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Performance of different stiffness connections against progressive collapse

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ABSTRACT

This paper presents the anti-progressive collapse performance of different stiffness connections of a steel frame. Three specimens with double full-span assemblies from a steel frame were subjected to internal column removal. Model tests and numerical analysis were conducted with three different stiffness connections, namely the welded unreinforced flange-bolted web connection (WUF specimen), top-seat angle with double web angle connection (TSDWA specimen), and double web angle connection (DWA specimen). Failure modes, load–deformation responses, and mechanical behaviors of the specimens were examined in detail. It was found that the resistance of the DWA specimen was mainly provided by catenary action. In the other two specimens, flexural action contributed more significantly to resistance in the early loading stage, and then, the force transfer mechanism was mainly shifted to catenary action. In comparison, the axial force in a TSDWA-loaded beam could be fully developed in the later stage, which exhibited a greater anti-collapse bearing capacity for reserve strength. In addition, detailed finite element models were established and validated. The influence of the peripheral components' constraints on the anti-collapse performance of the assembly was assessed. It was found that if the constraint provided by the side column is sufficient to develop catenary action in a beam, the constraint provided by peripheral components will have little effect on the bearing capacity against progressive collapse.

1. Introduction

Progressive collapse of high-rise buildings has been the focus of engineers and researchers for many years. From the notable collapse of the Ronan Point Apartment Tower in East London (1968) to the World Trade Center Twin Towers in New York City (2001), progressive collapse of buildings (especially those with high occupancy) has been a problem that most people do not anticipate. Initial local damage of one or more bearing members of a structure owing to abnormal or accidental loading (impact, blast, collision) results in the failure and collapse of surrounding members, and eventually, leads to the collapse of the overall structure or a disproportionately large part of it [1,2]. Because of the catastrophic consequences of progressive collapse, various design standards [1–4] have been proposed to limit the degree of damage and prevent initial local collapse. The alternate load path method (APM) is recommended by the current codes and manuals of practice [1,2] for anti-collapse design and analysis. In this method, the robustness of a structure is evaluated through notional removal of the critical vertical bearing column(s) to determine whether the local damage may be absorbed by the remaining structural members and whether the structural system can bridge over the removed member(s). After a vital column is suddenly removed from a steel frame, the transverse beams connected to the removed column will resist the vertical load, first by flexural action and then through a new alternative equilibrium path formed by catenary action in the remaining structure to balance the vertical load of the upper parts under large deformation. This is possible if the joint possesses large rotational capacity.

In the present experimental studies based on the APM, the beam–column assembly is used to investigate the anti-progressive collapse mechanism of a structure mainly owing to the simplicity of stress analysis. As shown in Fig. 1(a) and (b), two typical beam–column assemblies exist when an internal column is lost: a double full-span assembly pattern [5–7] and a double half-span assembly pattern [8–10]. The double half-span assembly comprises the failure column and two connected half-span beams, assuming that the inflection point of the beam was located at the mid-span of the beam when the assembly was extracted from a prototype steel frame building. The double full-span assembly comprises two full-span beams connected to a failure column and two side columns. The difference between the two lies in the setup for the boundary conditions of each beam-end, which are different. In practice, in the double half-span assembly, the position of the inflection point of the beam may change under large deformation, which is not consistent with the simplified assumption. For example, after the tension flange of the beam-end connected to the removal column fractured with the practical beam-to-SHS column connections [11], the boundary conditions of the beam-ends immediately changed,

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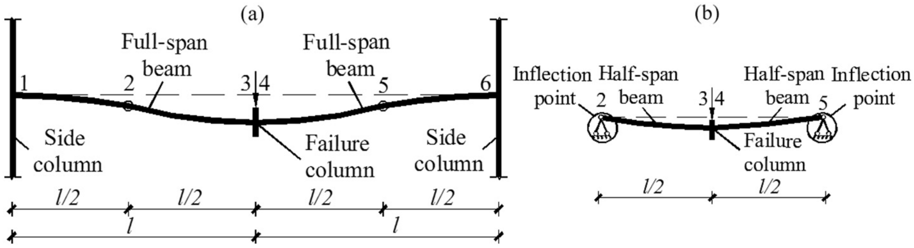

Fig. 1. Two typical beam-column configurations: (a) double full-span assembly; (b) double half-span assembly.

