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Thermal Effects on the Bearing and Ductility of Tubular Reduced Beam Section Connection: Numerical Investigation

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ABSTRACT

In the present paper, an innovative fire-earthquake resistant joint called high-performance tube (HP-T) connection is presented and numerically validated. This HP-T connection improves the axial and rotational ductility as well as prevents brittle failure. Two series of models were simulated in ABAQUS software. In the first set of models, which was designed for heat simulation, a sequentially coupled thermal-stress analysis was performed to investigate the effects of different parameters such as web and flange tube thickness and the ratio of the applied load. To simulate the fire damage, two probable scenarios were considered: bottom flange tube damage and beam web damage when exposed to combined initial loading and fire. In the second set of models for seismic simulation, the failure mode, hysteretic curves, and strain distribution were analyzed. According to the results, HP-T robust connection not only provides appropriate ductility enhancement in force-variable fire conditions but also withstands at least 8% inter-story drift without considerable strength reduction.

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NOMENCLATURE

k	material conductivity in [W/m°C]	T_0	Initial temperature[°C]
$T_{m,t}$	surface temperature in [°C]	**Greek Symbols**	
$T_{g,t}$	gas temperature in [°C]	ε	Resultant emissivity
n	surface outward normal direction	σ	Stephan-Boltzmann constant [W/m^2 K^4]
T_z	Absolute zero temperature[°C]	α	Coefficient of convection [W/m^2 K]

1. INTRODUCTION

Annually, natural phenomena such as earthquakes, hurricanes, etc. and manmade ones such as fires and explosions inflict tremendous damage to structures, causing remarkable economic loss as well as jeopardizing lives. After the terrorist attacks on September 11th, 2001, the total collapse of the twin towers and the progressive failure of WTC in New York was a result of the thermal stress caused by the explosion, fire [1]. Cardington large-scale fire tests [2] in 1993 demonstrated that steel joints are particularly vulnerable in a fire scenario. Hence, the capability of the connection is critical for the overall stability and integrity of the structure and to alleviate the risk of progressive failure. On January 19, 2017, an unintentional fire resulted in the total collapse of the Plasco high-rise metal structure in Tehran [3]. As one of the causes, it should be noted that the structure was built in the years 1960s and modern fire engineering requirements were not met during its manufacturing, operation, or maintenance. The partial structural failure was initiated in the floor system and connections. Subsequently, the degradation of material properties simultaneous with intensifying load during the fire

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resulted in the buckling of external columns and an increase in the column slenderness. The collapse of external columns finally led to the abrupt destruction of the whole structure. These are just a few important examples which indicate that connections have the most crucial role in a structure. Since they supply strong links between the principal structural parts for transferring all the applied loads. Furthermore, the efficiency of the connection at normal temperature differs greatly from high temperatures. Hence, studying the connection behavior during different stages of a fire incident may help achieve the most optimum fire engineering design. In general, internal forces in a connection can be categorized into four phases during a fire scenario. In the initial stage, under normal temperatures, the connections are only considered to be subjected to simple load combinations such as vertical shear or shear and moment. In the early stages of heating, a considerable compressive force may be generated in the connection due to restrained thermal expansion of the connected beam. At elevated temperatures, as a result of a reduction in material strength and stiffness, and subsequently, rapid increase in the beam's vertical deflection, the connected beam's bending resistance will not be sufficient to carry out the imposed load and to keep equilibrium, catenary (tensile) forces will be generated in it. Therefore, connections undergo tension. In the cooling stage, with the thermal contraction of the beam, tensile forces may also develop in the beam and the connection. Extensive efforts have been made to assess the vulnerability of steel or steel-concrete composite connections during a fire event. Kruppa [4] was one of the pioneers of conducting fire tests on connections. This study did not focus on the global behavior of joints and aimed generally to determine the performance of high-strength bolts. Lawson [5] studied the global rotational behavior of conventional connections subjected to ISO834 standard fire. Leston-Jones [6] examined the moment rotation relationship of the steel beam-columns using flash endplate connections and presented that its stiffness and strength decreased as temperature increased. Al-Jabri [7] modeled flush endplate bolted connection at elevated temperatures using general commercial program ABAQUS and evaluated connection moment rotation characteristics under degradation of steel properties. He established that testing of isolated joints could not accurately reflect the behavior of connections due to the absence of concurrent axial force. Sarraj [8] successfully evaluated the application of the Component-based method and the fin plate connection tying resistance. Hu and Burgess [9] performed a quasi-static analysis using ABAQUS code to investigate the ductility and capacity of flexible endplate connections subjected to fire. Yu et al. [10] examined the robustness of web cleat connections under tying force at higher temperatures and also developed the component-based method for different types of connections. Han et al. [11] accomplished fire tests to assess the effect of the ISO834 standard fire on CFST column-RC beam joints. Wang and Ding [12] experimentally investigated the response of CFST column-steel beam connections under fire exposure conditions and the temperature variation effect on the joint was measured. A numerical simulation of a Constrained CFT columns-steel beam connected by a reverse channel was investigated by Elsawaf et al. [13].

