVIOUR OF REVERSE CHANNEL JOINT COMPONENT AT ELEVATED TEMPERATURES

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ABSTRACT

Reverse channel connections typically connect steel beams to steel hollow sections columns: the channel legs are welded to the column face and the channel web is bolted to a conventional endplate on the beam side. From previous studies, this connection appears to have the best combination of desirable features under fire loading: moderate construction cost, ability to develop catenary action and extremely high ductility through deformation of the web channel.

This paper presents the experimental results on a series of tests at both ambient and elevated temperatures on reverse channel component in tension. The work intends to enhance the experimental research started in COMPFIRE project, to assess the non-linear behaviour of this component in tension and to establish a relationship between force, displacement and temperature.

The current work is in the framework of the research project ImpactFire PTDC/ECM/110807/2009, which is focused on characterization of the behaviour of steel connections when subjected to accidental loads, such as impact and fire.

Keywords: Connection; Elevated temperature; Reverse-channel; Endplate.

INTRODUCTION

The use of steel hollow sections in the steel construction has been increasing in the last years, because their advantages such is construction speed, visual and aesthetical appealing and better fire resistance than conventional open sections. However, connecting to hollow sections can be complicated and therefore expensive as the inside of these sections is not accessible. There were proposed several solutions for beam-to-column connections where the joint is performed through plates welded to the column. The common solutions for beam-to-column joints use bolted connections through of attachments welded to the steel profile of the column; an example is the fin plate connection by using a flat plate welded to the column wall. Other alternative joint configuration is the web cleat connection, where a single or double angle sections are welded to the column wall. Recently, an increasingly popular option is the use of the reverse channel connection. Reverse channel connections typically connect steel beams to steel hollow sections columns: the channel legs are welded to the tubular column face and the channel web is bolted to the endplate on the beam side. From previous studies (Ding and Wang, 2007), it appears to have the best combination of desirable features under fire loading: moderate construction cost, ability to develop catenary action and extremely high ductility through deformation of the web channel. These results are in agreement with the results of the experimental program, performed at the University of Sheffield in order to evaluate the robustness of different types of connections to composite columns (Huang *et al.*, 2012).

Moreover, in fire design for structural robustness, the demand for connection performance to prevent fracture is very high.

Recently, in the framework of the RFCS COMPFIRE project, which the main focus was to characterize the behaviour of steel joints between steel beams to concrete filled tubular columns under natural fire loading, a series of different types of channel sections under tension and compression was tested at the University of Coimbra.

The current paper presents a complementary experimental study on a series of tests at both ambient and elevated temperatures on reverse channel component in tension. The work intends to enhance the experimental research started in Compfire project, to assess the non-linear behaviour of this component in tension and to establish a relationship between force, displacement and temperature. This work is in the framework of the research project ImpactFire PTDC/ECM/110807/2009, which is focused on characterization of the behaviour of steel connections when subjected to accidental loads, such as impact and fire.

STRUCTURAL DETAILS AND GEOMETRICAL PROPERTIES

The studied reverse channel components are built from a steel hollow section (SHS 200) cut lengthwise (Fig. 1). The web of the reverse channel is bolted to the end plate through two bolts M24, grade 10.9 partial threaded. Three reverse channel dimensions are considered: SHS 200x200x8; SHS 200x200x10 and SHS 200x200x12. These dimensions are chosen in order to allow a comparison with the test results performed during Compfire project (Lopes *et al.* 2012). The tested sections in Compfire were steel hollow sections SHSx200 cut lengthwise with 8, 10 and 12 mm thickness only at ambient temperature.

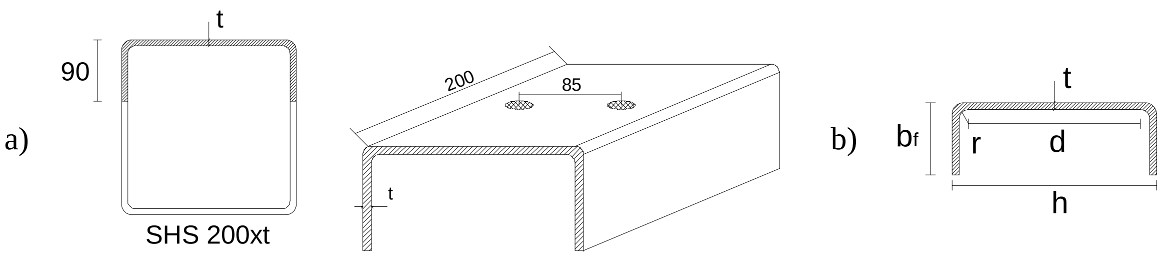


Fig. 1 Geometry of specimens: a) connection geometry; b) Reverse channel section.

