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Numerical analysis of channel connectors under fire and a comparison of performance with different types of shear connectors subjected to fire

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Abstract. The behavior of shear connectors plays a significant role in maintaining the required strength of a composite beam in normal and hazardous conditions. Various types of shear connectors are available and being utilized in the construction industry according to their use. Channel connectors are a suitable replacement for conventional shear connectors. These connectors have been tested under different types of loading at ambient temperature; however, the behavior of these connectors at elevated temperatures has not been studied. This investigation proposes a numerical analysis approach to estimate the behavior of channel connectors under fire and compare it with the numerical analysis performed in headed stud and Perfobond shear connectors subjected to fire. This paper first reviews the mechanism of various types of shear connectors and then proposes a non-linear thermo-mechanical finite element (FE) model of channel shear connectors embedded in high-strength concrete (HSC) subjected to fire. Initially, an accurate nonlinear FE model of the specimens tested at ambient temperature was developed to investigate the strength of the channel-type connectors embedded in an HSC slab. The outcomes were verified with the experimental study performed on the testing of channel connectors at ambient temperature by Shariati *et al*. (2012). The FE model at ambient temperature was extended to identify the behavior of channel connectors subjected to fire. A comparative study is performed to evaluate the performance of channel connectors against headed stud and Perfobond shear connectors. The channel connectors were found to be a more economical and easy-to-apply alternative to conventional shear connectors.

Keywords: composite structures; finite element modeling; channel connectors; elevated temperatures; load-slip relationship

1. Introduction

The efficiency of a composite beam significantly relies on the capability of shear connectors to transfer shear force at the steel-concrete junction. The importance of the shear connectors increases when the fire safety design of the building is considered. In case of fire, both the concrete and steel parts experience a considerable amount of heat, which is indirectly transmitted to the associated shear connectors by the top flange of the steel part. To obtain a structural

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performance of composite beams subjected to fire with less error, care should be taken to ensure an efficient shear transfer between different parts of the structure. According to statistics, almost 70% of structural damages occur on the connecting part. Therefore, in the analysis and optimization of composite structures, the key point is the prediction of the connection behavior by identifying the influence of each parameter on the joint strength.

Shear connectors are classified according to their geometry, the distribution of shear forces, and the functional dependency between the strength and the deformation. To resist shear forces and perpendicular uplift in steel-concrete composite beams, the head stud, which is the most commonly used type of shear connector, is utilized (Fig. 1). The head stud shear connector is designed to work as a curved welding rod, and, simultaneously, after welding, it resists the shear forces and perpendicular uplift in the structure. Perfobond connector was developed in Germany and includes a welded steel part with a number of holes (Fig. 2). When the concrete passes through the holes of the ribs, it forms dowels, thereby enabling the connector to perform the desired actions. This type of connector is a feasible substitute for the headed stud connector. From the Perfobond connector, an improved shear connector called the T-Perfobond connector was developed. The derivation of a new connector from the Perfobond connector was created by adding a flange to the plate, which acts as a block (Fig. 3). The need to combine the large strength of a block type connector with some ductility and uplift resistance that arise from the holes at the Perfobond connector web is a motivating factor for the development of this T-Perfobond connector.

For many years, the use of the headed and Perfobond studs has been preferred by professionals. However, in recent times, channel connectors have been proven to be a more economical solution than other connectors. These types of connectors do not require any specific welding arrangement

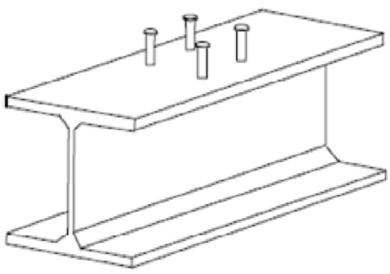


Fig. 1 Headed stud shear connector

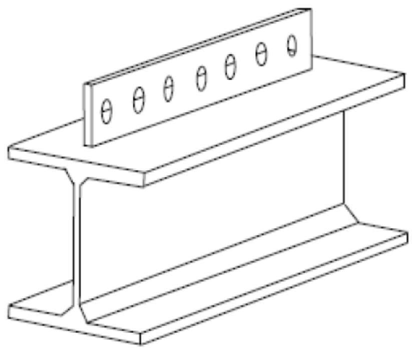


Fig. 2 Perfobond rib shear connector

Fig. 3 T-Rib shear connector

Fig. 4 Channel shear connectors in bridge and building structures

and on-site examination. Furthermore, these connectors possess reliable load carrying capacity (Shariati *et al*. 2012).

Channel connectors may provide economic and enhanced performance in many construction applications, such as composite beams and girders in buildings and bridges (Fig. 4) under fatigue and monotonic loading (Maleki and Bagheri 2008, Shariati *et al*. 2012), and can be efficiently embedded in fiber-reinforced concrete (Shariati *et al*. 2010), plain reinforced, and lightweight concrete (Shariati *et al*. 2011), solid and metal deck slabs (Pashan 2006), and high-strength concrete (HSC) slabs.

The strength of composite beams subjected to fire mainly depends upon its strength and how the flow of heat occurs inside the beam components. Therefore, the main components that affect these properties are the concrete slab, steel reinforcing, structural steel, and shear connectors. Numerical investigations on different types of connectors at ambient temperature are extensively available. However, research that predicts the structural behavior of the channel connectors under elevated temperature is almost non-existent. With regard to FE modeling of different types of shear connectors subjected to fire, Lam and El-Lobody (Lam and El-Lobody 2005) and El-Lobody and Young (Ellobody and Young 2006) tested the shear connectors embedded in solid and profiled type slabs. Nguyen and Kim (Nguyen and Kim 2009) developed a finite element (FE) model of headed connectors, which includes material nonlinearities of concrete, headed stud, steel beam, and rebar. The concrete slab, steel beams, and headed stud were meshed with an eight-node brick element (solid element) with reduced integration stiffness. Each node has three translational degrees of freedom. The steel beam and headed studs were meshed with the eight-node 3D cohesive element, and the rebar part was modeled by the truss element. Meaud *et al*. (2014) performed an experimental and non-linear FE study on steel–concrete bonding interface. A four-node element was used to mesh both the steel and concrete elements. A four-node adhesive element was used to mesh the bonding joints. The size of elements was reduced to ensure convergence and to keep the results independent from the mesh.