After the occurrence of the Northridge (California,1994) and Kobe (Japan, 1995) earthquakes, brittle fractures of the weld-flexural joints to high ductility demands were widely observed. The most extensive study has been conducted by the SAC committee leading to useful results published in the set of FEMA350 (2000). Several studies were conducted to improve the seismic performance of moment connections [14]. The reduced beam section (RBS) moment resistance is one of the most economical and popular connections among the post-Northridge prequalified ones. In comparison to straight and tapered cuts, radius cut RBS connections have shown improved seismic behavior [15]. RBS connections were designed based on a novel technique named "weakening". By this technique, the plastic capacity of the beam section is deliberately reduced in the vicinity of the column face to act as a fuse for damage and seismic energy absorption in this weakened region. There have been numerous studies on the seismic efficiency of different RBS connections. Chen and Chao [16] have experimentally investigated the effects of the floor slabs on the performance of the RBS connections. Jones et al. [17] have examined the cyclic response of the RBS connection with concrete slabs and different panel zones. Roeder [18], Ricles et al. [19], and Lee et al. [20] have investigated the plastic rotation capacity of the connections with variable panel zone strength. According to their research, strong panel zones would centralize all inelastic loads on the shortened segment of the RBS connection; thereby, they would have harmful effects on the deformation capacity of the connections. Zhang and Ricles [21] have demonstrated that a composite floor slab can provide restraint to the top flange of the beam and increase the ultimate load in the plastic hinge. According to Han and Moon [22], reduced beam sections with web bolted connections are not suggested if the span-to-depth ratio is less than ten and the beam flanges provide less than 70% of the section's overall flexural strength. Despite the many advantages of RBS connections, these connections would experience local buckling of beam web and are vulnerable to lateral-torsional buckling [23]. Several RBS connections with rectangular hollow sections [24], hollow webs [25], and reduced beam web height [26] have been proposed. Mirghaderi et al. [27] suggested an earthquake-resisting technique named AW-RBS connections with the provision of at least 8% story drift and efficient flange stability of the connected beam at larger rotational demands. Morrison et al. [28] experimentally studied HBS (heat-treated beam section connections) and presented that HBS connections experienced story drift as high as 6% without any weld or near weld fracture. Saleh et al. [29] attained approximate inter-story drifts of 6% without lateral-torsional buckling on newly developed tubular-web RBS connections. Zahrai et al. [30] utilized two pipes in TW-RBS for deep beams to increase plastic hinge length. A multitude of the literature review mentioned earlier has studied the performance of External, Through, and Internal diaphragm connections either subjected to fire or earthquake or fire after an earthquake event. These researches were investigated by Han et al. [31], Song et al. [32]. There is not enough research on the provision of fire-earthquake resistant connection with high ductility. The current study proposes an innovative connection to provide appropriate axial ductility enhancement in fire events simultaneous with favorable energy absorption in a seismic zone to prevent an abrupt failure and subsequent progressive collapse. Figure 1 depicts the configuration of the proposed connection, in this configuration, the beam web and flange are replaced with vertical and horizontal tubular sections in a restricted region near the column. Since the loss of material characteristics at high temperatures results in nonlinear behavior of structural components and given the limitations associated with costly fire tests, the construction of a numerical model is required. Therefore, the main objective of this paper is to develop robust numerical models to simulate the fire and seismic performance of innovative connections, separately. This study is divided into three parts. In the first part, discussed in section 2, relevant details about the numerical model of the proposed connection when exposed to fire are given including temperature field and stress analysis. When performing the model's thermal-mechanical analysis, two approaches may be proposed: performing either a sequentially or a completely coupled thermal-stress analysis. Since the completely coupled analysis requires long computational time and powerful computers, a sequentially coupled thermal-stress analysis is used in this investigation. The heat transfer model is first to run to obtain the temperature field of the connection during the ISO834 fire [33], and the temperature field findings are then imported as a predetermined field into the stress analysis model to execute the mechanical analysis. Based on the FEM model, the characteristics failure mode, midspan deflection of the beam, axial force variation of the beam, and plastic strain are the key aspects considered. In the second part, presented in section 3, due to the absence of experimental data, the mechanical subframe investigated by Liu et al. [34] is employed to verify the FE model. In the third part, detailed in section 4, finite element modeling of the proposed connection is conducted to assess the nonlinear cyclic response, the energy dissipated in the connection by plastic deformation and hysteresis curves.