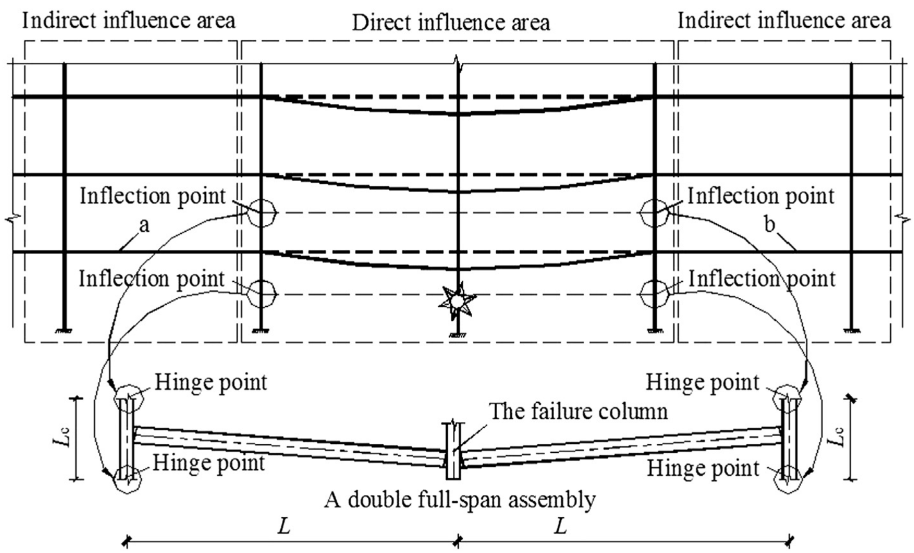

Fig. 2. Beam-column assembly extracted from steel frame.

leading to the movement of the inflection point. However, the double full-span assembly does not exhibit any such problem during the entire loading process, even for an asymmetrical structure. Furthermore, the double full-span assembly can be used to comprehensively investigate the failure sequences and the load transfer path of the entire structure, which is closer to what happens in a prototype structure. Thus, the double full-span assembly was selected as the research object in this study.

The beam–column joint is a critical element of a steel frame structure and enables catenary action when an internal column is lost [5,8,12]. It may be divided into three typical connections according to its working performance: rigid connection, semi-rigid connection, and simple connection. More recently, the seismic behavior of the beam–-column joint has garnered much attention, and investigations on the influence of the joint on anti-progressive collapse are currently underway. Lew et al. [5] investigated the behavior of two rigid connections in a welded unreinforced flange-bolted web connection subjected to column loss and a reduced beam section connection. Yang and Tan [8] experimentally examined semi-rigid connections and simple connections, including seven types of bolted beam-to-column joints, and showed that the tensile capacity of joints usually controls the failure mode and the development of catenary action after large rotations. Liu et al. [10] experimentally and numerically investigated the dynamic behavior of web cleat connections subjected to column loss. Wang et al. [11] studied the progressive collapse resistance of practical beam-to-SHS column rigid connections. Qin et al. [13–14] conducted experiments and numerical simulations to investigate a reinforced welded flange-bolted web connection and a conventional connection for progressive collapse prevention. Their study showed that the reinforced flange-bolted connection has a better anti-collapse performance in terms of deformability and strength than the conventional connection. In summary, previous studies mainly focused on the anti-progressive collapse performance of one or two of three typical connection configurations. Furthermore, the information gleaned from comprehensive comparisons of the anti-collapse performances of the three typical connections is still very limited.

Therefore, this study comprehensively examines the basic anti-progressive collapse performance of double full-span assemblies with different stiffness connections subjected to internal column loss. In particular, a comparative analysis of the connections was performed and their effects on the global behavior of the assembly were investigated. A welded unreinforced flange-bolted web connection, top-seat angle with double web angles connection, and double web angle connection were chosen, which are a type of rigid connections, semi-rigid connections, and simple connections, respectively. Three specimens, detailed in accordance with a prototype structure, were tested by monotonic static loading. The experimental results—including failure modes, load–displacement responses, stress states, and load transfer mechanisms throughout the loading process—for the assemblies with different stiffness connections are presented and discussed comprehensively. Finally, detailed numerical models are presented to enable further interpretation of the results, especially for the failure modes/sequences. In addition, the constraint influence of peripheral components on the anti-collapse performance of the assembly is further assessed.

2. Experimental program

2.1. Design and fabrication of specimens

After an internal column of a steel frame is artificially removed, the steel frame can be divided into the direct influence area and the indirect influence area (Fig. 2) according to the APM. In general, the APM considers the direct influence area as the main research region. To