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Component-based model of fin plate connections exposed to fire-part I: Plate in bearing component

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ABSTRACT

Connections are important components for maintaining the robustness of a structure. The behaviour of connections and their influence on the structure exposed to fire can only be properly understood if either the substructure or the entire structure that contains the connections are investigated. The costs of fire testing a structure that contains connections are very high and using three-dimensional (3-D) solid elements to simulate connections in a finite element analysis (FEA) can be very time-consuming. A component-based model is therefore a realistic approach to model the behavior of the connection under the complex stress history when exposed to fire. The key to establishing such a component-based model for connections exposed to fire is to determine the temperature-dependent force-deflection relationships of the components which have not been extensively explored. In this study, the plate in bearing component using fully threaded bolts was investigated at ambient and elevated temperatures. The behaviour of the component was determined by establishing a 3-D solid finite element modelling of lap joints with the FEA software ABAQUS. The effects of parameters such as edge distance, bolt pitch, end distance, plate thickness, bolt hole diameter, bolt bearing angle and temperature on the behaviour of the plate in bearing component were investigated. The failure mode, resistance, initial stiffness and the force-deflection relationship of the component for different values of these parameters were noted and prediction models for the resistance and initial stiffness of the components were proposed. A nonlinear function relation for force-deflection was also established.

1. Introduction

Connections are important components for maintaining the robustness of a structure. The collapse of the World Trade Centre (WTC) [1] and the results of the Cardington full-scale fire tests [2] show that the performance of connections can be severely affected by fire, and this may lead to the progressive collapse of a structure. Due to the interactions among the structural members, expansion effects and the degradation of material properties, connections are subject to a continuously varying axial force, shear force and moment when exposed to fire. Therefore, the behaviour of connections and their influence on the structure can only be properly understood if either the substructure or the entire structure that contains the connections are investigated. However, fire tests on an entire structure or even part of a structure, such as those at Cardington, are costly and time-consuming. With the increasing functionality of finite element analysis (FEA) and the improved performance of computers, FEA has become a common research method. In order to model the detail of connections under complex stress history when exposed to fire, three dimensional (3-D) solid elements are generally required. However, a significant amount of contact exists in bolted connections, which renders 3-D solid FEA costly. As an indication of this, four days were required to simulate a single-line 3-bolt fin plate connection using four central processing units (CPUs) in the high-performance computing platform at Central South University by employing the general finite element program ABAQUS/Explicit. Obviously, it is impractical to directly apply the 3-D solid finite element model of connections to the fire resistance analysis and performance-based design of an entire structure. Instead, a simplified mechanical model for connections, which can be used for the FEA of fire resistance of an entire structure, is needed.

The main purpose of studying the behaviour of connections at ambient temperature is to establish the moment-rotation relationship, which enables the use of the rotational stiffness of normally pinned connections to optimise traditional structural design. Xu et al. [3] find the moment-rotation characteristic, rotation capacity and failure mode of high strength-steel endplate connections in fire by conducting the experimental tests at fire temperature 550 °C. Since the collapse of the WTC towers, the focus has been to assess the robustness of connections, which needs to be extended to the effects of temperature on the connection characteristics. Moreover, in case of fire exposure, connections are subject not only to bending moment and shear force but also to

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axial force. Consideration of only the moment-rotation-temperature relationship does not provide a realistic model of the fire response of connections. A component-based method for establishing the moment-rotation relationship at ambient temperature has been proposed by Wales and Rossow [4] and is applied in Eurocode 3 part 1–8 [5]. In this method, connections are considered to be an assembly of basic components in series or in parallel, which is based on the force transfer path (Fig. 1). The moment-rotation relationships of the connections are obtained through an examination of the properties of relatively simple basic components and properties, such as resistance and stiffness. The component-based model can be used to describe the behaviour of the connections when they are simultaneously subjected to axial force, shear force and bending moment. If the mechanical properties of each component exposed to fire have been modelled, they can be used in the analysis to determine the fire resistance of an entire structure, using the component-based model instead of a vast number of solid 3-D elements. Moreover, the failure mode of the connections exposed to fire can be predicted according to the resistance of each component, which renders a more pertinent fire resistance design for the entire structure.