In addition to the channel connectors, the FE model of different types of shear connectors was also subjected to fire. Huang *et al*. (1999) modeled a 3D procedure for the analysis of shear connectors under fire. In statically determinate elements, the failure of connectors abruptly changes the behavior at high temperatures. Ranzi and Bradford (2007) proposed a numerical model to analyze both the longitudinal and transverse interactions in the composite beams subjected to fire. The study highlighted the importance of combining tension and shear force to determine the full capacity of the shear connectors. Mirza and Uy (2009) analyzed the solid and trapezoidal profiled slab subjected to fire by proposing a 2D thermal and 3D mechanical model. Three-dimensional solid elements were used to model the push-out samples. For both the concrete slab and structural steel beam, a 3D solid eight-node element was used to improve the rate of convergence. A second-order 3D 30-node quadratic brick element was adopted for shear connectors. A four-node double curved thin shell element was used for the profiled steel sheeting with six degrees of freedom. The reinforcement was modeled by a two-node linear 3D truss element that kept the axial direction released. The analysis did not focus on the slip amount between the concrete and steel bars. The failure occurred because the concrete cracked and crushed prior to the fracture of the shear connectors near the weld collar. Results showed that the area of the concrete under elevated temperature significantly dominates the failure.

Wang (2011) performed a numerical investigation on the behavior of shear connectors using FE modeling techniques. The temperature of the bottom layers in the concrete was considerably higher than that in the other portions, thus causing the connectors to fail in an overturning mode instead of shearing-off mode, which leads to a low strength. Fahmi Hani and Tamara (2012) proposed a nonlinear 3D FE model to analyze composite beams subjected to BS476 fire test. Thermal analysis was incorporated by modeling the solid slab and steel beam using eight node isoparametric brick elements. The eight-node isoparametric brick elements have been used to model the reinforced concrete slab in the structural analysis. The eight-node isoparametric structural solid brick elements were used to model the steel beam, whereas the shear connectors were modeled using truss (spar) elements and nonlinear spring elements to resist slip and uplift the separation between the steel beam and concrete slab. The number of shear connectors highly influenced the beam failure. Thus, the fire resistance of the composite beam decreased significantly by reducing the number of connectors. Quevedo and Silva (2013) analyzed the push-out tests performed under fire. The sensitivity of the calibrated model to various connector diameters and heights was also assessed. Furthermore, different alternatives on the level of concrete temperatures were evaluated. Their model concluded that the shear connector height, the concrete compressive strength, and the concrete temperature greatly affect the shear strength of a connector. The concrete failed prior to the failure of the connector.

Majdi *et al*. (2014) modeled the concrete slab by using 3D solid elements, whereas all steel parts were modeled using 2D shell elements because of their small thickness. A continuous hat channel (furring channel) was modeled as the shear connector, and FE analysis of new composite floors that have cold-formed steel and concrete slab was performed. Recently, Lu *et al*. (2012) investigated the behavior of shear connectors in cold-formed steel sheeting at elevated temperatures by using FE modeling. The connections were heated to different levels of isothermal conditions. The end of a thick plate is fixed, and the end of a thin sheet can be either free or fixed.

Almost no research has been conducted on predicting the structural behavior of channel connectors at elevated temperatures. The successful use of channel connectors at ambient temperature as a replacement for other popular types of connectors (Shariati *et al*. 2012) proves that it is an efficient tool for safe transmission of longitudinal shear forces when a composite beam is subjected to fire. Channel connectors may perform relatively better than the other types of connectors.

The behavior of channel connectors subjected to fire has been completely ignored. In this study, the monotonic experimental results of (Shariati *et al*. 2012) are validated by an FE model. After validation, the FE model at ambient temperature was further extended to a thermal FE model using the finite element package ANSYS to investigate the performance and behavior of channel shear connectors embedded in an HSC and subjected to elevated temperatures. A total of 50 FE models were prepared according to the varied sizes of specimens. Second-order 3D solid elements were used to simulate the push-out specimens to improve the convergence rate and ensure high accuracy. The thermal actions were applied in accordance with the standard ISO fire test (Tests 1975). The guide for modeling the push-out specimens and channel connectors for ambient and thermal models was adopted from literature (Mirza and Uy 2009, Nguyen and Kim 2009, Fahrni Hani and Tamara 2012). Finally, a non-linear thermo-mechanical FE model of channel shear connectors embedded in HSC subjected to fire is proposed. A comparative study was then carried out. The results of the FE modeling of channel connectors at elevated temperature were compared with the results of numerical testing of headed stud and Perfobond connectors tested under fire, and are available in the literature.

2. Finite element analysis at ambient temperature

2.1 Specimen details

Models have been created using the special abilities of the ANSYS for non-linear static analysis and modeling push-out specimen in case of contact surface problems. The channel shear connectors were used to satisfy the shear and uplift resistance of composite systems. The push-out geometrical FE modeling of channel shear connector is shown in Fig. 5. The specimens have been assigned with specific names to identify each behavior. The geometrical properties of the specific push-out specimens are given in Table 1. The mix proportion and material properties for the HSC slab are shown in Table 2, and the material properties for the steel section are provided in Table 3.

The main reason for using ANSYS software is its exceptional ability in the analysis of the issues with regard to the plasticity and mechanical problems associated with this research. The application of the linear and non-linear static analysis is used in this research. In the modeling of the push-out tests, the concrete slab size is 300 mm × 250 mm × 150 mm. Only half of the slab is modeled because of symmetry. The channel section has a height of 100 mm, web thickness of 6 mm, and flange thickness of 8.5 mm; the channel length is 50 mm. The concrete compressive strength is 38 MPa in all cases. The steel part dimensions are shown in Fig. 6.

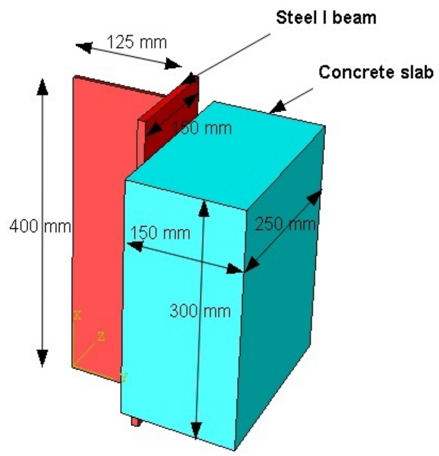


Fig. 5 Push out geometric modeling

Table 1 Geometrical properties of specimens SP-1 to SP-6

Specimen ID	Height (mm)	Length (mm)	Web thickness (mm)	Flange thickness (mm)
SP-1	75	50	5.0	7.5
SP-2	75	30	5.0	7.5
SP-3	100	30	6.0	8.5
SP-4	100	50	6.0	8.5
SP-5	60	30	4.0	7.0
SP-6	60	50	4.0	7.0

Table 2 Mix proportions of high strength concrete materials

Mix No.	Cement (kg/m^3)	Coarse aggregates (kg/m^3)	Fine aggregates (kg/m^3)	Water (kg/m^3)	Silica fume (kg/m^3)	SP (%)	W/C	Modulus of elasticity (GPa)	Compressive strength (MPa)
H_1	460	910	825	168	40	0.5	0.37	39	82
H_2	360	940	870	180	-	1	0.50	32	63