REVERSE CHANNEL DESIGN

A typical reverse channel beam-to-column connection, subject to moment and axial force is divided into three major zones: tension, shear and compression. In each zone is identified the active components (Fig. 2a) based in the component method from Eurocode 3 part 1-8: (1) beam flange and web in compression; (2) bolts in tension; (3) end-plate in bending; (4) beam web in tension; (5) bolts in bearing; (6) bolts in shear; (7) welds; (8) reverse channel in bending; (9) reverse channel in compression; (10) column wall in bending; (11) column side walls in shear; (12) column side walls in transverse tension; (13) column side walls in compression. The components (1) to (11) are extensively defined and characterized in the Eurocode 3 part 1-8. The component (10) are not included in the Eurocode 3 part 1-8 but, is dealt with in CIDECT Report 5BP-4/05 (Jaspart *et al.*, 2005) and includes the failures modes: i) shear strength of the tube wall adjacent to a weld; (ii) punching shear through the tube wall; (iii) yielding of the tube wall using a yield line mechanism (Kurobane *et al.*, 2004). The components (8) and (9) are not covered in the literature, even though reverse channel presents some features that are similar to the column web/column wall in bending or in compression. Fig.2b) presents the load transfer mechanism in the reverse channel joint under negative moment.

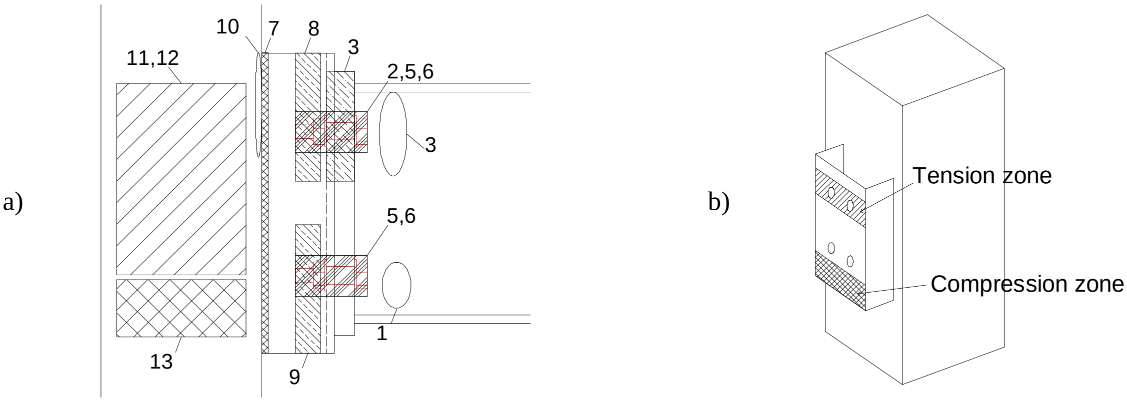


Fig. 2 Reverse channel connection active component

This paper is focused on the study of reverse channel component in tension, which is one the relevant component and one of the main source of deformations in the joint. The failure of the joint can be result of two different mechanisms: local and global. The proposed joint to be study presented failure by local mechanism. In the tension zone two main active components are: bolts in tension and RHS in transverse tension. For the resistance of bolts in tension was used the prescribed in the CIDECT Annex A.10 and for RHS in transverse tension the prescribed in the Annex A.32, for both local and global mechanism. Table 1 presents the design values for each component.

Table 1 – Resume of the design values.

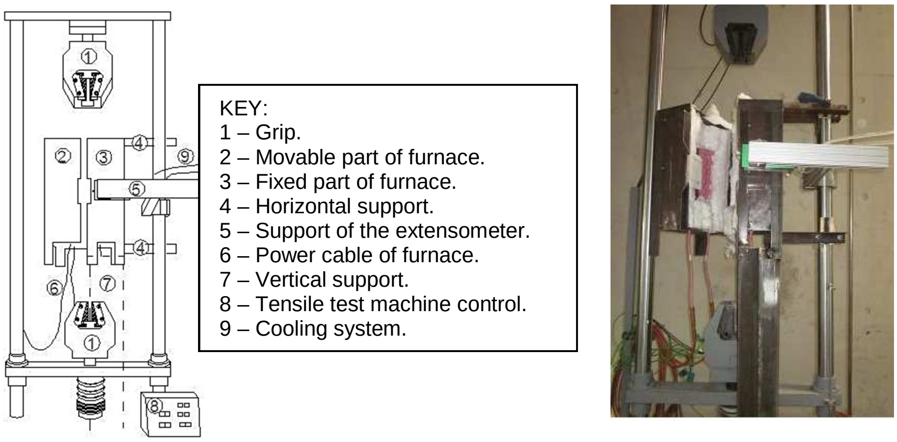
	Bolts		**RHS tension**		
	Tension (KN)	**Punching shear (KN)**	**Local failure (KN)**	**Global failure (KN)**	**F_{pl} (KN)**
RC-8	317.2	937.3	144.2	149.1	144.2
RC-10	317.2	937.3	220.4	230.4	220.4
RC-12	317.2	937.3	310.1	328.2	310.1

