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# Capacity of semi-rigid composite joints in accommodating column loss

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ABSTRACT

In the scenario of column loss, joints would be subjected to bending moment combined with a tensile force due to large vertical displacement, where tensile force plays a critical role in resisting progressive collapse of structure by providing the catenary force. In order to study the effect of tensile force on the behavior of semi-rigid composite joints in structures in the case of column loss, six semi-rigid flush endplate connections tests were conducted, which include pure flexural tests, pure tensile tests and combined flexural and tensile tests. The experimental results indicate that under pure bending moment condition, the semi-rigid composite joint displays sufficient rotation capacity for forming "catenary action". It is characteristic of the semi-rigid composite joint that its moment capacity decreases in a linear manner together with the increase of tensile load. Also, the capacity of semi-rigid composite joints is compared with that of the full-welded rigid composite joints. The tensile strength of high-strength bolts would not exert any effect on the initial stiffness of semi-rigid joint, but bring about decline in the moment resistance and tensile resistance of semi-rigid joint. The joints tend to fail at "catenary phase" under tensile force. A simplified *M-N* correlation formula for composite joint is proposed to describe the behavior of joint in structures under column loss. The finite element model with material failure criterion can predict the fracture of bolt in semi-rigid composite joint.



## 1. Introduction

Nowadays, the events of terrorism are on the trend of increase. Public buildings such as hospital, shopping mall and car parks, whose collapse would lead to catastrophic results, turn vulnerable to terrorist attacks. Normally the abnormal loads caused by terrorist attacks such as bomb explosion, fire or vehicle impact are not explicitly taken into account in design. These abnormal loads may result in a significant local loss to load-carrying capacity of critical columns and subsequently to the collapse of the whole building. To prevent this type of failure, the alternate load path method is recommended in design [1–3] which is checked through the performance evaluation of the remaining structure in the removal of a critical column. The load-carrying mechanisms of the remaining structure will change from plastic hinge action to tensile catenary action where the beam-column connection is subjected to the combination of bending moment and tensile force as shown in Fig.1.

In order to avoid brittle damages of joint and behave properly, the joint should possess enough redundancy and ductility. Therefore, the features of joint behavior are identified as follows: under plastic hinge action, the reverse load-carrying capacity of the joint is required in where the joints at the damaged column are under sagging moment rather than under hogging moment; During the transition of load-carrying mechanism, the joints at the damaged column and the adjacent columns should be capable of carrying the particular load sequences involving bending moments, axial forces and shear forces; After tensile catenary action is triggered on the beams, the joints would undergo large deformation without any significant reduction in strength. The development of large deformations, as locally usual in the damaged structure is accepted, as long as progressive collapse is prevented [4]. There features are seldom to encounter in conventional design but essential for preventing progressive collapse in structure under column loss.

Steel-composite structures are widely used in the construction of public buildings. Commonly steel beams are acting compositely with the concrete slab. Compared with bare steel joints, steel-concrete composite joints possess higher bearing capacity and initial stiffness, especially higher redundancy which is a critical feature of joints employed in design of preventing progressive collapse. Moreover the reinforcement in the slab of composite joint is a key component of "catenary action", especially when the steel joint fails to meet the rotation demand to activate "catenary action". According to the joint's rotational stiffness, a joint may be classified as rigid, nominally pinned or semi-rigid. In reality, there is no real fully rigid joint. For an example, even the full rigid designed joint will exhibit some rotations in real engineering project. According to EC3, if the rotational stiffness of the joint is over a special value, the joint can be assumed as rigid joint. Compared with simply supported joints, semi-rigid or rigid joints

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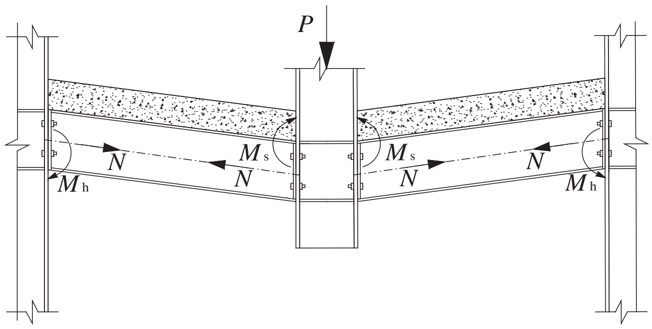
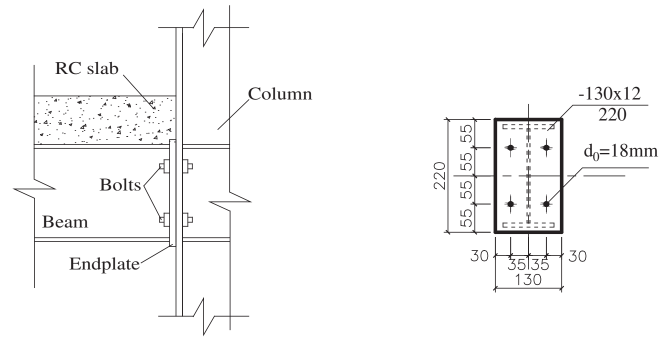



**Fig. 1.** Load-carrying mechanism transition.




(a) flush endplate connection (b) dimension of endplate

**Fig. 2.** Semi-rigid beam-to-column connection.

intended to sustain bending moments may display comparatively enhanced behavior [5]. Due to the relatively complicated configuration, however, semi-rigid joints are not widely used in public building structures even though semi-rigid joints can optimize the bending moment distribution in the connected beams. And above all, semi-rigid joints possess good rotation capacity which is especially beneficial for activating "catenary action" in the system in preventing progressive collapse.