Table 3 Material Properties of steel

Member	Young's modulus (*E*)	Poisson's ratio (*v*)	Yield strength (*fy*)	Ultimate strength (*fu*)
Steel I beam & Shear connector	205	0.3	283	385

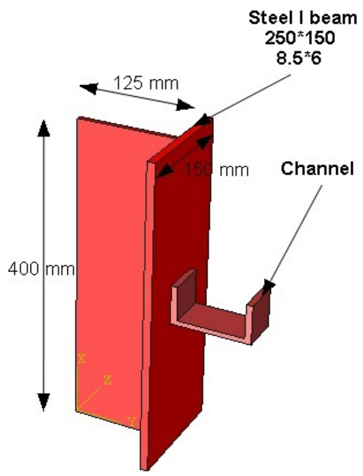


Fig. 6 Steel parts in push-out specimen

2.2 Finite element type, mesh, boundary conditions

The push-out samples are modeled using 3D solid elements. Much attention has been paid to minimize the convergence issues. Thus, a 3D eight-node element (C3D8R) is used for both steel and concrete parts. Shear connectors have been modeled using second-order 3D 30-node quadratic brick element (C3D30R) for better results. The steel reinforcement is modeled using a two-node linear 3D truss element (T3D2), and the axial direction is kept released.

Fig. 7 shows the FE mesh and boundary condition for the solid slab model. Fig. 8 shows the typical FE mesh of half of the push-out specimen to the geometry model of the tested specimen. Fig. 9 shows the steel part mesh in the push-out specimen. The mesh size was selected to fully achieve accuracy and a reasonable computational time. The FE mesh was applied to half of the connector to minimize the simulation time and represent half of the channel of the push-out test to optimize the simulation procedure. The rest of the specimen was assigned the coarse mesh, whereas the fine mesh was used to surround the channel connectors.

For all the modeled components, the nodes that lie on the other symmetrical surface (Surface 1) are constrained in the x-axis. The nodes at the center of beam web (Surface 2) are kept constrained in the y-axis. Surface 3 consists of the nodes assigned to the concrete element and are kept constrained to move in z-axis.

2.3 Loading

A well-known Riks method was utilized to concentrate the static load in the middle of the web.

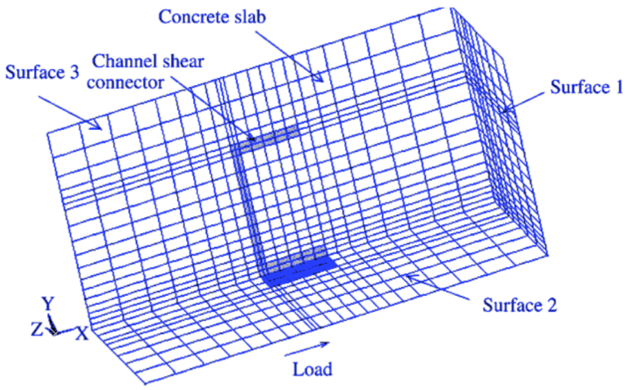


Fig. 7 Finite element mesh and boundary condition of the solid slab model

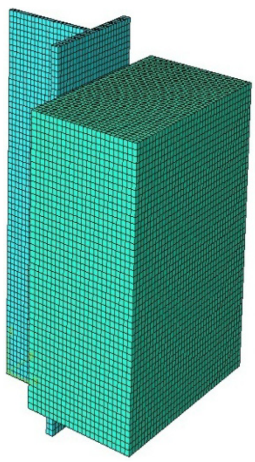


Fig. 8 Meshing of whole the half push-out specimen

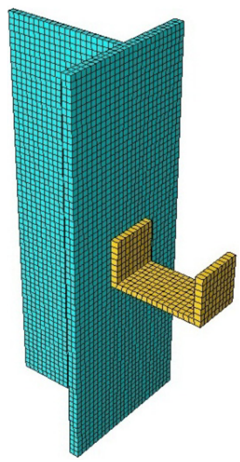


Fig. 9 Meshing of steel part in push out specimen

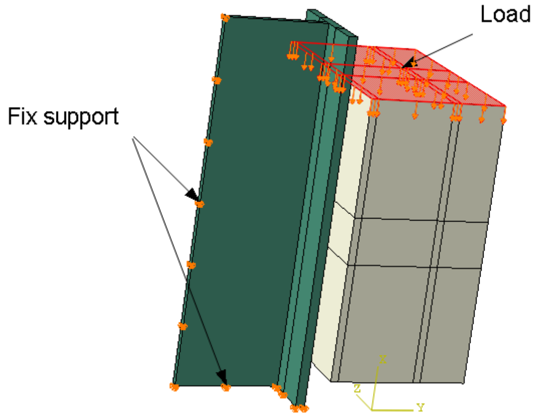


Fig. 10 Loading with respect to boundary condition in the push out specimen

This method can be achieved by an iteration series for each increment when simulating a non-linear structure and simulation of any unloading event in the structure. The load magnitude has been used as an additional unknown; it solves for the loads and displacements simultaneously. Riks method can adjust the initial increments in the case of convergence issues. Load control of 0.04 mm/s for all specimens was used for loading rate, as shown in Fig. 10.

2.4 Interaction

To model the interaction among the components, the general contract method was employed since it is an important part in the analysis and needs to be given more attention as inappropriate interaction may cause a convergence problem. The FE analysis is dependent on an accurate definition of the relation between the parts. Two steps were considered to define the interaction between steel, concrete and reinforcing parts, embedded element and contact interaction. The interaction between the reinforcing bars and the concrete slab was assumed to be full bond with no slip between them.

The contact and interaction between the column and infill, and between the beam and infill is provided through an angle section. The properties of these interactions are introduced to express the behavior of the tangent to the contact surface. The friction coefficient of 0.3 is used because of the popularity of the Mandar behavioral model for concrete for confining biaxial behavior.

2.5 Coupled thermo-mechanical load characterization

As two independent processes, mechanical and thermal loading may present arbitrary time histories. For generality and in reference to a fire event characterized by an arbitrary fire–loading curve, the mechanical loading takes place after a fire event has reached its maximum temperature (anisothermal fire loading) at sustained temperature conditions (isothermal fire loading). The FE analysis adopted in this study is based on an isothermal fire loading process.

2.6 FE modeling at elevated temperature

High temperature produces considerable degradation in the properties of a composite structure. In addition, the behavior of a composite beam at elevated temperature is controlled by the rate of heating. This investigation analyzes both the mechanical and thermal response of channel connectors. The mechanical analysis is tested by simulating the testing of specimens at ambient temperature. In thermal analysis, the time versus thermal distribution in specimen components are simulated.