Where: F_{pl} – analytical plastic load;

MECHANICAL PROPERTIES

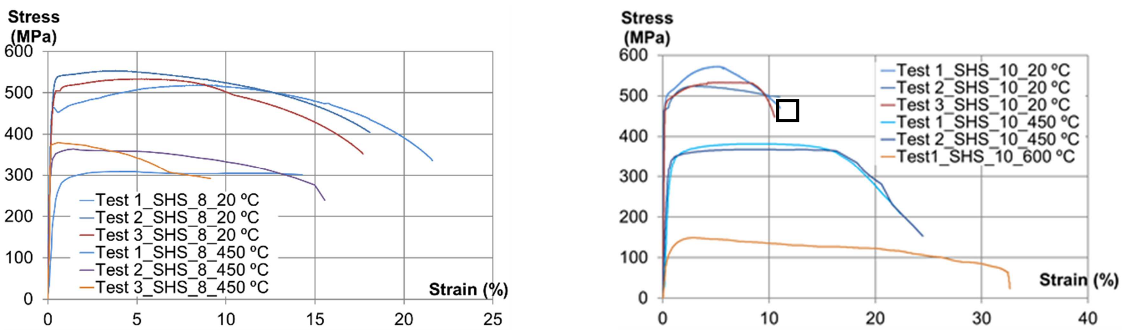
In order to characterize the mechanical properties of structural steel and bolts, tensile tests at ambient temperature, 450 ºC and 600 ºC were previously performed, whereas for bolts only ambient temperature tests were considered. The tensile tests on structural steel were performed according NP EN 10002-1, (2006) for ambient temperature tests) and NP EN 10002-5, (1992) for elevated temperature tests. A heating furnace controlled by a Mannings power unit was used for the elevated temperature tests. The tensile test layout for elevated temperature tests is depicted in Fig. 3.

Fig. 4 depicts the tensile test results at ambient and elevated temperature. From the analysis of the curves can be concluded that: (i) reduction of the yield strength and the Young's modulus with the increase of the temperature; (ii) the yielding plateau does not exists at both ambient and elevated temperature; (iii) the strain hardening process slow down when the temperature rises; softening can be observed in some tests at elevated temperature. During the ambient temperature tests on SHS 200x10, slipping of the displacement transducer was observed and the plastic extension may not have been correctly measured.



a) b)

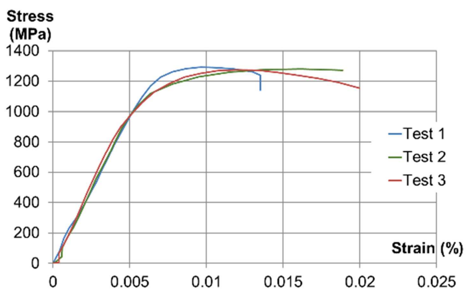
Fig. 3 Layout for elevated temperature tensile test: a) schematic; b) view of the furnace open.



a) b)

Fig. 4 Tensile test results for: a) SHS 200x8; b) SHS 200x10

The bolt testing were carried out according EN ISO 898-1 (2009) procedures; a SERVOSIS tensile testing machine with 1000kN capacity was used. The experiments comprised three tests for M24 grade 10.9. Each bolt was tested in tension, under displacement control in a custom made holder with a load axially applied between the head and a nut in a suitable fixture. The engineering stress-strain curves and the tested bolts after failure are shown in Fig. 5. All the bolts failed by fracture in the threaded zone.

a) 

b) M24 grade 10.9

Fig. 5 Bolt test: a) engineering stress-strain curves for bolts; b) tested bolts.

DESCRIPTION OF THE EXPERIMENTAL PROGRAMME

The experimental programme comprised twelve tests on reverse channel components with three different thickness (t = 8, 10 and 12 mm) and three different temperatures (θ = 20 ºC, 500 ºC and 600 ºC). At ambient temperature, two reference tests were performed for each reverse channel thickness.

