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Axial restraint forces in shear endplates of steel frames due to fire

Elie G. Hantouche *, Sarah A. Sleiman

Department of Civil and Environmental Engineering, American University of Beirut, Lebanon

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ABSTRACT

The results of a series of finite element (FE) simulations and experimental studies are used to develop a mechanistic model that predicts the axial restraint forces in steel shear endplate beam-column connections during a fire. First, FE models are developed to predict the total force-rotation response and failure modes, and are validated against experimental results available in the literature at both ambient and elevated temperature. Second, a parametric study is conducted to investigate some major parameters that impact the behavior of shear endplate connection assemblies during a fire. This includes beam length, load ratio, fire intensity, and endplate thickness. Based on FE and experimental results, a mechanistic model is proposed for the connection of typical steel frames subjected to fire exposure. The characteristics of the proposed model such as stiffness, tension and compression forces are determined based on each component of the connection. The proposed model is capable of predicting the axial restraint forces in shear endplate connections of typical steel frames for different geometric properties, under varied loading conditions, and elevated temperatures. The results can help inform future design guidelines to account for the thermal induced forces in shear endplate connections during a fire.

1. Introduction

Shear endplate connections, also known as flexible endplates are widely used to connect steel beams to columns or girders in multi-story buildings. These connections possess large rotational ductility, and are considered as pinned joints. According to the design guidelines at ambient temperature, only gravity loads are accounted for in the procedure. However, during a fire event, shear or pinned connections are subjected to large axial forces, rotational demands, and significant loss of strength and stiffness [1]. Bailey et al. [2] stated that the axial restraint provided against the thermal expansion of beams results in compressive forces in the heating phase of the fire. At the end of the heating phase, tensile forces start to develop. Furthermore, tension develops in the connections as the beams contract during the cooling phase of the fire. The large thermally induced forces may result in failure of the connections during or after fire.

Many experimental and analytical studies were conducted in the past few years to understand the behavior of shear endplate connections at elevated temperature. Al-Jabri [3,4] and Al-Jabri et al. [5,6] conducted an experimental investigation to study the performance of composite shear endplate connections in fire. Also, a mechanistic model was developed by the same authors to predict the moment-rotation of the connections at elevated temperature. However, these studies and models only apply for the case of unobstructed rotation about the lower edge of the endplate, assuming no contact between the beam and column flange. Also, no prediction of the thermally induced forced on the connection was reported. In addition, Hu et al. [7,8] investigated the capacity strength of shear endplate connection in fire both experimentally and analytically. The governing failure mode encountered was plate rupture in the vicinity of the weld. Yu et al. [9] developed a mechanistic model for simulating the behavior of isolated flexible endplates in fire.

Studies were also conducted on other types of shear connections such as shear tab, double angle, top and seat angle, and extended endplate connections. For instance, Wang et al. [10,11] developed a mechanistic model to predict the temperature-rotation of extended endplate bare-steel joints at elevated temperature. Hu and Engelhardt [8,12] conducted experiments and FE simulations to study the behavior of shear tab connections at elevated temperature, and to characterize their stiffness, strength, deformation capacity, and failure modes. They also studied the impact of several parameters on the connection response. In addition, Daryan and Yahyai [13] conducted experimental tests and FE simulations to study the behavior of bolted top and seat angle connections in fire. Kodur et al. [14] developed FE models to predict the behavior of typical beam-slab assemblies with different shear connection types exposed to different fire scenarios. In a very recent work, Selamet and Garlock [15,16,17] studied the behavior of shear tab, single angle, and double angle shear connections in fire. The connections were tested as part of a subassembly. They showed that the different shear connection types have similar global behavior. The response was governed by beam local buckling near the connection. Despite the progress that was made in understanding the capacity of shear

* Corresponding author at: Department of Civil and Environmental Engineering, American University of Beirut, P.O. Box 11-0236, Riad El-Solh, Beirut 1107 2020, Lebanon.
E-mail address: eh12@aub.edu.lb (E.G. Hantouche).

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endplate connections at elevated temperature, limited research has been conducted to predict the thermal induced forces encountered in shear endplates during a fire event. Existing work available in the literature did not include possible parameters (such as beam length, load ratio, endplate thickness, and fire intensity) that affect connection failure in fire (Al-Jabri [3,4], Al-Jabri et al. [5,6], Hu et al. [7,8], and Yu et al. [9]). Also, the component-based models available in the literature considered only isolated connections and did not include the prediction of the axial restraint forces in shear endplate connections of typical steel frames at elevated temperatures. Conducting an extensive experimental investigation is time consuming and not economically feasible since it requires large scale heating facilities. FE analysis can be used as an alternative after a thorough validation with existing experimental results of isolated shear endplate connections at elevated temperature.

It should be noted that the main focus of this paper is to predict the fire induced axial restraint force in shear endplate connections of typical steel frames due to fire exposure. First, FE models of isolated shear endplate connections at ambient and elevated temperatures are developed to predict total force-rotation response and failure modes, and validated against experimental results available in the literature. Second, FE models of the connection assembly are generated and used to conduct an extensive parametric study to identify the key parameters that affect the behavior of the connection. The results of the study are then used to develop a mechanistic model that predicts the thermal induced axial forces during a fire.