2.7 Structural analysis

For the purpose of structural analysis, the specimen was prepared and simulated according to the testing protocols mentioned in Eurocode 4 (1994). On the basis of the theory that the steel beam transmits the load equally to the channel connectors, only one connector is attached to each flange of steel beam.

2.8 Temperature analysis

Keeping the geometry of specimens equal, the thermal analysis is carried out separately from the structural analysis. Thermal analysis is considered more complicated than structural analysis because the material properties could differ from member to member, and the change in behavior of all materials is not identical under an elevated temperature (Eurocode 1994).

The effects of temperature are charted as a temperature–time curve, which provides the typical temperature in case of a fire event in the furnaces utilized for testing purposes. Relevant design standards use the heat exposure given by ISO834 (Tests 1975) as testing basis, in which T is the mean temperature (°C) and t is the time (min).

A simulation of flow of temperature in a composite slab was performed by Cooke *et al*. (1988) and the time-temperature curve was determined, which was later verified accurately by Lamont *et al*. (2004) using a software. This study adopted simulation approaches that are similar to those that were used in (Cooke *et al*. 1988, Lamont *et al*. 2004). The ideal temperature distribution diagrams for a solid concrete slab are presented in Fig. 11, which shows that the concrete, structural steel beam, and shear connectors were divided into layers. This process differentiates the temperature

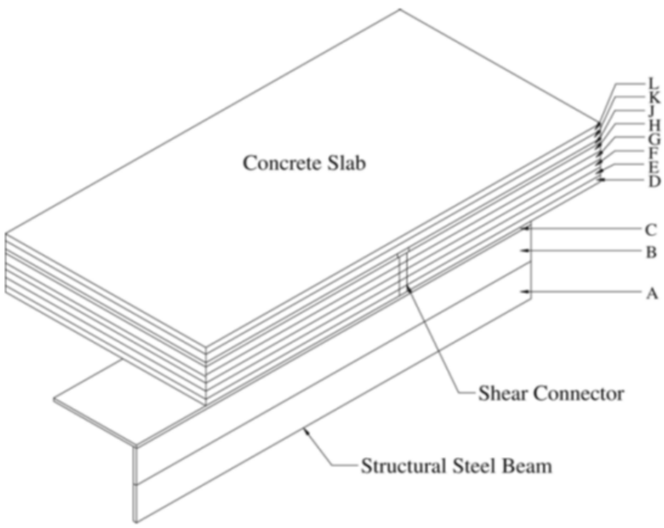


Fig. 11 Temperature distribution diagram for solid slab

Table 4 Temperature changes according to time

	Layer (*T*) (°C)										
Time (*t*) (min)	A	B	C	D	E	F	G	H	J	K	L
10	575	505	430	430	355	280	205	130	55	25	10
20	720	625	550	550	475	400	325	250	175	100	25
30	770	705	630	630	555	480	405	330	255	180	105
60	870	780	705	705	630	555	480	405	330	255	180
90	900	825	750	750	675	600	525	450	375	300	225
120	900	860	785	785	710	635	560	485	410	335	260
180	900	900	825	825	750	675	600	525	450	375	300

distributions according to time. The thermal distribution for channel connectors was obtained at different time intervals at 10, 20, 30, 60, 90, 120, and 180 min. Table 4 provides the temperature distribution of the layers with respect to time.

All FE push-out tests were modeled to determine the load–slip behavior of the shear connectors and to study the effects of temperature on their behavior. The FE models were modified to study the effects of fire with respect to change in time and comprised constant temperature with different time intervals. The mechanical load levels were incremented as 20%, 40%, and 60% of the ultimate load.

3. Results and discussion

Numerical analysis was conducted on the structural performance of the channel shear connector surrounded in HSC slab subjected to ambient and elevated temperatures. The simulations of the specimens and experimental arrangement, and the results were accurately demonstrated by the FE model at ambient temperature, compared with the experimental investigations. The prediction of the behavior of channel connectors under elevated temperature is provided in the proposed FE model. However, experimental investigations are required for the degradation of channel shear connectors under fire.

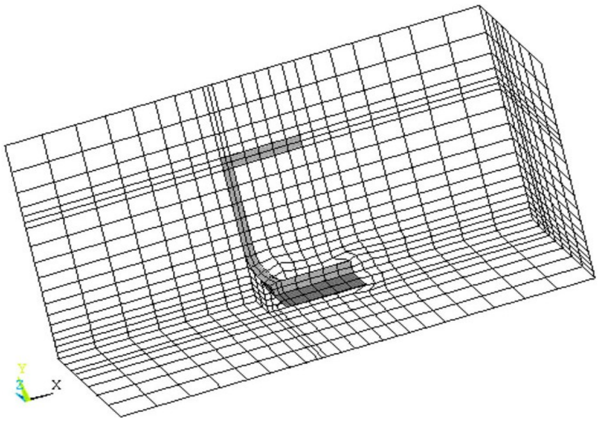
3.1 FE model at ambient temperature

Two types of push-out specimen failures are defined in the literature. The first type is channel fracture, and the second is concrete crushing/splitting. Channel connector fracture occurred in all the experimental tests of the push-out specimens embedded in HSC (Shariati *et al*. 2012). Moreover, the FE model developed at ambient temperature exhibited the same failure mode. The FE results showed that the channel yielded and fractured at the junction of the web and the bottom flange. Figs. 12(a)-(b) shows the deformed shape of the channel at the end of the experimental test, and its direct comparison in shown in Fig. 12(c) as the von Mises stress contours and the deformed shapes of the FE model at the maximum load level for the specimens are illustrated.

A comparison of the results of the experimental investigations in (Shariati *et al*. 2012) and FE analysis at ambient temperature showed that the initial stiffness of the specimens and the model were quite suitable for each other. Fig. 13 illustrates a direct comparison of the load-slip relationship of specimens obtained after the experimental tests and the FE analysis at room temperature. Both approaches obtain acceptable results, which validates the accuracy of the FE model. For the push-out specimens (SP-1), the maximum load per steel channel was recorded at 170 kN compared

(a) Fractured channel in slab

(b) Fractured channel achieved to steel I-Beam



(c) Stress contour and deformed shape for channel connector from FE analysis

Fig. 12 Comparison of failure of channel connector during experiments (Shariati *et al*. 2012) and FE modeling

Table 5 Maximum load levels for all the specimens for experimental and FE investigations

Name of specimen	Maximum load level at ambient temperature experimental testing (kN)	Maximum load level at ambient temperature FE modeling (kN)
SP-1	170	180
SP-2	160	160
SP-3	210	200
SP-4	180	220
SP-5	160	140
SP-6	220	190