Test procedure

The ambient temperature tests were performed by a hydraulic actuator under displacement control (0.02 mm/s) applied in the column at point (1). When the load is applied, the column rotates around the hinge (2) and the load is transferred to the specimen, placed between the hinges (3) and (4), up to collapse of the reverse channel. The specimen was welded by its flange to a rigid plate 400 mm x 400 mm x 30 mm, steel grade S355 which is bolted to the reaction structure. The test layout is presented in Fig. 6a). In the Fig. 6b) are depicted the details of the reverse channel test.
The elevated temperature tests were performed in two steps; first, heating of the specimens with a heating rate of 300 ºC/h (thermal expansion of the specimens was allowed); when the specimen temperature reached the target (500 ºC or 600 ºC), the temperatures remained constant and the monotonic mechanical load was applied (in the same way as in the ambient temperature tests). The thermal load was reproduced using an electric furnace purposely built for these tests; it consists in a rectangular box covered with two Flexible Ceramic Pads (FCP) heaters, controlled by a Mannings 65kVA power unit, and two layers of 25 mm thickness ceramic fiber blanket for the thermal insulation (Martins, 2012).

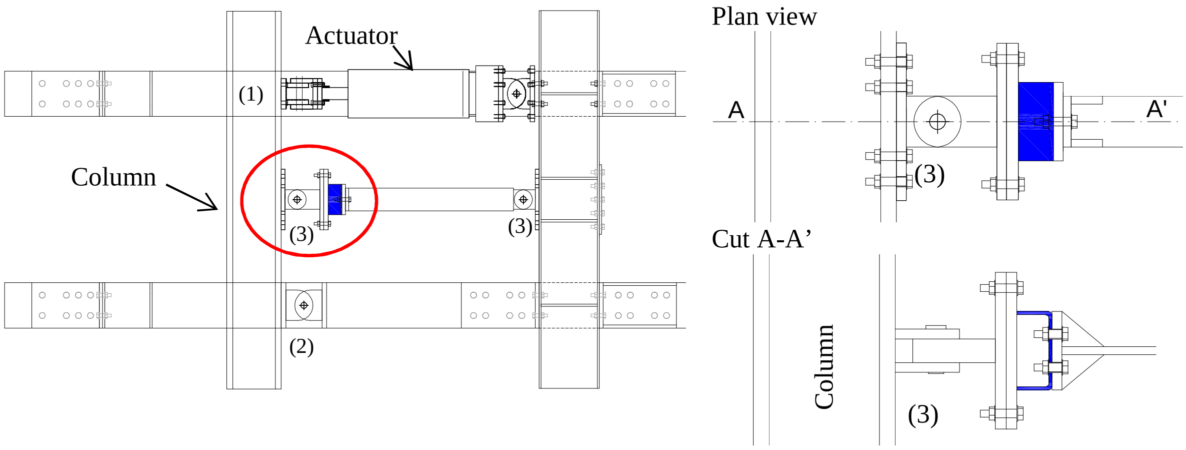


Fig. 6 Schematic of layout: a) plan view; b) details of the testing device (plan and cut).

The main requirements of instrumentation were to measure the distribution of internal forces, the deformed shape of the reverse channel and temperature (elevated temperature tests). The displacements were measured by displacement transducers (LVDTs) (Fig. 7a); uniaxial strain gauges (SG) FLA-6-11 and 3-element rosette (R) TML FRA 5-11 were used to measure strains inside the channel and in the both webs (Fig. 7b) and the bolt elongation was measured through strain gauge TML BTM 6-C with strain limit up to 0.5%.
During the elevated temperature tests, the temperatures in the specimens were assessed with thermocouples type K, inside and outside the reverse channel. The displacements were measured in the same points as the previous ambient temperature tests, except the point D_2 that was not accessible. Thermocouples wire (with low thermal expansion) brought the measurements from D_1, D_3, D_4, D_5 and D_6 to the LVDT located outside of the furnace. No strain gauges were considered at elevated temperature.

