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Effect of preloading in high-strength bolts on bolted-connections exposed to fire

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ABSTRACT

Preloading is an important process for bolted connections. Previous studies over the last few decades investigated the fire behaviour of typical bolted connections. However, there is a paucity of studies that examine the effects of preloading in high-strength bolts with respect to the responses of bolted connections that are exposed to fire. This study includes a series of numerical analyses to investigate the fire behaviour of two types of bolted connections, namely extended endplate connections and fin plate connections with and without preloading. Various parameters including preloading and thickness of the connecting plate were considered. The study also demonstrates numerical methodology with respect to preloading and parameters of the damage index by using an explicit dynamic solver. The failure modes, mid-span deflections, displacements of beam ends, and fire-induced axial forces in beams are also discussed in detail. The results indicate that preloading in the bolts has little or no effect on the response of endplate connections exposed to fire because the preloading in endplate connections is offset at the thermal expansion stage. In contrast, the fire behaviour of the fin plate connections is influenced by preloading and fin plate thickness. The use of a thinner fin plate results in the connections receiving a limited effect from the preloading in the connections in fire. The use of a stronger connecting plate in fin plate connections indicates that it is not possible to ignore the effect of preloading on the fire response of connections, and this can improve safety.

1. Introduction

Beam-to-column connections in steel buildings play a critical role in resisting all types of loads including earthquakes and fires. The connections transfer internal forces induced by sub-structural deformation, and thus it is important for these connections to possess strength and deformation capabilities to prevent the collapse of the structures [1].

Previous studies on the fire behaviour of connections mainly focus on five types of connections, namely fin plate, flexible endplate, web cleat, flush endplate, and extended endplate connections [2]. Fin plate connections and extended endplate connections exhibit good behaviour including simple construction, an ideal mechanical model, and expectable behaviour under cyclic loading under service loads due to their advantages [3]. Therefore, they are widely used in several buildings [4]. With respect to the fore-mentioned two connections, high-strength bolts provide a clamp force to produce friction by applying a preloading that achieves the following two mechanical properties: (1) the ability to bear high tensile stress due to the preloading; and (2) resistance to combined shear and tension under external loads [5].

Several researchers identified that high-strength bolts and the thickness of the connecting plate correspond to the direct causes of connection fractures at elevated temperatures [6,7]. Jabri, et al. [8] presented a multi-spring model for extended endplate connections in fires based on the component method proposed by Zoetemeijer [9]. This theoretical model was validated by various researchers by using experiments and finite element analysis (FEA) [10–12].

With respect to extended endplate connections, Spyrou, et al. [13] presented a T-stub mode for bolts and endplates to investigate high-temperature behaviour of the connections. The results indicated that the bolts of extended endplate connections eventually fracture under tension, and the study hypothesised that deterioration of the strength of bolts in a fire is a direct cause of the fracture [10]. However, Daryan, et al. [11] used an experimental analysis and determined that 8.8 bolts failed under tension although 10.9 bolts fractured under a combination of tension and shear. This implied that different bolts in the same assemblies bear different stress distributions. Gao, et al. [12] and Yang, et al. [14] conducted a series of tests to study the relationship between high-strength bolts and extended endplate connections. Their analysis methods and results provide helpful information to understand the

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response of endplate connections in a fire.

With respect to fin plate connections, Yu, et al. [15] observed that fin plate connections failed due to the shear fracture of high-strength bolts. The study revealed that the resistances of the fin plate connections were significantly influenced by temperature although the failure modes were controlled by shear.

However, the above studies did not examine the effect of preloading in high-strength bolts. The consideration of preloading in high-strength bolts is an indispensable stage in manufacturing as this provides design and construction guidance [16]. This process makes bolts serve as a high stress case. Tests conducted by extant studies did not provide a value of preload in high-strength bolts and failed to explain effects on the fire performances of bolted connections. The process of modelling preload in bolts was ignored in FEAs conducted in a few studies. Additionally, studies that considered the process of modelling preload modelled the preload in a static solver that provided the predefinition of bolt loads (as the remaining pretensions in bolts or holding the length of bolts). Analyses on the effects of preloads on the fire behaviour of bolted connections continue to suffer from deficiencies due to uncertainties of bolt forces in the structural heating. Furthermore, with respect to a dynamic solver, the function of bolt forces are illegal, and thus studies neglect the effects of preload on the fire performances of bolted connections.

Hence, the present study discusses the effect of preloading in high-strength bolts on the fire behaviour of two typical bolted connections, namely extended endplate connections and fin plate connections at an elevated temperature. The study is intended as a reference for researchers investigating the fire behaviour of connections and to model bolts with pretension in a dynamic solver. A significant difference between the two connections occurs in the axial direction. With respect to extended endplate connections, the axis of the bolts is parallel to the axis of the beam. Conversely, the axes of the bolts in fin plate connections are orthogonal with respect to the axis of the beam.