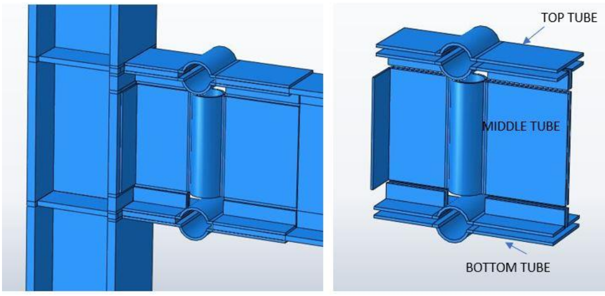


Figure 1. Assembly and related configuration of the proposed connection

2. NUMERICAL MODEL UNDER FIRE

2. 1. Heat Transfer Analysis

To simulate the effect of fire loading on tubular connections, ABAQUS software was used to run a Nonlinear FE model. The proposed subassembly, geometry, material, boundary conditions, and heating were modeled precisely the same as those used in the reference test [34, 35] in order to explore the effects of dimensional parameters on the fire resistance and ductility of tube connections. To save computational expense, only half of the beam was modeled, and a symmetric boundary condition was implemented at the beam midspan. The specification of these sections with an appropriately designed tubular connection is presented in Table 1.

2. 1. 1. Thermal Properties and Element Divisions

For structural steel, the temperature-dependent properties including thermal conductivity coefficient, specific heat, and density recommended in EN1993-1-2 (CEN 2005) were employed in the current

TABLE 1. Specification of Tubular RBS connection

Column section (mm)	UKC 305*305*198
Beam section (mm)	UKB 533*210*109
Inner radius of semi cylindrical Tubular RBS section (mm)	50
Connection depth (mm)	360
Beam span (m)	7.5

FE model. The model was meshed using 8-node brick elements (DC3D8). The results of the sensitivity of simulation presented that mesh sizes of 10 and 20mm are ideal for the finer and coarser areas of main structural elements. Nodal temperatures were saved as output data and then exerted to the mechanical model as the findings of temperature field analysis.

2. 1. 2. Thermal Boundary Condition and Loading

The heat is first transported to the outside surfaces subjected to fire via convection and radiation in the transient heat transfer analysis, followed by conduction into the internal surfaces of the members. The emissivity of a material is the ratio between the radiative heat absorbed by a surface made of this material and that of a black body surface. The temperature of the air as determined by the ISO834 standard fire curve, the fire temperature-time relationships and boundary conditions during the heating stages are presented by Equations (1), and (2), respectively.

$$T = T_0 + 345log_{10}(8t + 1) \tag{1}$$

$$-k\,\partial T/\partial n = \alpha\left(T_{m,t} - T_{g,t}\right) + \varepsilon\sigma\left[(T_{m,t} - T_z)^4 - (T_{g,t} - T_z)^4\right] \tag{2}$$

Table 2 lists the constants of the heat transfer run.

2. 2. Structural Analysis

2. 2. 1. Loading and Boundary Conditions

Two steps were considered in the second structural model. In the first step, three levels of loading (load ratios of 0.3, 0.4 and 0.5) were applied to the beam flange at ambient temperature and were kept constant throughout the whole analysis. The load ratio is designated as the ratio of the applied load under fire conditions to the design bearing capacity of the simply-supported beam at room temperature. In the second step, a transient time-temperature heat loading was applied as a predefined field. The * NLGEOM=ON was set to tackle such a geometric nonlinear analysis. Since the excessive deflections caused development of catenary action in the model, the simulated method proposed by Dai et al. [36] was used to achieve numerical stability with the static solver. The selection of a suitable damping factor (0.00001-0.00002) was tested by evaluating the applied loads in relation to the support reaction force and by restricting the ratio of damping dissipated energy to total strain energy (ratio of parameter ALLSD to ALLIE in ABAQUS) to roughly 10%. Figures 2a and 2b illustrate the thermal and mechanical boundary conditions of assembly for the proposed connection. Also, Beam to the column and tubes are bounded together with tie constraints to simulate the welded zones.

TABLE 2. Thermal constants and parameters used in heat transfer modeling

Parameter	Definition	Value
α	Coefficient of convection	25 W/m^2 K
ε	Resultant emissivity	0.5
σ	Stephan-Boltzmann constant	5.67*10^{-8} W/m^2 K^4
T_z	Absolute zero temperature	-273.15°C
T_0	Initial temperature	20°C

2. 2. 2. Material Mechanical Properties and Element Divisions

Material properties required in the stress analysis generally include elastic and plastic properties with thermal expansion coefficients. For steel, temperature-dependent values of stiffness (E) and thermal expansion coefficient (first derivative of thermal elongation) from EN1993-1-2 [37] were adopted, while the Poisson's ratio was considered to be temperature independent and a constant coefficient of 0.2 was selected. Note that the effect of thermal creep was not considered in this study. The stress-strain relationships at the ambient and heating stages are different for structural steel. A user-developed material subroutine UHARD was implemented to simulate the temperature-dependent mechanical properties recommended in EN1993-1-2 [37]. For the UHARD subroutine, the input parameters are, $\partial\sigma^0/\partial\bar{\varepsilon}^{pl}$, $\partial\sigma^0/\partial\dot{\bar{\varepsilon}}^{pl}$ and $\partial\sigma^0/\partial\theta$ in which $\bar{\varepsilon}$ pl is equivalent plastic strain, $\dot{\bar{\varepsilon}}$ pl is equivalent plastic strain rate, σ^0 is SYIELD and θ is the temperature. In the second structural model, the solid element with reduced integration (C3D8R) was employed to manage the hourglass modes. Moreover, at least two layers of elements in the thickness direction of the beam and tubes were used to prevent premature buckling. The same element meshing and node numbers used in the temperature analysis model were adopted in the structural analysis model.