It is common for the component method from Eurocode 3 to describe the behavior of steel-concrete composite joints. The mechanical properties of any beam-column connection could be estimated through decomposing it into individual components sustaining a specific action [5]. Based on the principles of component method, experimental and theoretical studies have been performed [6–9] to investigate the moment resistance, initial stiffness and rotation capacity of composite joints. Although the rules of component method theoretically work on any combination of actions, only 5% of axial resistance of the supported beam is allowed to apply on the joint in the Eurocode 3. However the joints in the structures under abnormal loads may withstand great axial force which may exceed the limits. Hence several experimental and theoretical studies have been conducted on the development of the component method to take a substantial axial load into consideration [10–13]. It should be noted that the focus of those researches was on development of the component method, rather than on description of the behavior of the joints in progressive collapse.

Based on that concept, a European collaborative research project [14] was set up to study the robustness of steel-concrete composite frame. In particular, a series of experiments was conducted on the behavior of composite frame in the scenario of column removal while an analytical method intended to predict M-N (bending moment-axial force) resistance interaction curves for composite joints was proposed based on the results of the experiments. Guo [15–17] also conducted a series of researches on the performance of steel-concrete frame under column removal. Five rigid composite joints employed in the frames were tested under bending moment in combination with tension. The experimental results indicated that the bending resistance of rigid composite joint decreases linearly with the increase of tension. Stylianidis and Nethercot [5] developed a mechanical model for evaluating the behavior of steel and composite joints used in anti-collapse analysis.

As can be seen from the aforementioned literatures, the previous studies on composite joints mainly focused on the moment resistance, initial stiffness and rotation capacity under conventional loading conditions. Up to date, few experiments have been conducted on the capacity of semi-rigid composite joints in accommodating accidental loss of adjacent structural members, especially the action of combined bending moment with tensile force. In this paper, tests were conducted on a series of flush endplate semi-rigid composite joints in the scenario of column removal. The loading conditions involve pure bending, pure tension and the combination of bending moment and tension in the tests. The mechanical performance of flush endplate composite joints in the scenario of column loss was studied first in detail and then compared with the studies on rigid composite joints. Moreover, a finite element model based on material failure was developed by ABAQUS software [18] and validated against the experimental results.

## 2. Experimental program

### 2.1. Design and fabrication of specimen

According to the loading capacity of actuator and experimental set-up, six 1/3-scale specimens of steel-concrete composite joints were designed and fabricated, whose parameters are presented in Table 1. The material properties and dimensions of the joints are identical as those of the joints employed in the semi-rigid composite frame in Ref. [17]. The configuration of flush endplate connection was employed in the specimens as shown in Fig. 2. Grade 10.9 M16 high-strength bolts were adopted in all specimens except that Grade 8.8 M16 high-strength bolts were adopted in specimen SJST2. The profile sections of beam and column were H200 × 100 × 5.5 × 8 (H-overall depth ($d$) × flange width ($b_f$) × web thickness ($t_w$) × flange thickness ($t_f$)) and H200 × 200 × 8 × 12 respectively. The thickness of the endplate was 12 mm. Detailed dimensions of the bare steel specimens are shown in Fig. 3.

The depth and width of reinforced concrete (RC) slab were 100 mm and 800 mm respectively. Along the length of the RC slab, two layers of 12-mm-diameter bars were utilized as longitudinal reinforcements beside the column. The longitudinal reinforcements in the middle of the rebar mesh were cut off at the location of beam-column connection. The longitudinal reinforcement ratio of the slab was 0.85%. Transverse reinforcements of 8 mm were distributed in two layers in the RC slab,

**Table 1**
Design parameter of specimens.

| Specimen | Column | Beam | Slab/mm | | Rebar ratio | Loading condition |
|---|---|---|---|---|---|---|
| | | | Thickness | Width | | |
| SJS | HW200 × 200 × 8 × 12 | HN200 × 100 × 5.5 × 8 | 100 | 800 | 0.85% | Sagging moment |
| SJST,SJST2 | | | | | | Sagging moment + tensile force |
| SJH | | | | | | Hogging moment |
| SJHT | | | | | | Hogging moment + tensile force |
| SJT | | | | | | Tensile force |