The key to establishing a component-based model of the connections exposed to fire is to determine the temperature-related force-deflection relationships for the components. Only few studies have addressed this topic while majority of studies have focused on end plate and the cleated connections. Spyrou et al. [6,7] conducted a high-temperature experiment on a T-stub component subject to a tensile force and a column web subject to compression, presenting a simplified mechanical model of the tension and compression zones. Block [8,9] investigated the effect of column axial force on the compression zone thereby improving the force-deflection relationships for the components of end plate connections. Al-Jabri et al. [10,11] established a component-based model for flexible end plate steel and composite connections exposed to fire, and this was further developed by Hu et al. [12]. Yu et al. [13] adopted a similar approach in proposing a component-based model for web cleat connections exposed to fire. Sulong et al. [14] used the finite element software ADAPTIC to establish a component-based model that represents end plates and angles as connections. The only study for a component-based model of fin plate connections was performed by Sarraj [15]; Sarraj conducted finite element analyses of plates in bearing, bolts in shear and friction components at ambient and elevated temperatures and proposed a model for the force-deflection relationships of the components. However, the geometry used for the parametric studies was a bolt bearing on a plate, which does not adequately reflect the "straight effect" of the connections and the stress state of each component, as shown in Fig. 2. In addition, Sarraj used small-sliding algorithm for the contact in the finite element model, which did not accurately simulate the changes in the contact area between the bolt and the connecting plates. Therefore, additional research on the behavior of each component of a fin plate connection exposed to fire is needed.

The component-based model for a single-line 3-bolt fin plate connection is shown in Fig. 1. For each bolt row, it includes an assembly of the fin plate in bearing, the bolt in shear and the beam web in bearing components in series, which are subsequently assembled with the friction component in parallel. All components are located around the centre of the bolt hole. The initial length of the spring component is zero. After being assembled in series and in parallel, the components are connected with two stiff bars (or plates), which are connected with the column flange and the cross-section of the beam that is located at the bolt hole, respectively.

In order to facilitate the analysis, friction was initially ignored. A 3-D solid FEA of the parameters that influence the behaviour of the plate in bearing component and the bolt in shear component was conducted to provide a model for the resistance, initial stiffness and force-deflection relationship for both components. Then, the effect of friction on the component-based model was evaluated. Finally, the component-based model was verified by comparing the component-based modelling results with the 3-D solid FEA results. In this paper, the plate in bearing component is investigated. The bolt in shear component, the effect of friction and the verification of the component-based model will be discussed in the companion paper.

2. Finite element analysis model

In order to represent the "straight effect" that exists in fin plate connections, a lap joint rather than a bolt bearing on a single plate was

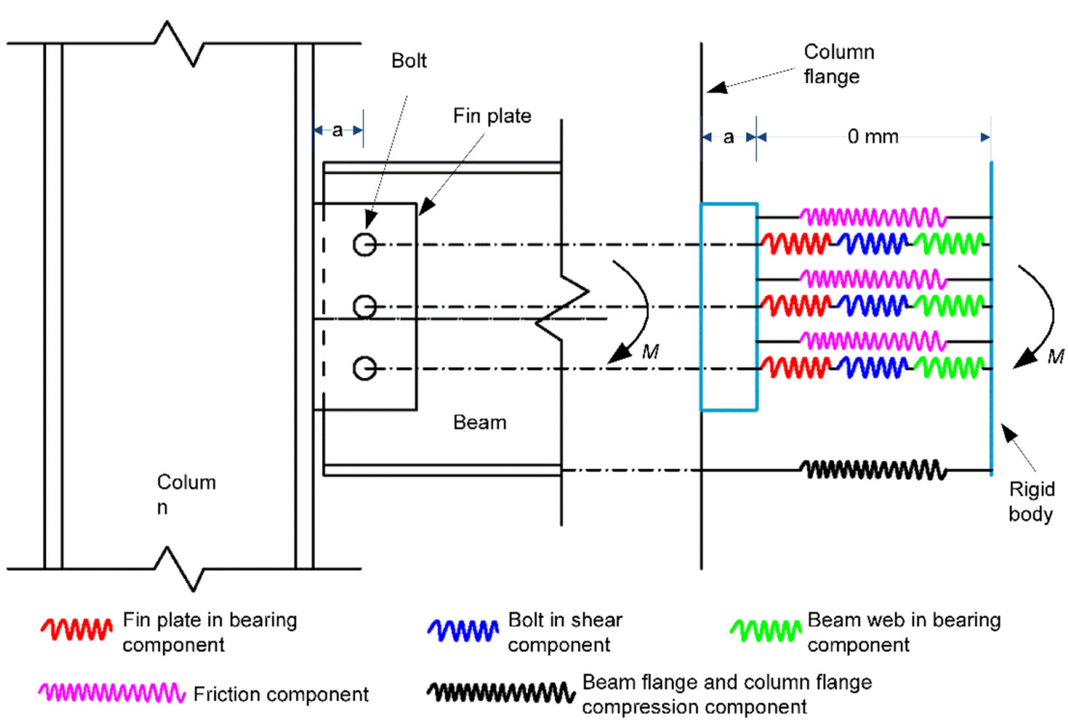

Fig. 1. Schematic of the component-based model for the fin plate connection.