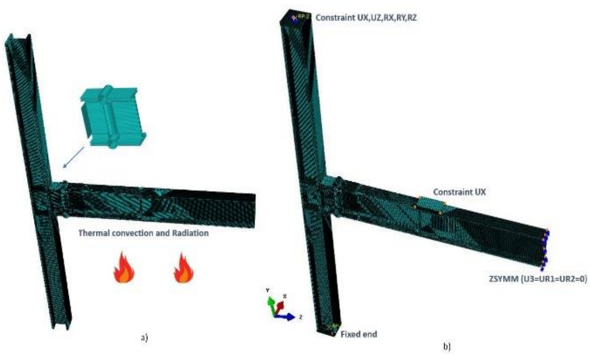


Figure 2. a) FE model for heat transfer analysis, b) FE model for mechanical analysis

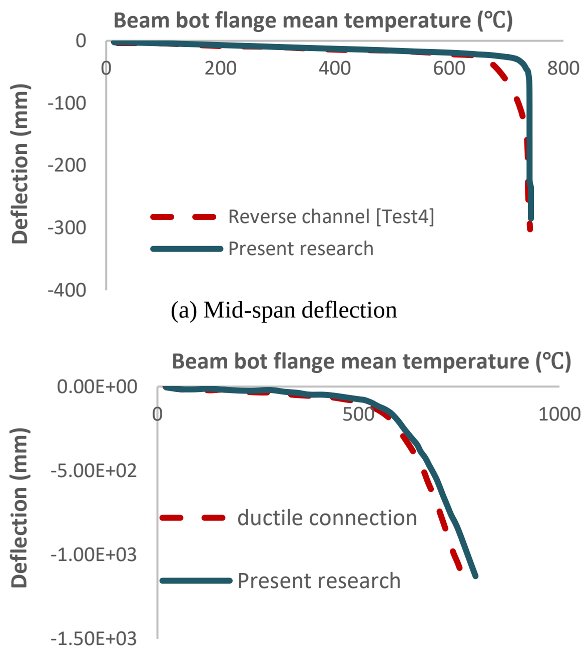
3. NUMERICAL RESULTS

3. 1. Verification of the FE Model

The experimental and numerical results of Wald et al. [38], Elsawaf et al. [13] and novel connection in the fire incident reported by Liu et al. [34, 35] were utilized to validate the FE model. In this paper, only the result of ductile connection in long-span beam [34, 35] and reverse channel connection in short-span beam [13] are presented. The steel sub-frame model [34, 35] consists of a beam connected to the column via a cylindrical connection. In the heat transfer model, the temperatures of connection and the lower column were about 50% of the temperature of the bottom flange of the beam. In the structural model the beam was initially exposed to an external load (load ratio 0.4) to generate the required moment. Then the temperature of the structure was gradually increased until the sub-frame failed to be convergent. Figures 3(a) and 3(b) demonstrate comparative results (mid-span deflection curves of the beam) between the frame [34, 35] or [13] predicted by the present research and the original studies. Based on Figures 3(a) and 3(b), the highest beam deflection was approximately 300 mm (15% of the beam span) and 1000 mm (13% of the beam span). The maximum deflection observed during the experiment [13] was 302 mm. The maximum deflection predicted by the present research was 285, a difference of only 5.6%. Furthermore, the difference between the maximum deflection of the original study [34, 35] and the present research was about 7%. These are very large deflections. According to these results, the FE model accurately captured the transition process from compression to tension in the beam during the fire and confirmed the model's capability to simulate large deflection behavior. However, using the different locations of measuring beam temperature may also lead to some minor differences in comparative results.

3. 2. Numerical Results of HP-T Connection

A parametric study was carried out to investigate the influence of tubular flange and web thickness of the proposed connection on its failure mode in the fire. The specifications of tubular connection with a constant height (360mm) are summarized in Table 3. In this table, the thickness of tubular flange and web vary for different models. TC1, TC2, TC3 and TC10 (series I) models, failed due to the formation of plastic hinges in the bottom flange tube in a specific location as shown in Figures 4 and 6. TC6 (series II) models failed due to bottom flange tube damage and minor-web local buckling (MI-WLB) as shown in Figure 5. For TC8 (series III), the damage mode of moderate-web local buckling (MO-WLB) was observed. Figures 7(a) and 7(b) show the relationship between mid-span deflection



(a) Mid-span deflection

(b) Mid-span deflection

Figure 3. Mid-span deflection investigated by a) Elsawaf [13] and, (b) Liu [34, 35] and present research

TABLE 3. Summary of the thermal models

Model series	Model Number	Top-bot tube thickness (mm)	Mid tube thickness (mm)	Load ratio
	TC1	9	5	0.3
I	TC2	9	6	0.3
	TC3	9	7	0.3
	TC4	10	5	0.3
II	TC5	10	6	0.3
	TC6	10	7	0.3
	TC7	11	5	0.3
III	TC8	11	6	0.3
	TC9	11	7	0.3
II	TC10	9	7	0.5

