http://dx.doi.org/10.14311/asfe.2015.023

Applications of Structural Fire Engineering, 15-16 October 2015, Dubrovnik, Croatia

EXPERIMENTAL RESEARCH ON T-STUBS UNDER ELEVATED TEMPERATURES

Ioan Both[a,b], Ioan Mărginean[a], Calin Neagu[a], Florea Dinu[a,] Dan Dubina[a,] Raul Zaharia[a]

[a] Politehnica University of Timisoara, Department of Steel Structures and Structural Mechanics, Romania
[b] Czech Technical University in Prague, Department of Steel and Timber Structures, Czech Republic

Abstract
Bolted end plate connections are widely used in multi-storey steel frame structures. Their design is based on the component method, which evaluates the behaviour of the basic components through equivalent T-stubs, to model the tension zone that constitutes the most relevant source of deformability. The paper presents the results of an experimental research on bolted T-stubs, tested under elevated temperatures, in normal and high strain rate loading conditions. The influence of the loading rate on the resistance and ductility of the T-stubs subjected to elevated temperatures is emphasized.

Keywords: bolted connections, T-stubs, elevated temperatures, strain rate

1 INTRODUCTION

The robustness of multi-storey steel frame buildings subjected to extreme loadings depends essentially on the performance of the beam-to-column joints to allow for the development of alternate loads paths. The connections should possess large deformation capacity, in order to avoid a progressive collapse in case of an extreme loading scenario, involving the collapse of one or more elements of the structure.

One of the widely used connections in multi-storey steel frame structures is the bolted end plate connection. Its design is based on the component method, which evaluates the behaviour of the basic components through equivalent T-stubs, in order to model the tension zone that constitutes the most relevant source of deformability (Dubina *et al.*, 2008). A thorough research on the T-stub response function of weld throat thickness, the size of the T-stub, the type and diameter of the bolts, the steel grade, the presence of transverse stiffeners and the T-stub orientation was presented in Coelho *et al*. (2004). The influence of elevated temperatures on the behaviour of bolted end-plate connections has been investigated more intensively in the last decades (Al-Jabri *et al.*, 1998) and is still a topic of interest (Barata *et al.,* 2013). However, in case of an extreme scenario such as a column loss under fire, dynamic effects also appear and should be considered when evaluating the resistance and the ductility of the connections. The dynamic effect of high loading rate of T-stub components were also studied at ambient temperature (Dinu *et al.,* 2014). A distinct approach for testing T-stubs subjected to impact loading at ambient temperature is presented in (Barata *et al.*, 2014).

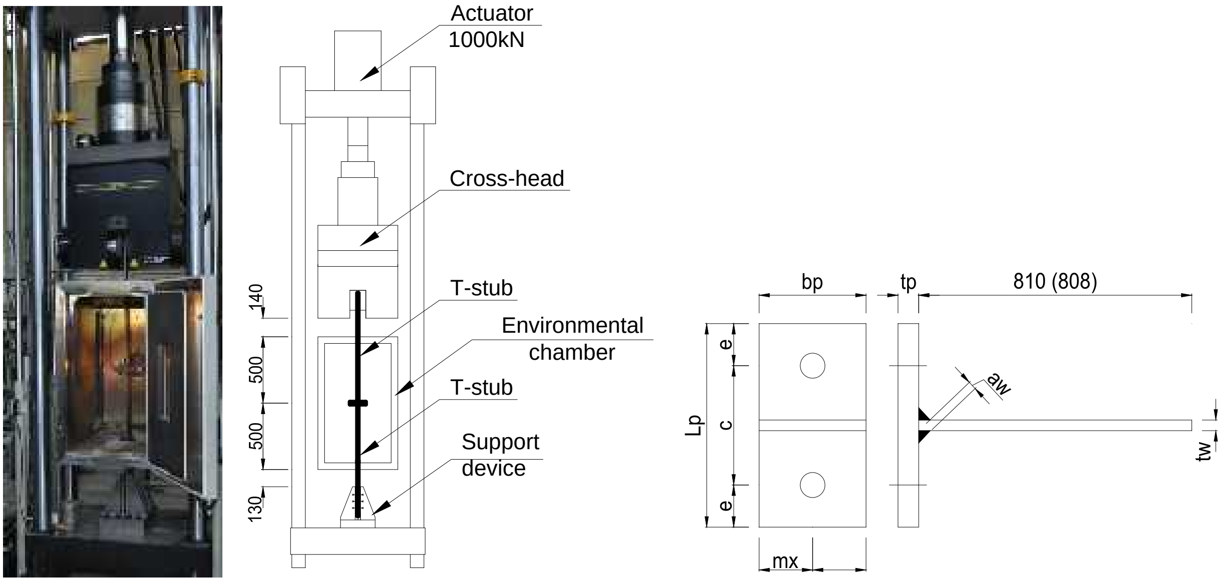
During a fire event, the joints may be already affected by heat, when the collapse of an element is produced, leading to a fast redistribution of forces. The paper presents the results of an experimental research on bolted T-stubs, tested under elevated temperatures, in low and high strain rate loading conditions. The specimens where tested inside an environmental chamber able to heat up the steel specimens up to 600 ^{0}C. The chamber was adapted to the dynamic universal testing machine of 1000 kN, within the laboratory of the Department of Steel Structures and Structural Mechanics from the Politehnica University of Timisoara. The influence of the loading rate on the resistance and ductility of the T-stubs subjected to elevated temperatures is emphasized.