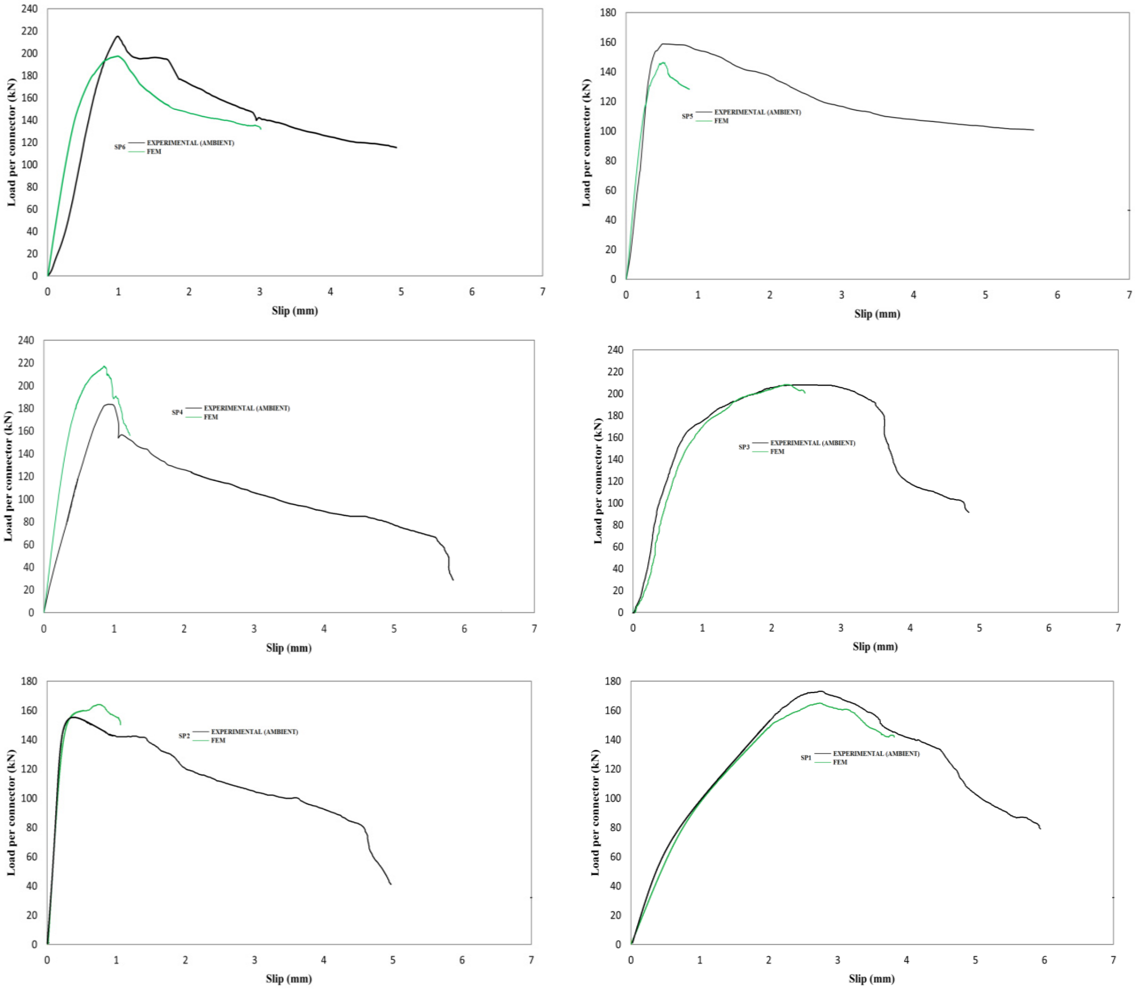


Fig. 13 Comparison of experimental results and finite element simulation in ambient temperature

with 160 kN, which was obtained from the FE analysis. For the SP-2, both the push-out test and FE model provided an ultimate load of 160 kN. The maximum loads are compared in Table 5. Table 5 shows that the findings of both the experimental and FE investigations have an excellent relationship. Fig. 13 further shows that the standard slip of 1 mm has been occurring at almost similar load levels for both the experimental and FE analyses; for instance, in the specimen SP-1, a slip of 1 mm was achieved at a load of 80 kN. Close agreement is observed in all cases between the test results and the FE solution. This finding proves the adequacy of the FE model in the nonlinear range up to failure.

3.2 FE model elevated temperature

3.2.1 Failure modes

Shear connection relies on the material strength and stiffness of the connector, as well as the strength of the concrete placed in front of the connector. Thus, the crushing of the small region adjacent to the connector with a permanent gap behind it is the most common crushing mode of the concrete. In this case, the connector failure may be observed or not, but the compression failure progresses through the thickness of the concrete forming a conical shape around the connector.

The FE model developed for elevated temperature showed that the stress concentration was higher in the lower layers than in the other portions as a result of thermal load applications. This condition caused the connectors to fail with a lower load-carrying capacity in an overturning mode instead of the shearing-off mode. The channel connector experienced shear stress and flexural stress, whereas high compressive stress occurred in the concrete element near the connector. Fig. 14 plots the deformed shape of the channel connectors according to the FE model. As can be seen from Figs. 14(a), 14(b), and 14(c), the maximum stress concentrated at the bottom initiated the failure of the connector. The failure mode finally resulted in the fracture of the channel connector, which is also because of the temperature profiles in the shear connector that are normally 100°C to 150°C higher than that of the surrounding concrete elements. This condition accelerated the deterioration in the shear connectors compared with that in the surrounding concrete. The failure mode switched from the crushing and splitting of the surrounding concrete, as commonly understood, to the yielding of the shear connector itself.

The push-out test setup that was predominantly used by previous researchers consisted of