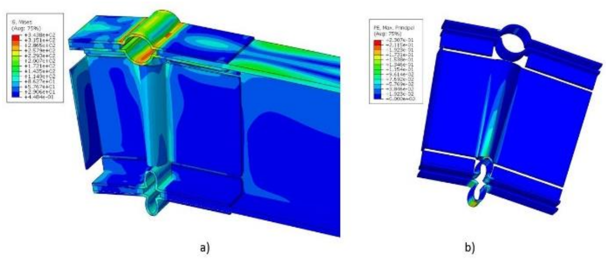


Figure 4. (a) Von mises stress, (b) strain counters at TC3 (plastic strain)

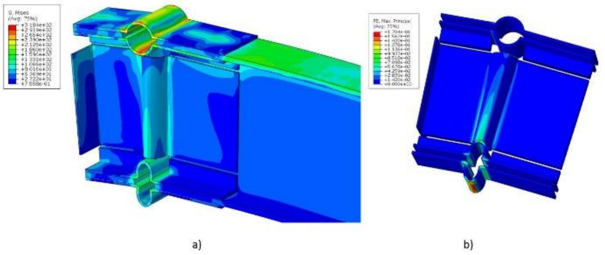


Figure 5. (a) Von mises stress, (b) strain counters at TC6 (plastic strain)

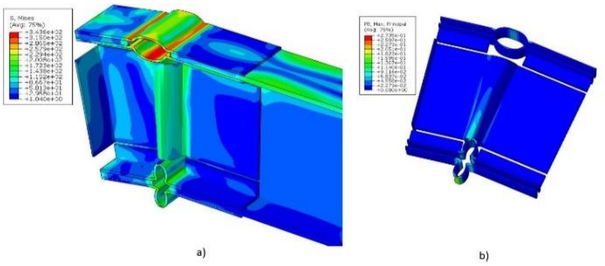
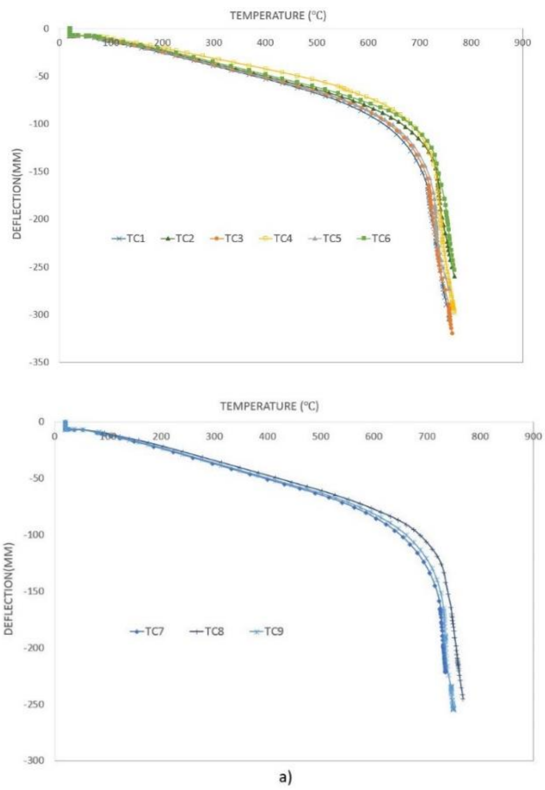


Figure 6. (a) Von mises stress, (b) strain counters at TC10 (plastic strain)

and beam axial force and temperature at the beam bottom flange. The results indicate that the proposed HP-T connection has the potential to develop more substantial catenary action and higher ductility through the deformation of the tubes.



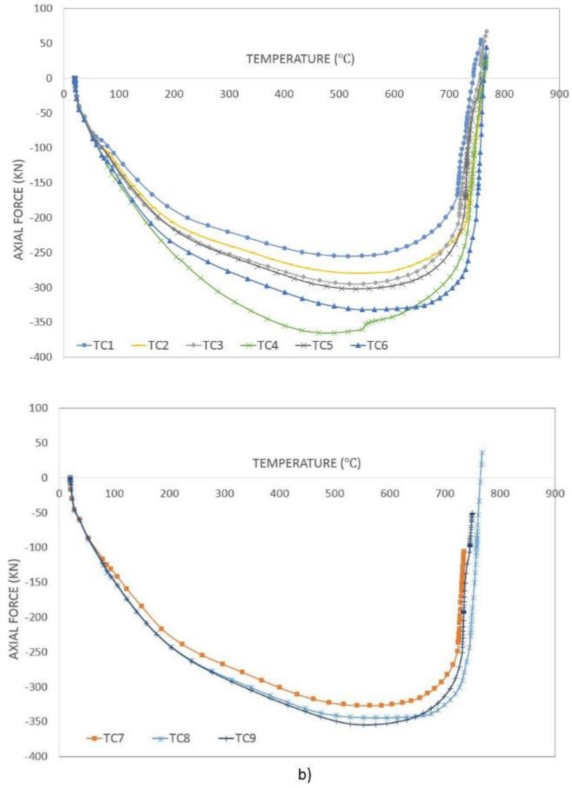
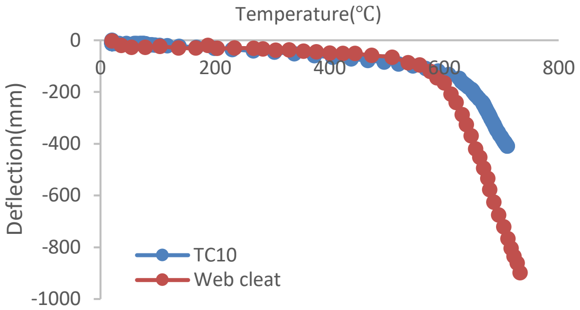