2. Isolated shear endplate connection

The FE model of the shear endplate connection is developed. The aim is to determine the force rotational response of the connection at elevated temperature and to predict the capacity and failure mode, assuming no induced thermal forces. The FE results of shear endplate connections are compared with those obtained in the experimental program at University of Sheffield [18].

2.1. Development of the FE model

The FE model of the shear endplate connection is developed to reproduce the experimental results conducted at the University of Sheffield [18]. An overall view of the model is shown in Fig. 1(a). The FE model of the connection is developed in ABAQUS [19].

2.2. Geometry of the connection components

The shear endplate connection used in the analysis consists of a PL 8 × 6 × 0.4 in. (PL 200 × 150 × 10 mm) bolted to the flange of a W10 × 60 (UC 254 × 89) column and welded to the web of a W12 × 26 (UB 305 × 40) beam cross-section. Details of the connection configuration can be found in [18].

2.2.1. Geometric and force boundary conditions

The model is loaded in two steps. In the first step, a pretension force is applied to the bolts. The bolt pre-tensioning is modeled by applying a body force in the bolts equivalent to the minimum required pretension force specified in the AISC specifications [20]. In the second step, an inclined force is applied at the tip of the beam (Fig. 1(a)), to produce combined shear and tension forces. The initial loading angle is 35° for the cases where the temperature is 20 °C, 450 °C, and 550 °C, and 45° for the case where the temperature is 650 °C. Throughout the load step, the loading angle varies and is described in the experimental program [18]. Boundary conditions are applied on the system throughout the analysis as shown in Fig. 1(a).

2.2.2. Material properties

An idealized bilinear model is used for the steel materials. The ambient temperature mechanical properties used for the beam are: the yield stress $F_y = 52$ ksi (356 MPa), and the ultimate stress $F_u = 73$ ksi (502 MPa) which are in accordance with Hu et al. [7]. For the shear endplate, the material model specified in Hu et al. [7] with $F_y = 50$ ksi (350 MPa) and $F_u = 66$ ksi (455 MPa) is incorporated in the FE model. For the column, the ambient-temperature mechanical properties used are A572Gr50 (S355) as specified by the experimental program [18]. For the structural bolts, an elastic-perfectly plastic material model is used. The ambient-temperature mechanical properties incorporated in the FE model for the structural bolts are: $F_u = 135$ ksi (930 MPa) which are in accordance with Hu et al. [7]. At elevated temperature, retention factors proposed by Lee et al. [21] are used for the base material whereas the retention factors proposed by the AISC specifications [22] and Eurocode 3 [23] are used for the bolts and welds, respectively. The retention factors for mechanical properties of structural bolt, weld, and steel materials incorporated in connection simulations can be found in Fig. 1(b).

2.2.3. Model discretization

All the connection components are meshed with eight-node brick elements with reduced integration (C3D8-R). Fig. 1(a) shows the mesh configuration of the model. To improve the accuracy of predictions, a finer mesh is used around the connection region, where failure is likely to occur. A mapped meshing technique is used to discretize bolts and their surrounding areas to account for stress concentration around the bolt-holes. The contact between the bolts and base material is modeled using surface to surface interaction with finite sliding. Finite sliding allows separation, sliding, and rotation of contact surfaces. A friction coefficient of 0.25 is utilized to model friction between the contact surfaces. The fillet welds are tied to adjacent parts by means of tie constraints applied at the contact surfaces.

2.2.4. Analysis procedure

To predict the strength of the flexible endplate connection at elevated temperature, steady state analysis is conducted. After heating the structure up to the desired temperature (20 °C, 450 °C, 550 °C, and 650 °C), a concentrated inclined load is applied while keeping the temperature constant, until failure of the connection. Note that the post ultimate behavior of the structure is not predicted. The objective is to identify the limit states in the connection at the specified temperatures under combined tension and shear loads.

2.2.5. FE vs. experimental predictions

The FE results are plotted against the experimental test results conducted at the University of Sheffield [18]. FE results show good agreement when compared to experimental results, as far as strength, stiffness, and rotation (Fig. 2).

The deformed shape and the failure mode of the shear endplate connection at ambient and elevated temperature are shown in Fig. 3(a), (b), (c), and (d). It can be seen from Figs. 2 and 3 that the FE simulation can predict closely the total force-rotation response of the connection as well as the failure mode which is plate rupture at the toe of the weld. Note that yielding is assumed to be the failure criteria.

The results of the capacity predictions and the comparison between the experimental and FE results are summarized in Table 1. The FE models predict the peak connection strength well.

3. Shear endplate connection assembly: evaluations of demand

Shear endplate connections are generally designed to resist gravity loads only. However, in fire, large axial forces can develop in the beam-end connection. To investigate the connection behavior in such conditions, a series of studies is conducted using 3D FE models in ABAQUS. The overall goal is to gain further insight into major key parameters that impact the performance of beam-to-column shear endplate connections in a fire.