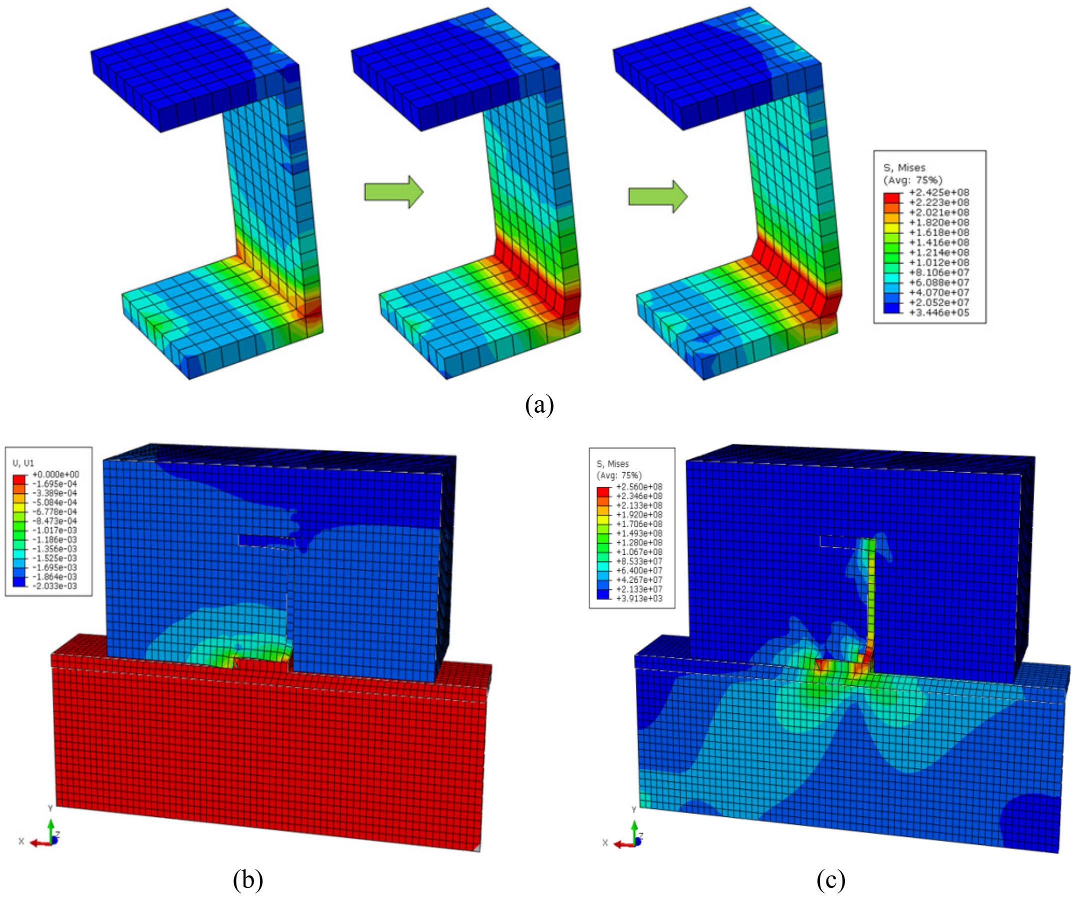


Fig. 14 Channel failure at elevated temperature in FE model

narrow-width concrete slabs. The narrow width may result in concrete cracking of the edges in the specimens, a failure that is not possible in internal composite beams with wide concrete slabs. In addition, narrow specimens are likely to experience longitudinal splitting failure. The FE model developed for elevated temperature exhibited high compressive stress in the concrete element near the connector compared with the other portions because of the thermal load applications and the narrow width of the concrete slab.

3.2.2 Load-slip relationship of FE model

Fig. 15 represents the load-slip relationship of the specimens analyzed at an elevated temperature. A particular observation demonstrates a difference in the intensity of temperature at the top and bottom surfaces of the channel connectors (Table 4). The temperature at the bottom of the channel connectors is typically 500 and 350°C higher than that at the top of the shear connectors for the elevated temperature resisting time of 10 and 30 min, respectively. The temperature difference up to this scale may lead to the failure of the shear connectors because of the softening of material and excessive slippage. Another detail that should also be noted is that depending on the location of higher stress concentration, the large pull-out forces also create failure when the ultimate tensile strength of the channel connectors was reached. These forces need to be considered carefully during design.

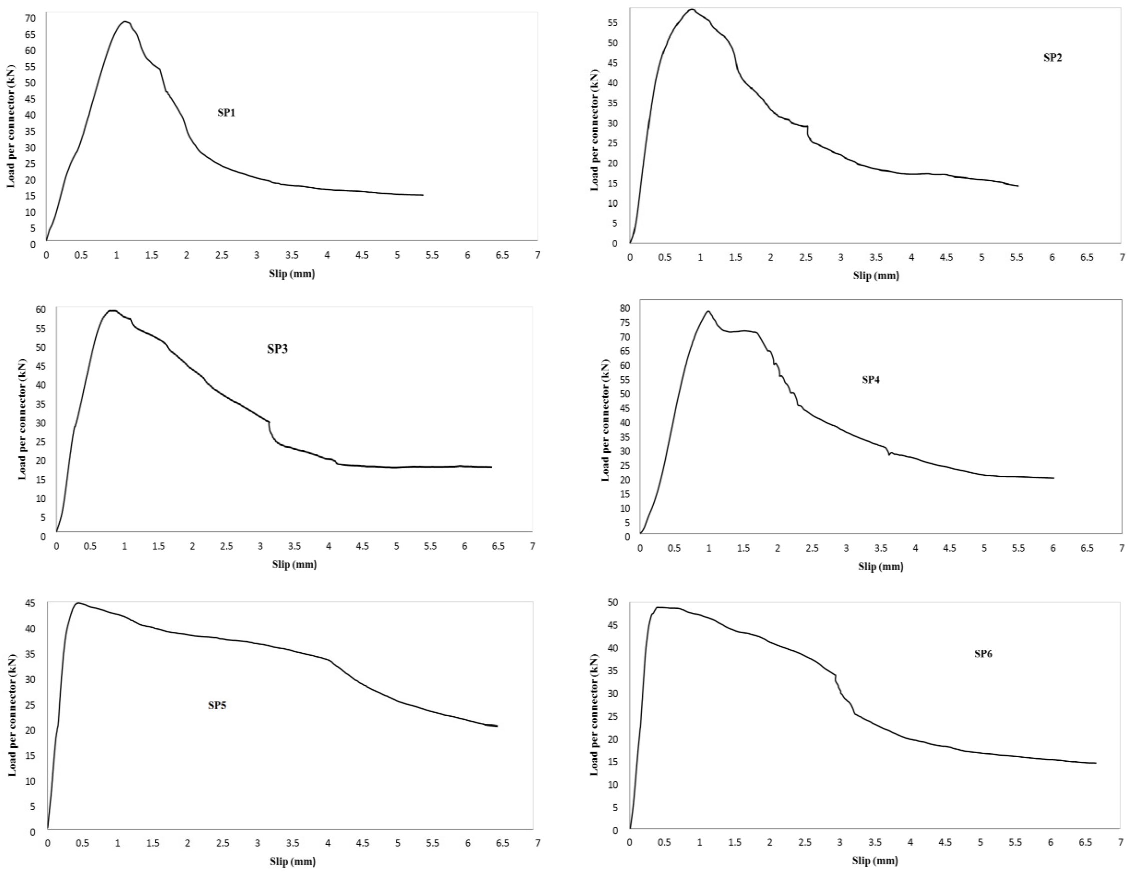


Fig. 15 Load-slip relationship of specimens at elevated temperature (FE model)

Negative placements are recorded in FE analyses because of the dominating effects of the thermal forces. In the initial stage of applying the elevated temperature, the thermal effects created higher expansion in the connectors compared with the deformation created by the mechanical forces. The degree of expansion divided by the change in temperature (thermal co-efficient) generally varies with the temperature. Considering the influence of thermal activities on the behavior of negative displacements, thermal coefficients of different levels, such as 0.9 and 1.0 αe, were assigned to the FE model. As can be seen from Fig. 15, assigning different thermal co-efficient resulted in the variation of the values of retarded displacements. This difference in displacements took place because of the variation in the volumes of the specimen as the temperature effects significantly depend on the volume of the concrete.

