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Robustness analysis of 3D Composite buildings with semi-rigid joints and floor slab

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ABSTRACT

Analysis of composite building structures has been performed mostly on skeleton frames or on plane frame (2D) without the presence of composite slabs and semi-rigid joints. This is because detailed modelling of non-linear behavior of steel–concrete composite joints and the floor slab is rather tedious and involves other structural components including interaction between floor beams with slab and beam-to-column joints. This paper proposes simplified composite slab and composite joint models, which can be easily incorporated within a commercial software for the analysis of three-dimensional composite building frames with less computational time. The steel concrete composite slab is modelled by representing the profile metal deck by rows of rebars with equivalent areas and the profile concrete slab is converted into an equivalent uniform concrete section. The semi-rigid composite joints in the building framework are modelled using the Eurocode's component model represented by axial and rotation spring connectors. The proposed simplified models have been verified against the established test and numerical data available in the literature and found to be accurate enough for analysing 3-D composite frames with less computational time. The robustness of moment frames and simple braced frames was then investigated under a column loss scenario. The incorporation of semi-rigid joints and composite slabs in 3D frame analysis tends to produce more realistic estimate of large scale steel–concrete composite frames subjected to accidental loads.

1. Introduction

Design engineers tend to avoid detailed modelling of composite joints in frame analysis due to complexity of geometric modelling, insufficient guidelines, high computational cost and complicated interaction behavior between joints and other structural components. As a result, joints are generally simplified into pin or rigid. In reality, these simplified assumptions may be inaccurate or unconservative. They represent the limiting cases of the joint behavior and lead to a wrong interpretation of the structural behavior in terms of force distribution and structural responses. Several researchers have proven that joint rigidity improves the robustness and redundancy of building frames [1,2,22]. Eurocodes 3 and 4 [10–11] provide sufficient details to realistically predict behavior of steel and composite beam-to-column joints based on the component method. As a result, the component method is now widely adopted for modelling semi-rigid joints for frame analysis.

A wide range of steel and composite beam-to-column joints has been investigated over several decades to determine their axial force–displacement and moment–rotational relationships, and a vast number of experimental data have been collected. Recently, several researchers have attempted to propose further simplification in modelling semi-rigid joints for frame analysis. Some of the significant contributions include the work done by Sadek et al. [2], Kwasniewski [3], Izzuddin et al. [4], and Alashker et al. [5], who have incorporated simplified composite joint models in progressive collapse analysis of building frames.

The computational time required for analysing the progressive collapse behavior of large building frame is still intensive even with the use of powerful desktop computers [3,5]. Fu [6] reported that the research on the behavior of the progressive collapse of a composite building has been limited due to (i) limited availability of analysis tools, (ii) the high cost and cumbersomeness of a full scale test, (iii) the complicated geometric models for detailed three-dimensional (3D) framework, and (iv) the fact that a two-dimensional model does not predict the overall structural behavior accurately and thus 3D analysis is often needed. Many researches focused only on analysing small scale single storey composite building to avoid high computational cost associated with detailed

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geometry modelling of composite slab, joint and the complex interactive behavior between the frame components [2,7].

This paper proposes a simplified semi-rigid joint model and a composite slab model to capture adequately their non-linear behavior so that their influence on the global stability of building frame can be assessed accurately. These avoid detailed finite element modelling of joint and slab components and lead to overall improvement in computational efficiency of analysing large scale 3D building framework.

2. Numerical modelling of composite building components

The incorporation of semi-rigid joint model and floor slab model in 3D frame analysis tends to produce more realistic estimate of frame behavior compared to frame model using pin or rigid joints or skeleton frame without the presence of slabs.

2.1. Beams and columns

Steel beams and columns are modelled using B31-two-node linear beam elements. Interaction between steel beam and floor slab is defined by tie constraint through ABAQUS library [8] to capture the composite action between the concrete slab and steel beam. Partial interaction in composite beams can be modelled using the tie constraint with spring stiffness. However, it was found that partial interaction in composite beams has negligible effects on the global response of 3D frames [9]. Therefore, rigid tie constraint is adopted to represent the full composite action between the concrete slab and steel beam, i.e., no slip between the two surfaces. Local buckling of steel sections can be avoided by using sections with at least Class 3 cross section. High strain rate effect may affect the section classification. In such case, a detailed modelling of critical members using shell elements is necessary to capture the local buckling phenomenon due to high strain rate.

2.2. Composite joints

The composite joint is modelled using a six degree-of-freedom (DOF) non-linear connector. The connector behavior is represented by axial force–displacement and moment–rotation relationships. These relationships can be established using a Eurocode 3–1-8 and Eurocode 4-1-1 component model approach [10–11]. Fig. 1 shows that the joint components (Fig. 1a) are represented by the simplified joint model in ABAQUS (Fig. 1b). The frame analysis assumes zero joint size and neglects the effect of panel zone shear deformation in the beam-to-column joints [12]. The details of the proposed simplified joint model and verification studies are given by Jeyarajan et al. [13].