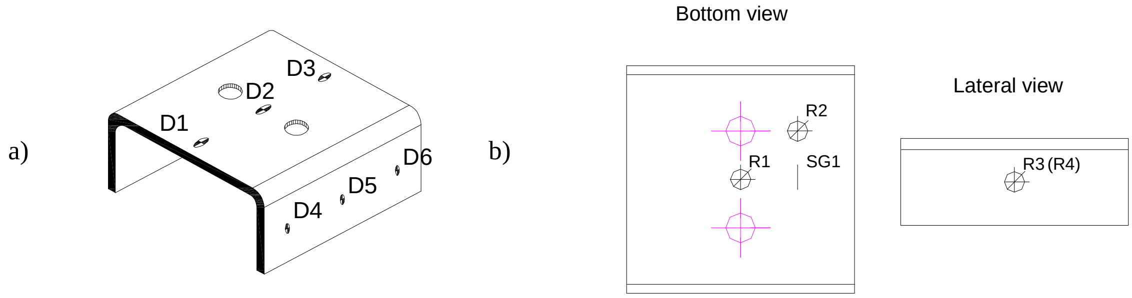


Fig. 7 Instrumentation of the specimens: a) displacement transducers; b) strain gauges.

TEST RESULTS

Ambient temperature tests

The reverse channel tensile tests results (Fig. 8), shows analogous behaviour: the strengths (plastic and ultimate strengths) increase with the increase of the thickness but without compromising the deformability capacity. The post limit stiffness decreases with the increase of the thickness; a reduction of 12 % and 22 % is observed from RC-8 to RC-10 and RC-12, respectively. In Fig. 8, RC refers to reverse channel, the first number is the thickness (8, 10 or 12 mm) and the last number is the number of the test.

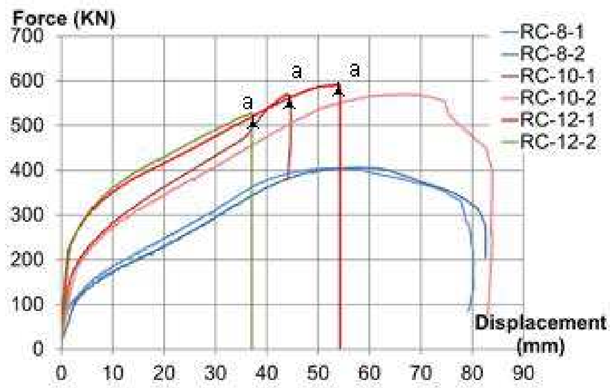


Fig. 8 Tensile tests at ambient temperature, displacement taken from point D2 (Fig. 5a).

After the tests, the two observed failure modes are: the excessive yielding around the bolt holes with bolt pull-out; the excessive yielding around the bolt holes with bolt failure in some specimens (RC-10-1 and RC-12). The fracture of the bolt is due the interaction of tension and bending in the bolts, Fig. 6a). Fig. 9b) to Fig. 9d) present the deformed specimens after the test.

a) b) c) d)

Fig. 9 Deformed specimens after the test: a)thread mark b) RC-8-1; c) RC-10-1; d) RC-12-1

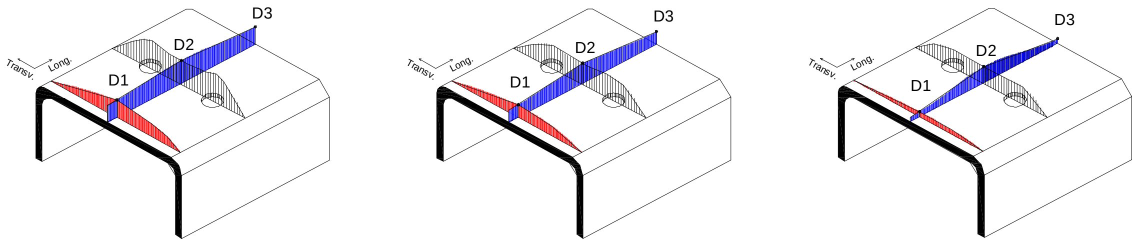
The experimental plastic load is found by a bilinear approximation of the force-deformation curve, based on the slope of initial and post-limit stiffness, as proposed by Jaspart (Jaspart, 1991). Concerning the strength, the experimental plastic load is lower than the analytical strength in all tests. However, the maximum applied loads reached in the tests are much higher than the analytical strength (Table 2). Concerning stiffness, an increase for the initial stiffness and a slight reduction for post-limit stiffness were observed with the increase of the thickness of the reverse channel; the ratio of maximum force *vs* plastic force decreases from 3.3 for RC-8 to 2.5 for RC-10 and to 1.8 for RC-12. This feature is in agreement with the connection demand performance to prevent fracture and to reach levels of high ultimate resistance. The ductility observed in the RC-8 tests and in the RC-10-1 is similar and reached a maximum vertical displacement after failure around $\Delta_{max} \approx 80$ mm. In the remaining tests the maximum displacement was lower, limited by the bolt failure, but after experiencing large deformations in the reverse channel.

Table 2 – Results of the tests.