Back analysis was performed to calculate the material properties that are needed to produce a required factor of safety. For the purpose of back analysis, the load carrying capacities predicted by the suggested FE model in the ambient temperature are defined to be equal to the load level or the time rating at a limiting slippage. This selected amount of slippage is sufficient to fully mobilize the shear resistances of some shear connectors (Standard 1994, Patrick 2000, Wang 2011).

The capability of a tested specimen to resist fire is calculated according to the time taken by the specimen to reach the limiting slippage (Standard 1994, Patrick 2000). To calculate the model factor, the test results from Zhao and Kruppa (Zhao and Kruppa 1995) were chosen. The model factor of Eurocode 4 (1994) was calculated by dividing the fire-resistant period observed by Zhao and Kruppa (1995) and by the fire-resistant period suggested by Eurocode 4 (1994) In the same manner, the fire-resistant period observed by Zhao and Kruppa was divided by the fire-resistant period observed by FE model in the present study. The average model factor achieved by the proposed FE model is 1.02, which helped provide a more accurate fire-resistant time of shear connectors than the guideline provided in Eurocode 4 (1994), which suggests the model factor as 1.07. However, the guideline provided in Eurocode 4 (1994) is also considered effective in conventionally predicting the time elapsed in reaching the maximum slippage by the specimen under different loading levels.

3.3 Comparison of FE ambient and elevated testing

A comparison of the FE model at ambient and elevated temperatures shows that the initial stiffness of the specimens has variations because of the involvement of thermal actions. The results indicate that because of the comparatively higher capability of steel to overcome the temperature effects, the thermal action was induced rapidly in the channel connectors up to 100°C to 150°C more than the surrounding HSC. This temperature effect initiated the weakening of the shear capacity of the connector before the mechanical load reaches its maximum intensity, which resulted in a faster deterioration in the shear connectors than the surrounding concrete. Thus, the failure mode was switched from the crushing and splitting of the surrounding concrete to the yielding of the shear connector itself, as observed in the experimental analysis. The FE modeling slightly over predicted the temperature histories in various parts of the shear connectors, which resulted in a conventional prediction of the fire-resistant periods of the shear connectors in the mechanical analyses.

All the specimens have a maximum load of about 60 kN to 70 kN, except SP-5 and SP-6; these values are more reasonable than those given in other studies on experimental fire testing of other connectors (Zhao and Kruppa 1995). For SP-5 and SP-6, the increased temperature caused early deterioration of the specimen, and a standard slip of 1 mm occurred in FE model at lower values of the load of 43 and 48 kN, respectively. In most cases, the indicated 1 mm slip is at the maximum load that ranges between 60 and 65 kN. However, in the specimen SP-1, the FE model resulted in a 1 mm slip at 74 kN. Unlike in the ambient experimental testing, for the specimen SP-5 and SP-6, the ultimate load decreased by 35% during the initial 10 min of applying the fire. A 57% reduction was observed in the ultimate load by applying the fire for 3 h. The FE results indicate decreased strength with respect to time elapsed under fire. For all the specimens modeled under fire, a considerable reduction in the ultimate load was observed between the time intervals of 0 to 20 min with a 35% strength reduction followed by a minor strength reduction for the rest of the time.

Fig. 15 also illustrates the effects of different load levels on the specimens exposed to elevated temperatures. The HSC slab specimen under push-out test sustained 30% of the ultimate load-up to 3 h (Zhao and Kruppa 1995). Increasing the load up to 60% of the ultimate load ensured that the composite structure sustained the load for only 10 min under fire conditions.

Table 6 Comparison of channel connector performance with headed and Perfobond connectors

Researchers	Temperature ranges tested (°C)	Connector type	Slab type	Maximum time of testing (minutes)	Failure mode	Results
Mirza and Uy	0-900	Headed stud	Solid	60	Shear connection	Sustained 40% of the load sustained at ambient temperatures for first 60 minutes
			Profiled	60	Concrete crushing	Sustained 60% of the load sustained at ambient temperatures for first 60 minutes
Aaron J. Wang	0-900	Headed stud	Solid	60	Shear connctors in overturning mode	4 mm slippage in 81 minutes
			Trapezoidal			4 mm slippage in 84 minutes
			Renntran			4 mm slippage in 70 minutes
Rodrigues and Laim	0-950	Perfobond shear connector	Normal weight concrete slab	90 (Cyclic loading)	Concrete crushing	The connectors with one hole and without any steel reinforcement passing through it can sustain higher load at high temperatures
This study	0-900	Channel connectors	HSC	90	Shear connctors in overturning mode	Maximum 60% for first 90 minutes of the load sustained at ambient temperature; 1 mm slip at 60-70 kN in 30 minutes at maximum temperature

4. Comparative study

A number of researchers tested the behavior of various types of shear connectors at elevated temperatures. Most of their research was conducted using FE modeling because of its complexity (Huang *et al*. 1999, Sanad *et al*. 2000, Mirza and Uy 2009, Rodrigues and Laím 2011, Wang 2011). Table 6 shows a comparison of essential results of the previously tested headed stud and Perfobond connectors with the channel connectors tested in this study.

Table 6 shows that the channel connectors embedded in HSC can perform better than the other two types of connectors when subjected to a standard fire. The use of channel connectors eliminates the need for on-site inspections. Moreover, the extraordinary type of welding arrangement makes channel connectors a more economical and suitable solution for composite beams in buildings that are vulnerable to fire.