2 EXPERIMENTAL TESTS

One of the objectives of the on-going CODEC (CODEC, 2012) research project is to study the robustness of structures subjected to exceptional loadings. The proposed experimental program comprises tests on joint components at ambient and at elevated temperatures in a steady-state approach, considering quasi-static and high strain rate loading protocols. The macro-components, i.e. the T-stubs, were selected such that two modes of failure, defined by EN1993-1-8 (C.E.N. 2005b) as mode 1 and mode 2, would characterise the load bearing capacity of specimens. The experimental program is in progress and the tested specimens presented in the following have the smallest resistance defined by mode 1 type of failure in ambient temperature conditions.

2.1 Specimens

Each test was performed by connecting two identical T-stubs using two bolts M16, grade 10.9 as presented in Figure 1a. The generic dimensions of a T-stub are presented in Figure 1b. The nominal and the measured dimensions are given in Table 1.



a) b)

Fig. 1 a) Experimental setup b) Specimen geometry

The name of the specimens denotes the type of specimen, flange thickness, bolt diameter, distance between bolts and loading procedure. The suffixes of specimens, i.e. T and TS, stand for normal strain rate and high strain rate respectively.

Table 1 Specimens dimensions [mm]

Specimen	Nominal						Measured							
	t_p	b_p	L_p	c	e	m_x	t_p	b_p	L_p	c	e	m_x	a_w	t_w
T-10-16-100T	10	90	160	100	30	45	9.7	89.4	160	99.9	30.2	44.3	7	10
							9.7	89.2	160	100.0	30.9	43.8	7	10
T-10-16-100TS	10	90	160	100	30	45	9.7	89.0	160	99.8	31.1	43.8	7	10
							9.7	89.0	160	100.6	30.5	43.9	7	10
T-10-16-120T	10	90	180	120	30	45	9.7	89.8	160	120.9	30.1	44.3	7	10
							9.7	89.3	160	121.5	29.7	44.0	7	10
T-10-16-120TS	10	90	180	120	30	45	9.7	89.3	160	120.4	30.3	44.5	7	10
							9.7	89.3	160	120.7	30.3	44.0	7	10

T-10-16-140T	10	90	200	140	30	45	9.7	89.2	160	141.9	29.3	45.9	7	10
							9.7	89.1	160	141.3	30.2	46.1	7	10
T-10-16-140TS	10	90	200	140	30	45	9.7	89.8	160	141.3	29.5	45.9	7	10
							9.7	89.1	160	141.3	29.9	44.5	7	10
T-12-16-100T	12	90	160	100	30	45	11.8	88.9	160	101.5	29.1	44.1	7	10
							11.8	89.0	160	101.6	29.2	43.5	7	10
T-12-16-100TS	12	90	160	100	30	45	11.8	89.2	160	101.9	29.4	43.6	7	10
							11.8	89.2	160	101.0	29.1	43.9	7	10
T-12-16-120T	12	90	180	120	30	45	11.8	88.2	160	119.9	30.4	43.8	7	10
							11.8	87.9	160	120.0	30.3	44.2	7	10
T-12-16-120TS	12	90	180	120	30	45	11.8	89.4	160	121.0	29.4	43.3	7	10
							11.8	88.7	160	121.2	29.7	44.3	7	10
T-12-16-140T	12	90	200	140	30	45	11.8	89.7	160	141.4	30.6	45.7	7	10
							11.8	89.4	160	140.3	30.0	46.0	7	10
T-12-16-140TS	12	90	200	140	30	45	11.8	88.7	160	140.0	29.4	44.7	7	10
							11.8	90.7	160	141.1	28.2	45.8	7	10