Although the component model is well developed for end-plate connections, limited work is done on fin-plate connections [14–20]. The

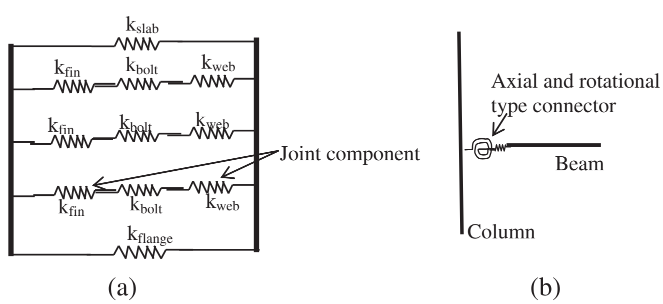

Fig. 1. Model for fin-plate joint (a) Eurocode 3 component model (b) joint representation in frame analysis.

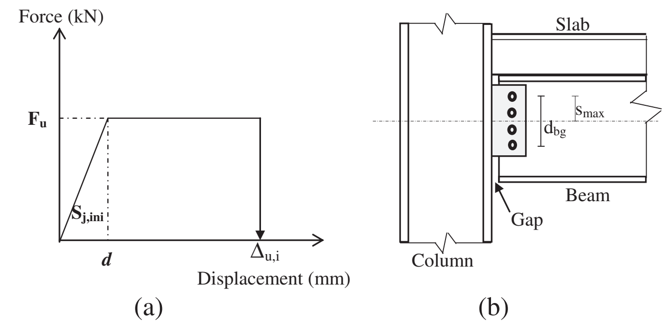

Fig. 2. (a) Force–displacement relationship of axial spring (b) typical four-bolt fin plate.

moment–rotation behavior of the fin-plate connection is more complicated because the centre of compression is moving with the increase in rotation. When a fin-plate beam-to-column connection is subject to hogging moment, the centre of compression zone moves from the centre of the bolt group to the bottom beam flange. This means that the Eurocode's component model cannot be applied directly to calculate the joint component's stiffness and maximum moment resistance. Therefore, a new component model for fin-plate connection is proposed as shown in Fig. 3a [13,26].

A typical four-bolt fin-plate composite connection shown in Fig. 2b is used as an illustration. Fig. 2a shows the force–displacement response of the axial spring. f_u is the maximum force of each spring, and $S_{j,ini}$ is the initial rotational stiffness. Series springs in the proposed component model are concrete in tension (ct) or concrete in compression (cc), bolt in shear (bs), fin plate in bearing (fb), and beam web in bearing (bwb). When subjected to hogging moment (i.e., concrete in tension), the tensile force acting on the slab reinforcement and its stiffness is located at the 1st spring row, whereas when it is subjected to sagging moment (i.e. concrete in compression), the concrete compressive force and its stiffness is at the 1st spring row. Row 6 spring is used to represent the gap element: k_{slab} is the stiffness of slab in compression, k_{rebar} is used in case of slab in tension, k_{rebar} is the sum of metal deck contribution and rebar contribution, k_{fin} is the bearing stiffness of fin plate, k_{bolt} is the shear stiffness of bolt; k_{web} is the bearing stiffness of beam web, k_{flange} represents the gap, and k_{eff} is the effective stiffness of series spring of a row. The stiffness of each spring component and its maximum resistance are calculated using Eurocode 3 Part 1–8 [10,25,29].

A tri-linear moment–rotation behavior is considered for end-plate connection, as shown in Fig. 5a. Initial rotational stiffness ($S_{j,ini}$) was used as a basis to develop tri-linear moment–rotation behavior [14]. Bi-linear moment–rotation response is derived for the fin-plate connection using the Eurocodes component model, as shown in Fig. 5b. The joint component's resistance and stiffness are firstly calculated using the component model and then the effective stiffness and effective resistance are calculated for each row. In the ABAQUS numerical model, two rigid bars (representing beam and column) are connected with axial springs (also known as connectors) as shown in Fig. 4. One rigid bar, representing the column, is fixed against displacement and rotation, and the other rigid bar, representing the beam, is vertically supported and free to rotate/move at the base. The effective resistance and stiffness of the components are represented by an axial spring in a two-rigid bar model. By applying the axial force and moment (F and M) on the rigid bar that representing the beam, the force–displacement (F–d) and moment–rotation (M–θ) relationships of a composite joint could be obtained. The rotational capacity ($\theta_{t,\max}$) and spring deformation limits ($\Delta_{u,i}$) of a fin-plate connection shall be obtained as [2,19]

$$\theta_{t,\max} = 0.17 - 0.00014 d_{bg} \tag{1}$$