		$F_{pl,an}$ (KN)	$F_{Rd,exp}$ (KN)	F_{max} (KN)	Δ_{pl} (mm)	Δ_{Fmax} (mm)	$K_{e,test}$ (KN/mm)	$K_{pl,test}$ (KN/mm)
RC 8	Test 1	144.2	133.7	404.7	1.12	58.1	119	6.57
	Test 2		121.1	406.5	0.92	53.3	131.6	6.48
RC10	Test 1	220.4	217.4	570*	1.11	44.02*	195.8	7.5
	Test 2		218.7	570	1.31	66.2	166.7	6.6
RC12	Test 1	310.1	308	591.2*	1.15	53.24*	267	5.8
	Test 2		309.1	528.6*	1.44	37.08*	214.3	5.9

Where: $F_{Rd,exp}$ – Experimental plastic load; Δ_{pl} – vertical displacement in point D2; Δ_{max} – vertical displacement for F_{max} at point D2; $K_{e,test}$ – experimental initial stiffness; $K_{pl,test}$ – experimental post-limit stiffness. *Values obtained when the bolt failure occurs.

The transverses and longitudinal deformations on the specimens after the tests are presented in the Fig. 10: the deformations decreases gradually from the center (D_2) to the edges (D_1 and D_3). The thinner specimen reaches large deformations in the edge than thicker specimens. As the thickness increases also is noted an increase of the gradient in the longitudinal direction. The same conclusion can be done by the analysis of the post limit results obtained from different locations (D_2 *vs* D_3). In the transverse section for the thinner sections, deformations are mainly located in the vicinity of the bolts, due the excessive yielding. However, with the increase of the thickness increases the membrane effect and the gradient decreases.



-a) b) c)

Fig. 10 Deformation distribution in the specimens: a) RC-8; b) RC-10; c) RC-12.

Elevated temperature tests

The tests at elevated temperature are depicted in Fig.11 to Fig. 13. The presented force–displacement responses are based on the displacement measured at point D_3 and D_2. Although the load reaches the same value, the vertical displacement is lower at point D_3, because is located in the edge of the reverse channel, see Fig. 10. In legend of Fig. 11, ID corresponds to the previously mentioned, but E refers to the extrapolated values for D_2.

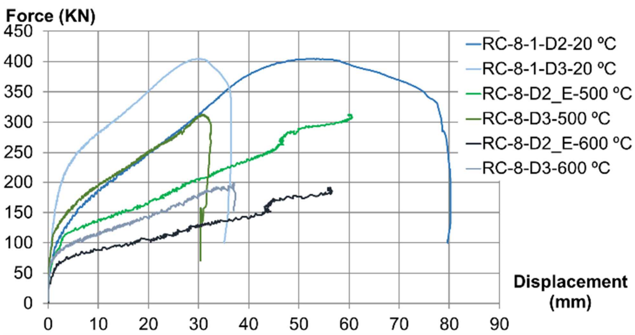


Fig. 11 Tensile tests for RC-8 at ambient and elevated temperature.

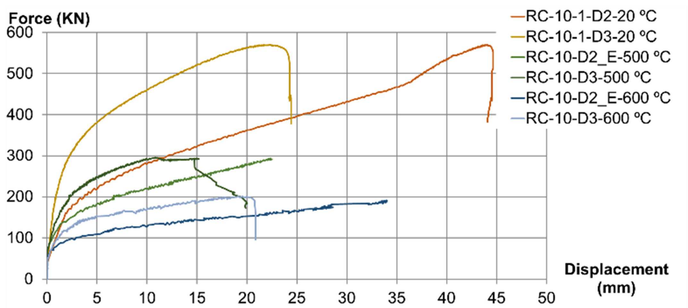


Fig. 12 Tensile tests for RC-10 at ambient and elevated temperature.