2.2 Material properties

The flange was chosen as S235 steel grade, while for the web S355 was considered, in order to avoid any plastic deformation. A fillet weld type was used.

Prior to the T-stubs testing, the material properties of each part were determined for ambient temperature on three test pieces machined according to ISO 6892-1:2009 (IHS, 2009). The material properties of the bolts M16 grade 10.9 were obtained at ambient temperature using a device able to transfer the load applied by the universal testing machine to the bolt. The material properties of the T-stub components are summarised in Table 2.

Table 2 Material properties for the tested steel plates and bolts

Element		f_y	f_u
		N/mm^2	N/mm^2
Web, t=10mm		390	569
Flange	t=10mm	310	408
	t=12mm	305	445
Bolt, M16		965	1080

2.3 Thermal loading protocol

Without a precise proportionality between imposed load and permanent load, it is difficult to estimate the reduction factor for load combination in fire situation, η_{fi}. According to EN1993-1-2 (C.E.N. 2005a), in a simplified manner, this factor may be considered with a value of 0.65. Using the reduction factor for effective yield strength provided in Table 3.1 of EN1993-1-2 (C.E.N. 2005a), by interpolation, the corresponding temperature at which the steel decreases at $0.65 f_y$ is 542^{0}C. Thus, this temperature was used in the experimental program.

The specimens were introduced in the Zwick environmental chamber able to increase the temperature up to 600 ^{0}C. Two orifices allow the web of the T-stubs to be connected to the support device bellow the chamber and to the top side-acting grips of the Instron dynamic universal testing machine of 1000 kN. The temperature inside the chamber was set by the dedicated Eurotherm

temperature controller, while the monitoring of temperature was performed by a type N thermocouple. The specimen temperature was monitored by four type K thermocouples: one for each bolt and one for each flange.
When the temperature within the specimens reached 542^{0}C, the temperature in the chamber was kept constant for another hour, in order to ensure a homogenous temperature within the T-stub.

2.4 Mechanical loading protocol

During the heating process, the specimens were fixed only at the bottom part, allowing the free thermal expansion. The hydraulic grips of the testing machine were closed just before the load introduction. The test involved both normal and high strain rate loading conditions in a displacement controlled procedure. The specimens marked with T were loaded at a velocity of 0.05mm/s while the specimens marked with TS were loaded at a velocity of 10mm/s. In order to avoid a sudden unloading, an initial displacement of 0.5mm was set at a normal strain rate, before initiating the high strain rate loading. This displacement corresponds in all cases, to a force that is lower than 30% of the yield force of T-stubs.
No controlled pretension force was applied to the bolts.

3 EXPERIMENTAL RESULTS

Figure 2 and Figure 3 present the deformed shape of T-stubs after failure, for flange thicknesses of 10 mm and 12 mm, respectively. Although the similar specimens tested at ambient temperature exhibited welding damage as presented in Dinu *et al.* (2014), for elevated temperatures the welding remained intact for both normal strain rate and high strain rate tests.

