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Robustness of bolted-angle connections against progressive collapse: Mechanical modelling of bolted-angle connections under tension

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ABSTRACT

Traditional design of connections is limited to moment-rotation characteristics and the information about the deformation capacities of connection components is quite limited. Thus, it is necessary to develop a new mechanical model, which could predict the deformation capacity of each connection component. In this paper, an experimental investigation of bolted-angle connections under tension is presented. In total, fourteen specimens were tested. The parameters studied in the experiments included bolt hole positions, angle thickness, bolt size and material properties. Depending on the strength ratio between angles and bolts, five types of failure modes were observed in the experimental tests. The test results demonstrated that the load increase at large deformation stage was much higher than the yield strength. Based on the experimental results, a new mechanical model of bolted-angle connections is developed. In the proposed model, the following issues are addressed: (i) the interaction between angles and bolts, (ii) failure criteria to determine the deformation capacities of connection components, and (iii) load limits due to bolt fracture. Finally, the proposed mechanical model is validated by the experimental results and the predictions of the model agree well with the test observations.

1. Introduction

Substantial interest in the topic of progressive collapse [11,9,10,14,28] has been generated during the past decade as a consequence of the World Trade Centre collapse in New York. Many experimental tests of steel and composite structures [6,12,17,21,22,23,24] were conducted and connection failures were observed under column-removal scenarios. Previous experimental tests [23] indicated that bolted-angle connections normally performed better than other types of connections in the development of catenary action. This is due to extremely high ductility (rotational capacity) through deformation of the connected angles. The experimental tests [22–24] have also shown that after large rotations have occurred, beam–column joints are subjected to pure tension and tensile failure controls the final failure modes of these joints. The research works of Yu et al. [25,26] also demonstrated that at the stage of large deformation, fracture of the connection components determined the ultimate resistances of joints. Thus, it can be concluded that the behaviour of beam–column joints under pure tension governs the structural resistances against progressive collapse. Therefore, the behaviour of beam–column joints under pure tension should be well understood in order to assess the robustness of steel buildings against progressive collapse. In addition, the failure criteria to determine the deformation capacities of beam–column joints under tension should be articulated and quantified to predict the ultimate resistances of joints at large deformation stage. However, traditional design of connections is limited to moment-rotation characteristics and the information about the deformation capacities of connection components is quite limited. Thus, it is necessary to develop a new mechanical model, which could predict the fracture of each connection component and the development of catenary action. In this research project, a component-based model will be developed to predict the behaviour of bolted-angle connections under pure tension. In this model, the deformation capacities of connection components can be predicted. Although in reality, beam–column joints were subjected to large tensile forces due to catenary action after large rotation, it is believed that the most critical connection component, which has the largest axial deformation, will control the final failure. The deformation capacity of this critical component can be predicted by the proposed model.

Eurocode 3-1-8 [7] uses component-based method to predict the behaviour of steel angle connections. The component of angles in bending is treated as an equivalent bolted T-stub. An elastic–plastic model is proposed for this component. Faella et al. [8] proposed a component model of bolted-angle connections, which produces good estimates of moment-rotation relationships at *small deformation stage*. Málaga-Chuquitaype and Elghazouli [13]

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developed a component-based mechanical model to predict the monotonic and cyclic responses of blind-bolted angle connections. In those models, only the strength and stiffness of the connection components were given and the ductility (deformation capacity) was not introduced into the model. Currently, the deformation capacity of each component has not been addressed and studied well [20].

Under other extreme loading conditions such as earthquake and fire, some research works have been conducted to develop the mechanical models of bolted-angle connections, which could predict fractures of connection components. Shen and Astaneh-Asl [18,19] performed an experimental investigation and proposed a hysteretic model of bolted-angle connections under seismic loading conditions. In this model, large deformation effect was considered and the deformation capacities of bolted-angle connections were also proposed. Further discussion about this model will be presented in this paper. Yu et al. [25,26] performed an experimental investigation and proposed a component-based model of web cleat connections subjected to tying forces at elevated temperatures. In this model, large deformation and component fracture were included. It was assumed that the ultimate capacity of the whole web cleat was reached when the angle was in pure tension. This failure criterion may not be accurate enough to predict the deformation capacities of bolted-angle connections. In the ambient tests of this research work, only one failure model (angle fracture) was observed and considered in the mechanical model. In addition, this model was too complicated to be used for hand calculations. Totally, as many as 54 equations have been involved in this model and a self-written program is needed in order to implement this model into the structural analysis.

In this paper, an experimental investigation of bolted-angle connections under tension will be presented first and a new mechanical model will be developed. The experimental tests have been conducted until the complete fracture of the connections occurs. The new mechanical model includes the interaction between the angles and the bolts, and considers the failure mode of bolt fracture. In addition, a new failure criterion to determine the deformation capacities of bolted-angle connections is proposed. Finally, this developed model will be validated by the conducted experimental tests.