Figure 7. (a) Mid-span deflection, (b) Axial force of beam with HP-T connection

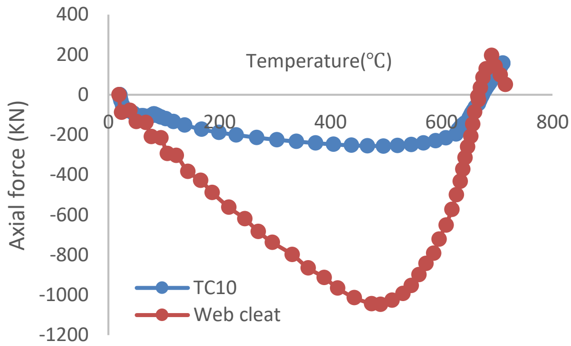
3. 3. Comparison of the Proposed Connection with Other Connection Types Figures 8(a) and 8(b) show the mid-span deflection and beam axial force versus beam bottom flange temperature curves of HP-T connection and conventional web cleat connection. Figure 8 indicates that the interactions between structural components trigger permanent changes in the internal forces of the connection during the fire. Not only was the thermally-induced force in the beam with new connection considerably reduced due to the high axial ductility capacity created, but also sufficient ductility was provided to accommodate the deformations generated by the attached beam exposure to fire.

4. SEISMIC PERFORMANCE OF HP-T CONNECTION

4. 1. Design Procedure of Tubular Connections The connection design approach is according to AISC seismic provisions [39] and according to the philosophy of AW-connection [27]. The foundation of the design of such seismic joints is the formation of a plastic joint in the reduced area of the beam and the uniform distribution of plastic strains in this area, in order to delay torsional buckling and avoid instability.

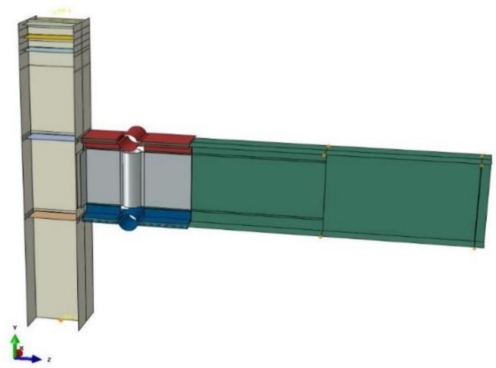


(a)

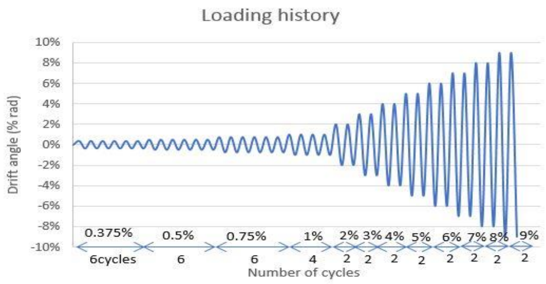


(b)

Figure 8. Results Comparing the new connection with Web cleat connections, (a) Deflection at beam mid-span (b) Axial force of beam



(a)



(b)

Figure 9. (a) 3D finite element modeling of HP-T connection, (b) Loading history

4. 2. Numerical Model Under Seismic Loading The proposed sub-assembly utilized in laboratory studies investigated by Saleh et al. [29] was chosen to simulate seismic behavior. It consisted of an exterior joint with a 2.4m beam attached to a 2m column. The specification of the seismic models is presented in Table 4. It should be highlighted that appropriately designing continuity plates in seismic demands not only tolerate a couple of concentrated forces from the beam's flange but also conversely convert the axial force to shear force in the panel zone. The 3D FE model is illustrated in Figure 9(a).

4. 2. 1. Geometry and Finite Element Mesh Two FE models were established to analyze the seismic performance of the HP-T connection. The geometries of the beam, column, and tubular connection were created separately, and were then assembled to form the model of beam-column connection and were bounded together with tie constraints. According to reference test [29], beam, column, connection, and continuity plates were modeled using 4-node shell elements with reduced integration (S4R). These elements include six degrees of freedom per node and three-section points to assess stress and strain variation through the thickness.