2. Effect of preloading in bolts at room temperature

High-strength bolts are used to connect a beam and column, and connections are designed to transfer loads from a structural member to other parts of the structure or to the supports [16]. The preloading in bolts causes connecting plates to be clamped together and produces friction to resist shear. With respect to bending moments, the capacity of the connections is determined by the type of bolt groups or the thickness of the extended plates [17,18].

Fig. 1a presents the process of a nut rotated on a bolt. The clamp force that is caused by the preloading in the bolt as shown in Fig. 1b is exhibited when the components are compressed, and the bolt is extended such that the assemblies or called connections can bear shear by using the contact friction between the components.

As shown in Fig. 1a, the slope of the lines $\overline{OA}$ and $\overline{BA}$ represent the stiffness of the components and the bolt, respectively. When an external tensile force is applied to the joint along the preloading direction, it reduces the clamp force and adds an additional force to the bolt. Thus, the external force overcomes the nut force, and this relieves the squeeze status between two plates. As a result, the bolts bear the combination of the tension and shear due to the loss in preloading. The ultimate shear strength of steel approximately corresponds to 0.6 of its ultimate tensile strength, and therefore the bolts fragilely fracture under the combination loads [19].

3. Numerical methodology for connections in a fire

3.1. Explicit dynamic solver

An explicit dynamic solver, ABAQUS [20], was used for numerical modelling in this study. It uses a consistent large-deformation theory that can model large rotations and large deformations, and the fracture of the models is displayed visually.

3.2. Connection models

The finite element model details are shown in Fig. 2. The beams of all the models possessed the same dimensions with nominal dimensions corresponding to 400×300×13×8 (depth×width×thickness of flanges×thickness of webs, unit: mm) and a length corresponding to 3000 mm. The columns of the connection models corresponded to 400×400×21×13 (depth×width×thickness of flanges×thickness of webs, unit: mm) with a height of 2000 mm. The thickness of the endplate and fin plate is listed in Table 1. Additionally, M24 grade 10.9 bolts (shown in Fig. 3) with Φ27 mm holes were used for connections, and the applied preloading force corresponded to 225 kN for each bolt. In the study, partially threaded shank bolts and fully threaded shank bolts were applied to the endplate connections and fin plate connections, respectively.

A physical loading of 97.8 kN (load ratio =0.5) was adopted at the mid-span. The load ratio was defined as the ratio of the applied bending moment to the bending moment resistance of the beam at an ambient temperature.

3.3. Model setup

All bolts were employed with a linear incompatible mode C3D8I that avoided shearing locking and was applied to composited contact conditions. The other parts were set by the reduced integration mode C3D8R that was satisfied with a large displacement analysis.

Grade S355 steel with a yield strength of 355 N/mm^2 and Young's modulus of 2.00×10^5 N/mm^2 at room temperature [21] was used for

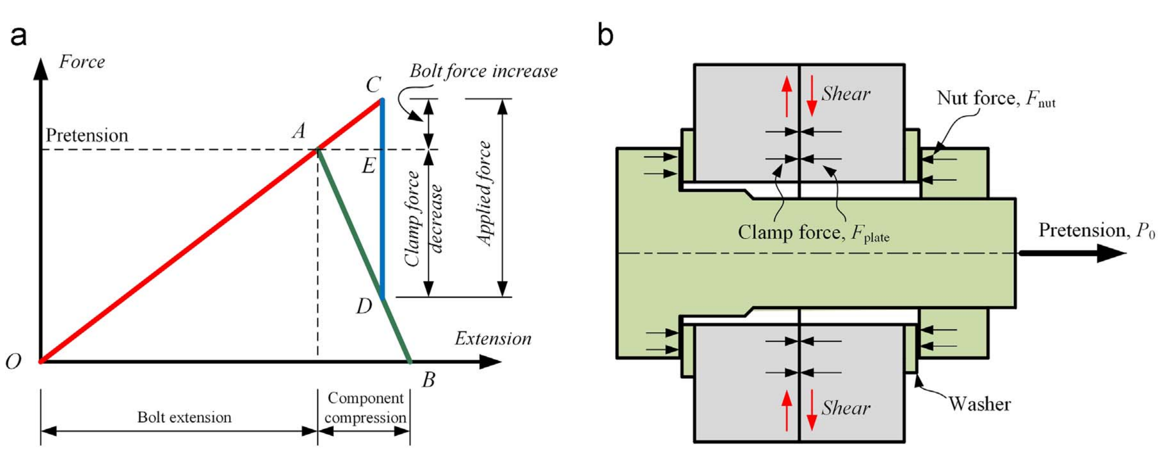

Fig. 1. Process of the nut rotated on the bolt. (a) The internal forces in bolts and components; (b) Preload works on the components.