2. Test programme

2.1. Test specimens

In total, 14 bolted-angle connections were tested under tension. A summary of the test specimens is given in Fig. 1 and Table 1. From BCSA/SCI [3] and Chen [5], it is found that for bolted-angle connections, the commonly used angle thickness varies from 7 mm to 12 mm and bolt size varies from M20 to M24. Therefore, in this experimental programme, two bolt sizes including M20 and M24 were used and the tested angle thickness varied from 7 mm to 11 mm. BCSA/SCI [3] and Chen [5] do not consider the resistances of beam–column joints under seismic conditions. Therefore, the proposal mechanical model is only useful to design a simple or semi-rigid connection under gravity loads. In the specimen design, the parameters studied include gauge length *m*, angle thickness *t*, bolt size and material properties. Fig. 1 illustrates the three connection configurations utilised (A, B and C). In Type A and B, only Grade 8.8 M20 bolts were used while in Type C, Grade 8.8 M24 bolts were used in horizontal legs and Grade 8.8 M20 bolts in vertical legs. Type B and C specimens are designed to avoid the failure mode of bolts in shear. This is because if this failure mode occurs, the interaction between the angles in bending and the bolts in tension could not be observed or measured in the experiments. Type B differs from Type C in the bolt size and gauge length *m*. The dimensions of *m* and *t* shown in Fig. 1, are given in Table 1. The other geometric properties are also given in Table 1. The average values of the angle thickness measured by digital callipers are also summarized in Table 1. The test specimens consisted of four angles. The bolt holes in the angles and thick steel plates were 2 mm oversize. To focus on the behaviour of angles and bolts, very thick steel plates were used to connect the bolted angles. The reference used for the specimens follows the nomenclature *XL-t-m-e* for equal angles and *XL*$_1$-*L*$_2$-*t-m-e* for unequal angles, where *X* represents the configuration type (A, B and C with reference to Fig. 1), *L* is the equal angle leg length in mm, *L*$_1$ is the longer leg length of unequal angle in mm, *L*$_2$ is the shorter leg length of unequal angle

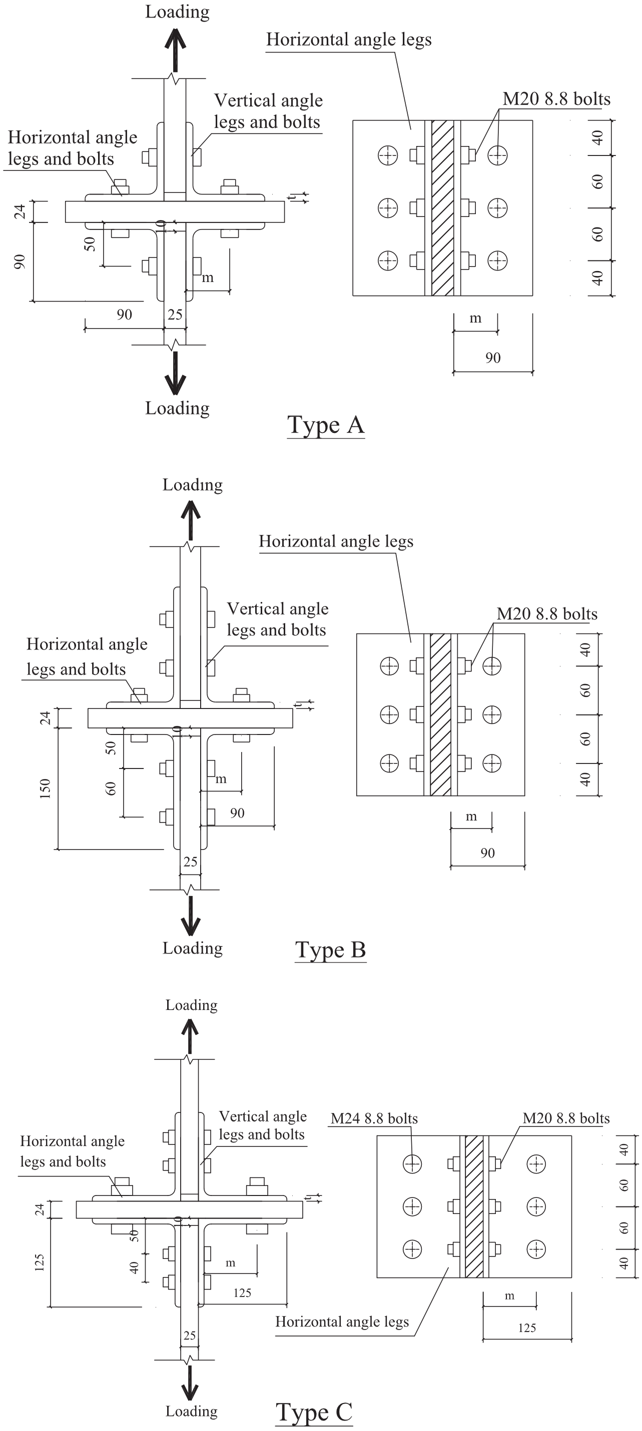

Fig. 1. Specimen configurations.