5. Conclusions

This paper proposes a non-linear thermo-mechanical FE model of channel shear connectors embedded in HSC and subjected to fire. Initially, an accurate nonlinear FE model of the push-out specimen tested at ambient temperature was developed to investigate the capacity of the channel shear connectors embedded in an HSC slab. The FE model at ambient temperature was further extended to identify the behavior of the channel connectors under fire. The thermal actions according to the standard ISO fire test were added to the model. The shear resistance of the channel connectors under fire was evaluated as a time-dependent factor. The FE model satisfactorily elucidates the comparison of the deformation under mechanical loads and thermal expansion due to fire. The material properties of both the elements constituting the composite structures were incorporated in the model. The major findings are as follows:

(1) With increasing temperature, the shear strength of the connector considerably decreases at a comparatively higher rate than the concrete part.
(2) The load carrying capacity of a channel connector increases almost linearly with increasing channel length.
(3) The influence of web thickness on the channel connector was significant when failure occurred because of the channel web fracture, but was minimal for concrete-related failures.
(4) The narrow slab width may result in concrete cracking of the specimen edges, and narrow specimens are likely to experience a longitudinal splitting failure.
(5) The degradation in the structural properties of the composite structure under fire changes the flexural and extensional stiffness of the beam and slab; this variation modifies the equilibrium along the beam axis and the shearing forces transmitted through the connection.
(6) The temperatures in the channel shear connectors are typically 100°C to 150°C higher than those in the surrounding concrete, thus leading to a fast deterioration in the shear connectors.
(7) The major thermal expansion caused a negative displacement in almost all specimens modeled under elevated temperature and may be transformed into thermal stresses under various levels of longitudinal restraints.
(8) The channel shear connectors may fail in an overturning mode instead of the well-known

shearing-off mode because of the relatively high temperature at the bottom layers of the concrete material, thus leading to a low load-carrying capacity.

(9) The thermal distribution of layers for the concrete, steel, and shear connectors showed that steel may work as a protective layer for concrete slab. The HSC solid slabs with channel shear connectors can resist 60% of their ultimate load at an elevated temperature for an initial period of 10 min. The FE model that simulates the behavior of the channel shear connectors under fire minimizes the requirements of the expensive and difficult-to-repeat experimental push-out tests to estimate the shear capacity of the channel shear connectors.

(10) A comparative study showed that the channel connectors are an economic and reliable alternative to conventional shear connectors.

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References

Cooke, G., Lawson, R. and Newman, G. (1988), "Fire resistance of composite deck slabs", *Struct. Eng.*, **66**, 253-261.

Ellobody, E. and Young, B. (2006), "Performance of shear connection in composite beams with profiled steel sheeting", *J. Construct. Steel Res.*, **62**(7), 682-694.

Eurocode, E. (1994), Eurocode 4: Design of composite steel and concrete structures–Part 1-2: General rules–Structural fire design, British Standards Institution, BS EN: 1-2.

Fahrni Hani, M. and Tamara, T. (2012), "Finite element analysis of composite steel-concrete beams subjected to fire", Nahrain University College of Engineering Journal (NUCEJ), **15**(1), 1-11.

Huang, Z., Burgess, I.W. and Plank, R.J. (1999), "The influence of shear connectors on the behaviour of composite steel-framed buildings in fire", *J. Construct. Steel Res.*, **51**(3), 219-237.

Lam, D. and El-Lobody, E. (2005), "Behavior of headed stud shear connectors in composite beam", *J. Struct. Eng.*, **131**, 96.

Lamont, S., Usmani, A. and Gillie, M. (2004), "Behaviour of a small composite steel frame structure in a "long-cool" and a "short-hot" fire", *Fire Safe. J.*, **39**(5), 327-357.

Lu, W., Ma, Z., Mäkeläinen, P. and Outinen, J. (2012), "Behaviour of shear connectors in cold-formed steel sheeting at ambient and elevated temperatures", *Thin-Wall. Struct.*, **61**, 229-238.

Majdi, Y., Hsu, C.-T.T. and Zarei, M. (2014), "Finite element analysis of new composite floors having cold-formed steel and concrete slab", *Eng. Struct.*, **77**, 65-83.

Maleki, S. and Bagheri, S. (2008), "Behavior of channel shear connectors, Part I: Experimental study", *J. Construct. Steel Res.*, **64**(12), 1333-1340.

Meaud, C., Jurkiewiez, B. and Ferrier, E. (2014), "Steel–concrete bonding connection: An experimental study and non-linear finite element analysis", *Int. J. Adhes. Adhes.*, **54**, 131-142.

Mirza, O. and Uy, B. (2009), "Behaviour of headed stud shear connectors for composite steel–concrete beams at elevated temperatures", *J. Construct. Steel Res.*, **65**(3), 662-674.

Nguyen, H. and Kim, S. (2009), "Finite element modeling of push-out tests for large stud shear connectors", *J. Construct. Steel Res.*, **65**(10-11), 1909-1920.

Pashan, A. (2006), "Behaviour of channel shear connectors: Push-out tests", M.S. Thesis; Department of

Civil Engineering, University of Saskatchewan, Canada.
Patrick, M. (2000), "Experimental investigation and design of longitudinal shear reinforcement in composite edge beams", *Progress Struct. Eng. Mater.*, **2**(2), 196-217.
Quevedo, R.L. and Silva, V.P. (2013), "Thermal analysis of push-out tests at elevated temperatures", *Fire Safe. J.*, **55**, 1-14.
Ranzi, G. and Bradford, M.A. (2007), "Composite beams with both longitudinal and transverse partial interaction subjected to elevated temperatures", *Eng. Struct.*, **29**(10), 2737-2750.
Rodrigues, J.P.C. and Laím, L. (2011), "Behaviour of perfobond shear connectors at high temperatures", *Eng. Struct.*, **33**(10), 2744-2753.
Sanad, A., Rotter, J., Usmani, A. and O'Connor, M. (2000), "Composite beams in large buildings under fire—numerical modelling and structural behaviour", *Fire Safe. J.*, **35**(3), 165-188.
Shariati, M., Ramli Sulong, N.H. and Arabnejad Khanouki, M.M. (2010), "Experimental and analytical study on channel shear connectors in light weight aggregate concrete", *Proceedings of the 4th International Conference on Steel & Composite Structures*, Sydney, Australia, July.
Shariati, M., Ramli Sulong, N.H., Arabnejad Khanouki, M.M. and Mahoutian, M. (2011), "Shear resistance of channel shear connectors in plain, reinforced and lightweight concrete", *Sci. Res. Essays*, **6**(4), 977-983.
Shariati, M., Ramli Sulong, N.H. and Arabnejad Khanouki, M.M. (2012), "Experimental assessment of channel shear connectors under monotonic and fully reversed cyclic loading in high strength concrete", *Mater. Des.*, **34**, 325-331.
Standard, B. (1994), "Structural use of steelwork in building", BS5950 Part 4: Code of practice for design of composite slabs with profiled steel sheeting.
Tests, I.F.R. (1975), "Elements of Building Construction, ISO-834", International Organization for Standardization, Geneva, Switzerland.
Wang, A.J. (2011), "Numerical investigation into headed shear connectors under fire", *J. Struct. Eng.*, **138**(1), 118-122.
Zhao, B. and Kruppa, J. (1995), "Fire resistance of composite slabs with profiled steel sheet and of composite steel concrete beams (Part 2, Composite beams)", Final Report; ECSC – agreement No. 7210 SA 509, CTICM, Luxembourg.

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