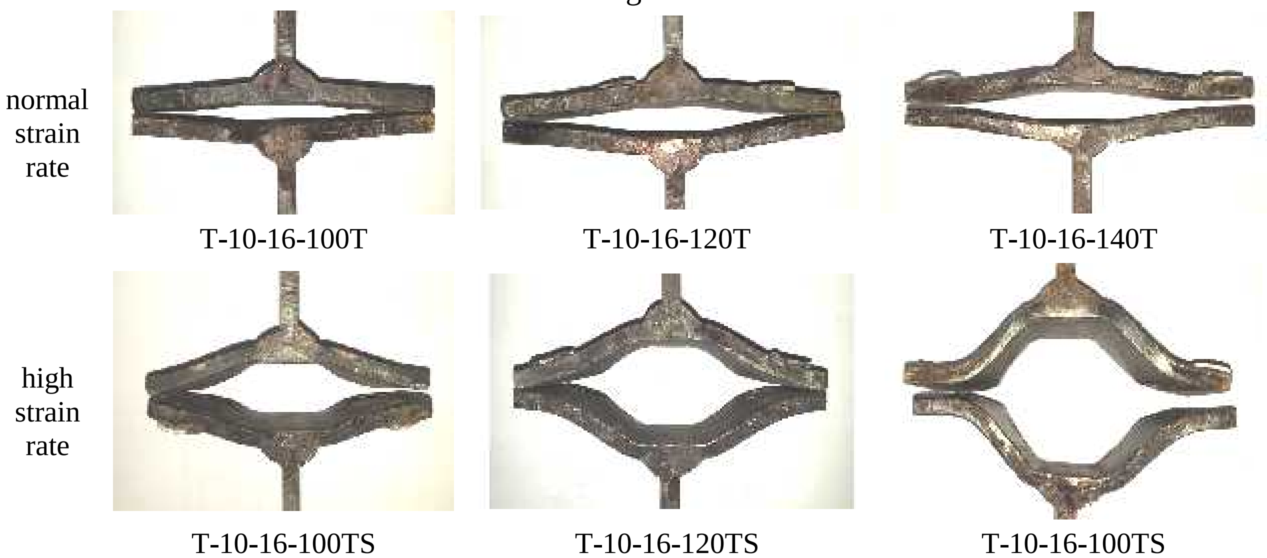


Fig. 2 T-stub specimens with flange thickness 10mm

The response of T-stubs at high strain rate loading presents differences in both load-carrying capacity and deformability with respect to the same specimens tested at a low strain rate. The qualitative results that may be observed in Figure 2 and Figure 3 are quantified in Figure 4.
For the same geometrical configuration, higher resistances are attained at high strain rate loading in comparison with the tests performed at normal strain rate. The ratio between the resistance of T-stubs tested at high strain rate and the resistance in case of normal strain rate presents a reasonable consistent variation, with values between 1.4-1.8, as it can be seen in Figure 5.