TABLE 4. Specification of the seismic models

Model number	**TC11**	**TC12**
Inner radius of Tubular RBS connection (mm)	50	50
Top-Bot tube thickness (mm)	9	10
Middle Tube thickness (mm)	7	6
Middle tube depth (mm)	360	360

4. 2. 2. Material Properties The behavior of steel was modeled by a nonlinear kinematic hardening model with a von mises yield criterion. The mechanical characteristic, i.e. young's modulus and Poisson's ratio were set to be 206 GPA, and 0.3, respectively. The yield strength (F_y) and ultimate strength (F_u) and also elongation was the same as the reference test [29].

4. 2. 3. Boundary Condition and Loading The standard solver of ABAQUS software was used to analyze the model. Based on the reference test [29] condition, the bottom of the column was modeled with a pinned end (the displacement of the centers of the column was constrained in the x, y, z directions $U_x = U_y = U_z = 0$). By fixing the degree of freedom in vertical direction ($U_y = 0$), roller support was defined at the beam end. Moreover, to define lateral support, out-of-plane displacement of beam web was fixed at x-direction from the side of the column ($U_x = 0$). The displacement-controlled loading was imposed on the structure by defining boundary conditions on top of the column based on AISC seismic provisions [40]. Total story drift was calculated by dividing lateral displacement at the top of the column-by-column height. Figure 9b demonstrates the adopted loading protocol.

5. NUMERICAL RESULTS

5. 1. Hysteretic Graph The lateral force-total story drift cyclic curves are presented in Figure 10 for the proposed connection. The suggested connection meets AISC seismic [39] approval standards, confirming that the strength reduction of connection should not reduce flexural capacity at 0.04-radian to less than 80% of the nominal flexural capacity and special moment frame connection tolerates at least 0.03-radian story drift. As can be seen in Figure 10, the connection provides a stable and cyclic behavior without strength reduction up to 9% story drift.

5. 2. Investigation of the Plastic Hinge Behavior and Failure Modes The Von-Mises stress and strain contours of drift angles 0.04, 0.06, and 0.08-radian are illustrated in Figures 11 and 12. The extension of the plastic hinge in the predetermined zone (9cm from the column edge) is proved by greater values

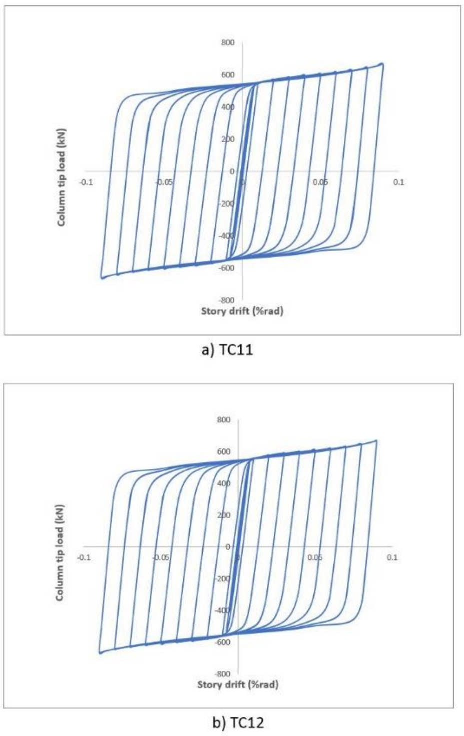


Figure 10. Column tip force versus story drift for HP-T connection a) TC11, b) TC12

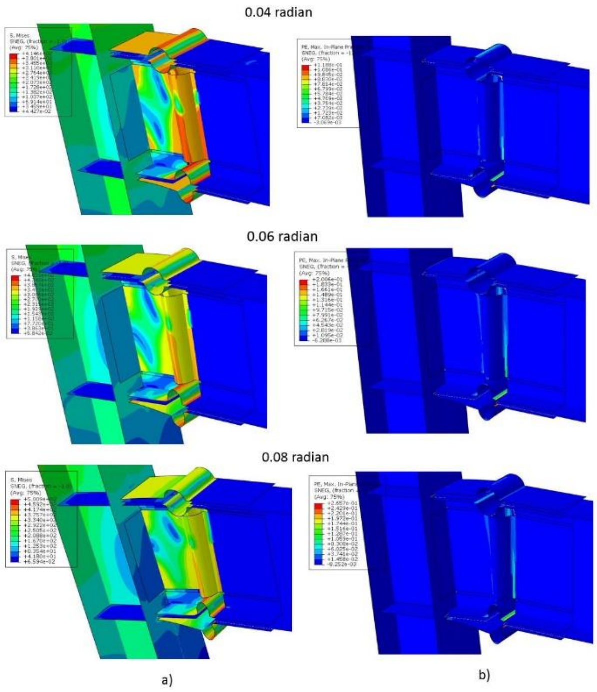


Figure 11. a) Von mises stress, b) strain counters at 0.04, 0.06 and 0.08 radian story drift (TC11)