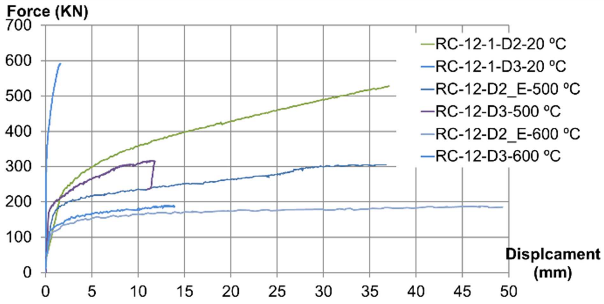
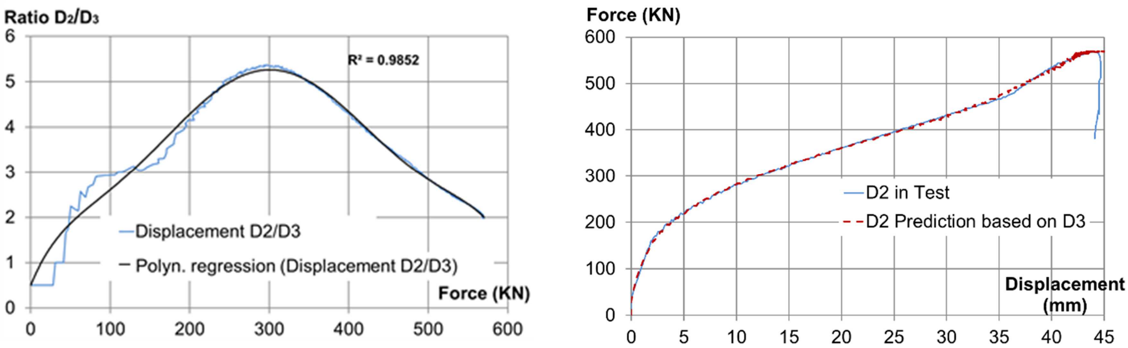


Fig. 13 Tensile tests for RC-12 at ambient and elevated temperature.

The displacement D_2 was predicted based on the ambient temperature results through a polynomial regression that was calculated using the ratio D_2/D_3 *vs* force (Fig. 14a)). The results present a coefficient of correlation (r^2) for the equations larger than 98 %. Fig. 14b) presents a comparison of the results: the value of D_2 measured during the tests and D_2 predicted by D_3 measurements. Good agreement is observed. This methodology was used for predicted D_2 in all tests at elevated temperature. Table 3 compares the results of the tests. Concerning the ductility, the deformation capacity decreased for 500 ºC, but an increase was observed for 600 ºC, which is in accordance with the material behaviour.



a) b)

Fig. 14 Estimation of the displacement at D2 point: a) polynomial regression: b) comparison.

Table 3 – Results of the tests.

		$F_{Rd,exp}$ (KN)	F_{max} (KN)	Δ_{pl} (mm)	Δ_{Fmax} (mm)	$K_{e,test}$ (KN/mm)	$K_{pl,test}$ (KN/mm)
	Amb. temp.	133.7	404.7	1.12	58.1	119	6.57
RC-8	500 ºC	108.4	312.94	0.97	61.63	111.5	3.49
	600 ºC	70.34	199.7	1.15	56.5	60.7	1.95
	Amb. temp.	217.4	570	1.11	44.02	195.8	7.5
RC-10	500 ºC	159.7	296.2	0.93	22.85*	170.2	6.25
	600 ºC	109.4	201	0.77	34.4*	141.7	2.57
	Amb. temp.	308	591.4	1.15	53.24*	267	5.8
RC-12	500 ºC	205.1	315	1.1	37.6*	204.1	3
	600 ºC	158.9	189	0.95	49.7*	166.7	0.6

The results of the tests show a reduction of the plastic strength with the increase of temperature of 14% and 45 % respectively for RC-8-500 and RC-8-600. A reduction of the maximum applied load was also measured: 23 % for RC-8-500 and 50 % for RC-8-600. Concerning to the initial stiffness, a reduction of 7 % and 48 % respectively for RC-8-500 and RC-8-600 was observed, while the post-limit stiffness exhibited greater reduction, 46 % for RC-8-500 and 70 % for RC-8-600.The behaviour of the RC-10 and RC-12 were similar concerning the strength and maximum applied load. For the initial stiffness and post-limit stiffness, reductions are also observed with the increase of temperature.

The results at elevated temperature showed that: i) reduction of the strength capacity; ii) reduction of the initial stiffness; iii) decrease of the post-limit stiffness. The reduction of post-limit stiffness is more evident for 600 ºC temperature ranges. The bolt failure was observed in almost tests after the specimens had experienced large deformations. The bolt failure occurs due the interaction of tension and bending in the bolts and also due to the pronounced decrease in the strength in the bolts compared with the steel; for example, at 600ºC, the reduction of the strength for bolts is 80 % while for steel is only 50%.