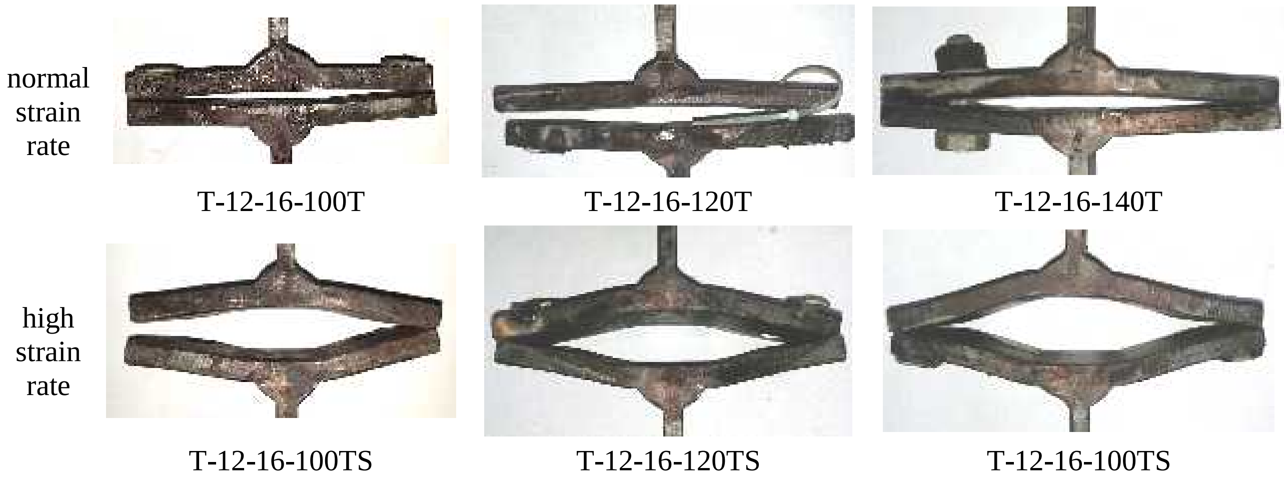


Fig. 3 T-stub specimens with flange thickness 12mm

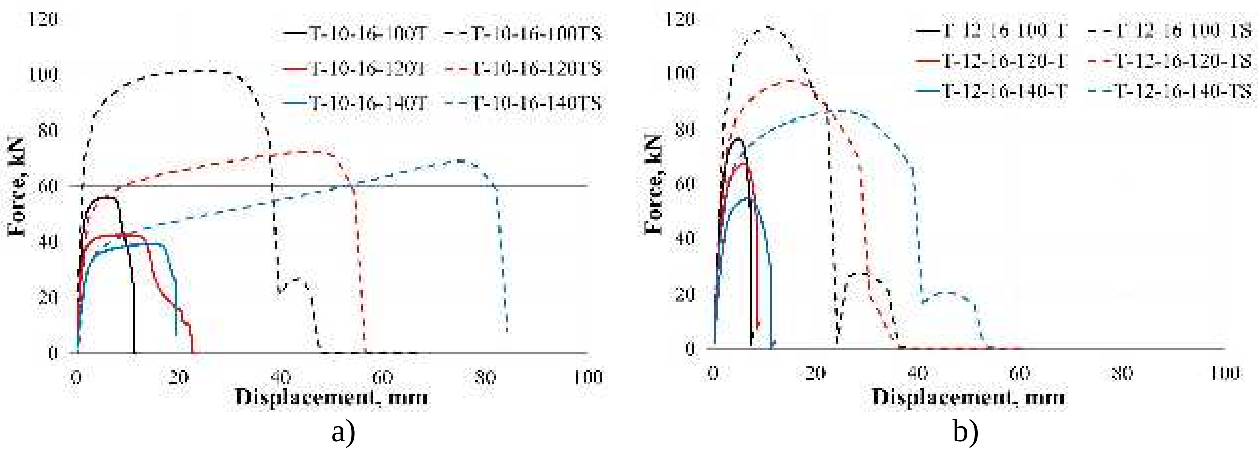


Fig. 4 Force displacement curves: a) flange thickness 10 mm, b) flange thickness 12 mm

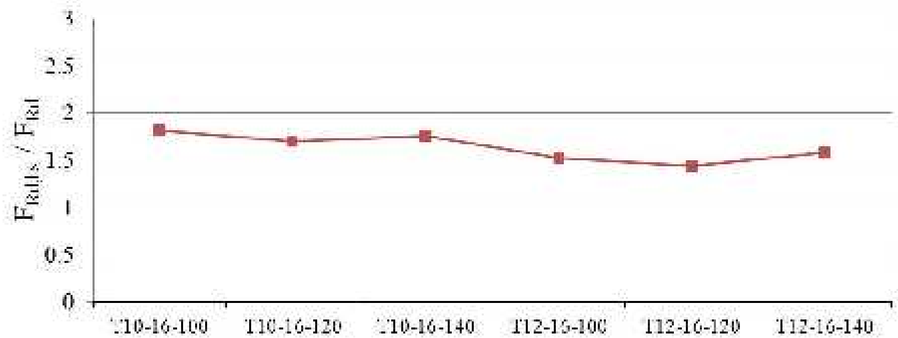


Fig. 5 High rate-to-static resistance ratio

For the same geometrical configuration, significantly higher deformations are attained at high strain rate loading, in comparison with the tests performed at normal strain rate. It has to be mentioned that the deformations obtained at 542 ^{0}C at high strain rate are very similar with the ones obtained at ambient temperatures, at both normal and high strain rate loading. In fact, at ambient temperature, there were very small differences in terms of deformations between normal and high strain rates, the higher strain rates leading to slightly smaller deformations. In case of elevated temperatures, the phenomenon is opposite.