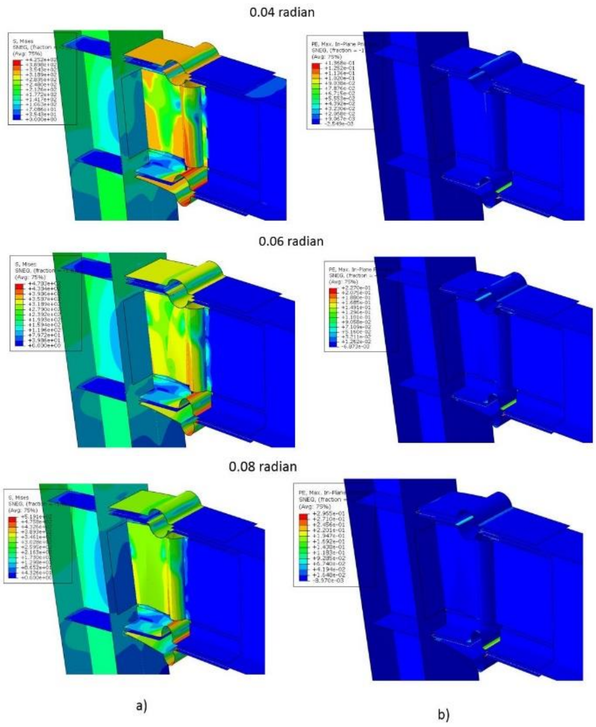


Figure 12. a) Von mises stress, b) strain counters at 0.04, 0.06 and 0.08 radian story drift (TC12)

of the plastic strain created in the beam flange, while the rest of the reduced area remains elastic. In other words, approaching the column face, the plastic strain diminishes and dramatically reduces the risk of failure at the welds in the beam-column connection. According to the results, local buckling of the middle tube at the reduced region occurred at 4% story drift.

6. CONCLUSION

The proposed connection is made through cutting continuous web and flange and replacing these parts with horizontal and vertical tubes at the designated position of the plastic hinge. The numerical validation of an innovative fire-earthquake resistant connection called HP-T connection is presented. To assess failure mechanism and plastic hinge formation models with variable tube thicknesses are simulated under fire and seismic loading separately. Based on the findings, the following can be concluded.

- The main exclusivity of using HP-T robust connection is satisfactory fire behavior with provision of appropriate axial ductility to reduce the compressive axial force which arises from thermal expansion of the connected beam and catenary tension forces generated by the beam exposed to fire.
- All of the numerical models, except for TC7, TC9, behaved in a ductile and robust manner in fire simulation. According to the results of the parametric study, under the tensile axial forces arising from the catenary action of the beam at elevated temperatures two damage scenarios were detected, namely bottom flange tube damage with minor beam web local buckling and bottom flange tube damage without beam web local buckling. Series I RBS connections exhibited much higher axial ductility through the development of more substantial catenary action as well as no beam web buckling being observed.
- The developed FE models can accurately predict the hysteretic behavior of the proposed connection. It is noteworthy that the HP-T connection displayed ductile seismic response and a large hysteretic enclosed area and more energy dissipation capacity. The HP-T connection can transfer the plastic strain zone away from the column edge and effectively concentrate the plastic strains zones within the flange tubes and as a result, prevent progressive failure.
- The HP-T connection can support 0.09 rad drift without any significant strength reduction which is higher than those stipulated by existing seismic codes for qualifying connections in a seismically active area. Besides, no lateral-torsional buckling (LTB) occurred at HP-T connection even in higher story drift.
- The discussed connection possesses a great potential to become one of the most practical ones. Nevertheless, experimental research is needed to assure the suitability of this innovative connection for eventual industry implementation.

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Persian Abstract

چکیده

اتصال ابتکاری تاب آور در برابر آتش سوزی و زلزله بنام اتصال لوله ای با عملکرد بالا (HP-T)، در مقاله حاضر ارائه گردیده و اعتبار عددی آن تایید شده است. اتصال HP-T، شکل پذیری محوری و دورانی را افزایش داده و همچنین از گسیختگی ترد جلوگیری می کند. دوسری از مدل ها با موفقیت در نرم افزار آباکوس شبیه سازی شدند. تحلیل تنش حرارتی کوپله متوالی، در اولین مجموعه از مدل های طراحی برای شبیه سازی حرارت، جهت بررسی اثرات پارامترهای مختلف ازجمله ضخامت لوله و نسبت بار اعمالی انجام گردید. بمنظور شبیه سازی آسیب آتش سوزی، دو سناریو احتمالی آسیب لوله بال پایینی و آسیب جان تیر در معرض توام بارگذاری اولیه و حرارت در نظر گرفته شد. در مجموعه دوم مدل های شبیه سازی لرزه ای، مود گسیختگی، منحنی های چرخه ای و توزیع کرنش مورد تجزیه و تحلیل قرار گرفتند. با توجه به نتایج، اتصال مقاوم HP-T نه تنها افزایش شکل پذیری مناسب را در شرایط آتش سوزی متغیر نیرو فراهم می کند، بلکه حداقل ۸ درصد جابه جایی نسبی میان طبقه را بدون کاهش مقاومت قابل توجه تحمل می کند.