COMPARISON WITH COMPFIRE RESULTS

Previous tests were also compared and discussed with the results obtained in the experimental campaign performed in the framework of the RFCS COMPFIRE project. Fig. 15 to Fig. 17 compare of the results of tensile tests for reverse channel RC-8; RC-10 and RC-12. The results obtained for RC-8 and RC-10 are in agreement for the initial and post-limit stiffness. Concerning to the strength, the results for RC-8 results are higher than those obtained in the Compfire tests. The main reason for these differences is related to the yield strength of the steel used in Compfire: f_y = 346 MPa and in the current tests: f_y = 500 MPa (Fig. 4a). The ductility were similar in the tests, was observed an increase in the ductility in the tests when compared with the observed in the Compfire test. Concerning the failure modes, in Compfire excessive yielding in the bolt hole was observed in all tests; by the other hand, bolt failure happened in the current tests for RC-10-2 and RC-12.

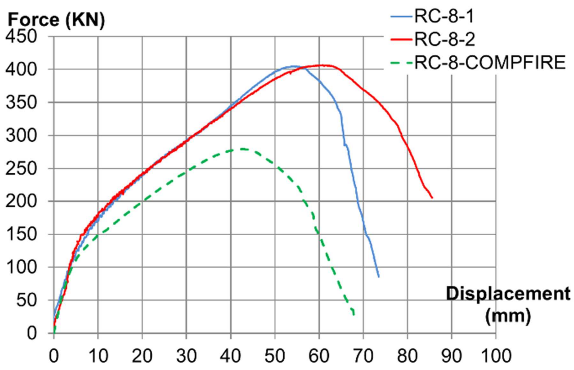


Fig. 15 Tensile test comparison RC-8 mm.

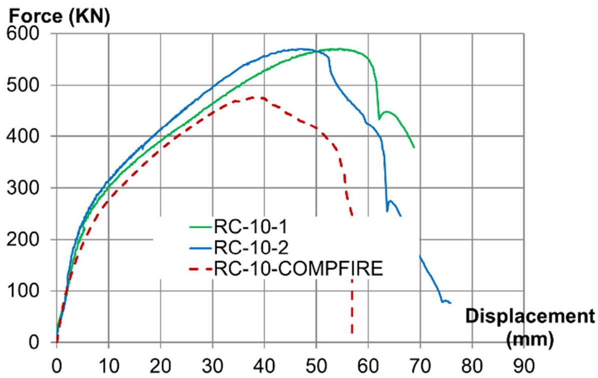


Fig. 16 Tensile test comparison RC-10 mm.

The results showed that for both RC-12 tests, the maximum force is reached with bolt failure, unlike the Compfire tests that where reached without bolt failure. For the plastic load the results presents an increase of the plastic load in the tests.

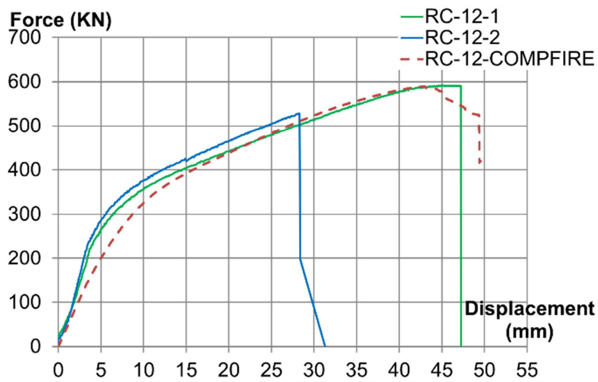


Fig. 17 Tensile test comparison RC-12 mm.

CONCLUSIONS

This paper presented and discussed the experimental results of a total of 12 tests, conducted to investigate the behavior of reverse channel component in tension at both ambient and elevated temperature. Additionally, a comparison with the tests performed in Compfire was performed.

The results of the tensile tests at both ambient and elevated temperature of three different thicknesses (8, 10 and 12 mm) of reverse channel component showed that: at ambient temperature, the analytical plastic load is lower than the obtained by bilinear approximation. Concerning the stiffness, was observed an increase of initial stiffness with the increase of thickness and a slight reduction in the post-limit stiffness. In the tests at ambient temperature two modes were observed: excessive yielding of the bolt holes without bolt failure and with bolt failure. The failure of the bolts occurs after experiencing large deformations.

At elevated temperatures, the resistance and the initial stiffness decrease with the increase of temperature, due the degradation of mechanical properties with temperature. This reduction follows the pronounced decrease in the strength for steel at 600ºC. The initial and post-limit stiffnesses decrease with the increase of temperature. Although, the tensile tests on steel at

600 ºC showed a strain softening, the post-limit stiffness in the reverse channel component is positive for each tested temperature.

The current tests presented a slight increase in the strength and maximum applied load with regard to Compfire results; this could be related to the different yield and ultimate stresses of the tested steel. Concerning the initial and post-limit stiffnesses, the current tests had a good agreement with the results of the Compfire tests.

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