The very small deformations obtained at 542 ^{0}C at normal strain rate may be explained by the fact that the ratio of the resistances of bolts/ flanges is different at elevated temperatures. At 542^{0}C, the steel resistance in the flanges is reduced to 65%, while the resistance of the bolts suffers a stronger reduction, to 41% (according to Table D1 of EN1993-1-2). Therefore, the relative resistance of the

bolt in the T-stub assembly is smaller at elevated temperatures and the failure of the bolt is produced in the normal strain rate tests before the flanges may develop important plastic deformations. It should be mentioned that, at ambient temperature, only failure *Mode 1* was obtained, while at elevated temperature, as it may be seen in Figures 2 and 3, the failure modes in the normal strain rate tests were closer to *Mode 2* or even *Mode 3* in case of 12 mm flanges.
On the other hand, the overstrength of the bolts due to the high strain rate loading (T-stubs resistance higher by 40-80%, as shown in Figure 5), allow the flanges to develop plastic deformations and to obtain also the *Mode 1* type failure, as shown in Figures 2 and 3.

4 CONCLUSIONS

The experimental program emphasised a significant increase of both resistance and ductility of the T-subs under elevated temperatures subjected to high strain rate loading, in comparison with the T-stubs loaded at normal strain rate.
The deformations obtained under elevated temperatures at high strain rate are similar with the ones obtained in the tests at ambient temperatures. While at ambient temperature there are small differences in terms of deformations between normal and high strain rates, the higher strain rates leading to slightly smaller deformations, in case of elevated temperatures the phenomenon is opposite.

ACKNOWLEDGMENTS

This publication was supported by the European social fund within the framework of realizing the project „Support of inter-sectoral mobility and quality enhancement of research teams at Czech Technical University in Prague“ CZ.1.07/2.3.00/30.0034. Period of the project´s realization 1.12.2012 – 30.6.2015

Partial funding for this research was provided by the Executive Agency for Higher Education, Research, Development and Innovation Funding, Romania, under grant PCCA 55/2012 “Structural conception and COllapse control performance based DEsign of multistory structures under aCcidental actions” (2012-2016) and by the strategic grant POSDRU/159/1.5/S/137070 (2014) of the Ministry of National Education, Romania, co-financed by the European Social Funds – Investing in People, within the Sectorial Operational Programme Human Resources Development 2007-2013.

REFERENCES

Al-Jabri K.S., Lennon T., Burgess I.W., Plank R.J. 1998. *Behaviour of Steel and Composite Beam-column Connections in Fire, Journal of Constructional Steel Research*, 46(1), p. 308-309.

Barata P., Santiago A. and Rodrigues J.P., 2013. Experimental behaviour of T-stub joint component at elevated temperatures, in *2º CILASCI – Congresso Ibero-Latino-Americano sobre Segurança Contra Incêndios*, June 2013, Coimbra. Portugal.

Barata P., Santiago A., Rodrigues J.P.C. and Rigueiro C., 2014, Experimental analysis of a T-stub component subjected to impact loading, in *7th European Conference on Steel and Composite Structures*, September 2014, Naples, Italy.

C.E.N. 2005a, EN 1993-1-2, Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design, Brussels.

C.E.N. 2005b, EN 1993-1-8, Eurocode 3: Design of steel structures - Part 1-8: Design of joints, Brussel.

CODEC, 2012. Structural conception and COllapse control performance based DEsign of multistory structures under aCcidental actions, 2012. Contract 55/2012/ UEFISCDI, Romania.

Coelho M., Bijlaard F.S.K., Gresnigt N. and da Silva, L.S. 2004. *Experimental assessment of the behaviour of bolted T-stub connections made up of welded plates, Journal of Constructional Steel Research*. 60(2), p. 269-311.

Dinu F., Dubina D., Marginean I., and Neagu C., 2014. Experimental tests of steel beam-to-column joints undercolumn loss scenarios, in *7th European Conference on Steel and Composite Structures*, September 2014, Naples, Italy.

Dubina D., Muntean N., Stratan A., Grecea D. and Zaharia R., 2008. Testing program to evaluate behaviour of dual steel connections under monotonic and cyclic loading in *Proc. of 5th European Conf. on Steel and Composite Structures*, September 2008, Graz, Austria.

IHS 2009, ISO 6892-1, Metallic materials — Tensile testing, Part 1:Method of test at room temperature.