Journal of Constructional Steel Research 140 (2018) 125–138

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Anti-collapse performances of steel beam-to-column assemblies with different span ratios

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ARTICLE INFO

Article history:
Received 22 September 2016
Received in revised form 20 September 2017
Accepted 14 October 2017
Available online xxxx

Keywords:
Steel frame
Beam-to-column assembly
Span ratio
Anti-collapse performance
Experimental study
Numerical simulation

ABSTRACT

The local failure of one or more structural members of a steel frame could trigger the progressive collapse of the structure. In this study, the anti-collapse performances of different beam-to-column assemblies comprising three columns and two beams were investigated. Three types of specimens with different span ratios (1:0.6, 1:1.0, and 1:1.4) and constructed using welded unreinforced flange-bolted web connections were considered. Static loading tests and numerical simulations were performed, and the local failures of all the specimens were observed to occur in the beam-to-column connection zones under large deformations. Each specimen exhibited multiple peak loads because of the repeated occurrence of local damage. The specimen with equal spans was found to exhibit a higher progressive collapse resistance in the latter phase owing to the synergistic action of the two adjacent beams. It also had a better load transfer mechanism, which enhanced the anti-collapse bearing capacity. Conversely, the peak loads of the specimens with unequal spans decreased with increasing loading displacement owing to the failure of the short beam before the long beam without full realization of catenary action. It was also determined through validated FE models that, when the constraints provided by the side columns were sufficient for the development of flexural and catenary actions in a beam, the assembly constraints provided by the peripheral components amounted to surplus constraints. Furthermore, more comparable linear stiffnesses of the column and beam enhanced their synergistic action and improved the resistance of the steel frame.

1. Introduction

Abnormal loading of a building structure, such as that due to an impact or explosion, may trigger the progressive collapse of the structure, with its responses to subsequent loads becoming disproportionate. The eventual collapse always involves significant losses, which may include the loss of lives. This has prompted the search by researchers and engineers for a means of preventing the progressive collapse of structures. The alternative load path method (APM) [1,2] is widely used for relevant analysis, and involves the removal of the critical gravity load-carrying component (column) based on a preliminary estimation. In the procedure, the cause and process of failure are not considered, and only the load redistribution process and the mechanism change of the remaining components connected to the removed column are investigated.

In a critical column removal scenario, the path of the gravity load carried by the removed column is changed, and a new equilibrium system is established by redistribution of the internal forces of the remaining structure. Initially, the transverse members (beams) adjacent to the removed column in a moment frame tend to resist the vertical load by the generation of a bending moment. With increasing vertical displacement, however, the axial force in the beam gradually begins to play a central role in withstanding and redistributing the external loads. The axial force also contributes to the so-called catenary action, which generates a resistance that prevents progressive collapse of the structure. Simultaneously, the constraints of the beam end provided by the side columns facilitate the transfer of the vertical load under a large deformation. Under this circumstance, the beam-to-column connection is key to the realization of an effective catenary action, and actually governs the failure of the structure [3–6].

A significant amount of analytical and experimental studies has been conducted on the prevention of the progressive collapse of steel frames in recent years. For example, Lew et al. [7,8] investigated the anti-progressive collapse performance of steel beam-to-column assemblies with two different types of moment-resisting connections. They found that the rotational capacities of the connections determined by monotonic loading tests were about twice those determined using seismic test data. Lee et al. [9] used nonlinear finite element analysis to investigate the action of the moment-axial tension interaction of double-span beams in a ductile welded steel moment frame against the progressive collapse. Yang and Tan [5,6,10] compared the mechanical behaviors of different types of bolted steel beam-to-column joints, and developed

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https://doi.org/10.1016/j.jcsr.2017.10.014
0143-974X/

component-based models of designs for preventing progressive collapse. Liu et al. [11] investigated the dynamic behavior of web cleat connections and their ability to resist progressive collapse. Stoddart et al. [12] investigated the behavior of fin-plate connections subjected to an axial tensile force and a moment, and developed component-based models of the connection for predicting its anti-progressive collapse performance. Li et al. [13,14] investigated both the failure mode and robustness in terms of strength and deformability of several types of steel connections under the condition of progressive collapse. Wang et al. [15] used experiments and numerical simulations to comprehensively analyze three types of rigid connections against progressive collapse. In these previous studies, beam-to-column assemblies were considered mainly because of the simplicity of the structural and stress analyses. Moreover, these studies focused on symmetrical-span assemblies, with very little attention given to asymmetrical-span assemblies, which are commonly found in multistory structures.

Beam-to-column assemblies can be divided into two typical configuration categories based on their composition, namely, double full-span assemblies (with two full-span beams connected to a failure column and two side columns), and double half-span assemblies (with only a failure column and two connected half-span beams) [13]. The distinction between these two types of beam-to-column assemblies can be simplified by the difference between the boundary conditions of the beam-ends. In the case of asymmetrical spans, the double full-span assembly is more suitable for simulating the actual boundary conditions compared to the double half-span assembly. This is because, in a double half-span assembly, the inflection point, which is assumed to be at the middle of the beam span, may move under a large deformation. Meanwhile, the double full-span assembly may completely cover the failure sequence of the connections and the load transfer path of the structure, affording a scenario closer to that of a prototype frame. The double full-span assembly is thus recommended for asymmetric spans in current paper.

In this study, experiments were performed to investigate the flexural and catenary behaviors of steel frames with welded unreinforced flange-bolted web connections under interior column removal conditions. The considered double full-span assemblies comprised three columns and two beams. The assembly specimens were of three tree groups with different span ratios of 1:0.6, 1:1.0, and 1:1.4, respectively. The specimens were designed in detail in accordance with a prototype steel building frame. Each specimen was constructed and statically tested under monotonically increased displacement of the top center of the failure column. The experimental results for the various assemblies with differing span ratios are presented and discussed in detail in this paper. To verify the experimentally determined failure modes and load transfer mechanisms of the specimens, numerical simulations were conducted using a detailed finite element model that considered the material fractures. Numerical analysis for different boundary conditions (side column stiffness and peripheral component constraints) were also performed. This was used to obtain more information for the analysis and design of steel frames to resist progressive collapse.

2. Experimental program

2.1. Test specimens

The test specimens were designed by the alternative load path method (APM). After the removal of an internal column of a steel frame, the steel frame can be divided into direct and indirect influence areas (see Fig. 1). Generally, the direct influence area is regarded as the main investigation region when using the APM. To investigate the anti-collapse performance of the present specimens under external loading, the main components connected to the failure column were simplified as a double full-span assembly consisting of two adjacent beams connected via a short column (failure column) between them and with two other side columns, as shown in Fig. 1. The indirect influence area provided some boundary constraints for the direct influence area, with the two beams connected to the two adjacent beams (a and b in Fig. 1) particularly providing rotational and axial constraints for the assembly. However, according to previous observations [7,16] and numerical analysis by the present authors, for a high stiffness of the side columns, the assembly boundary constraints provided by beams a and b could be neglected. The gravity load of the remaining framework was concentrated as a vertical load acting on the top of the failure

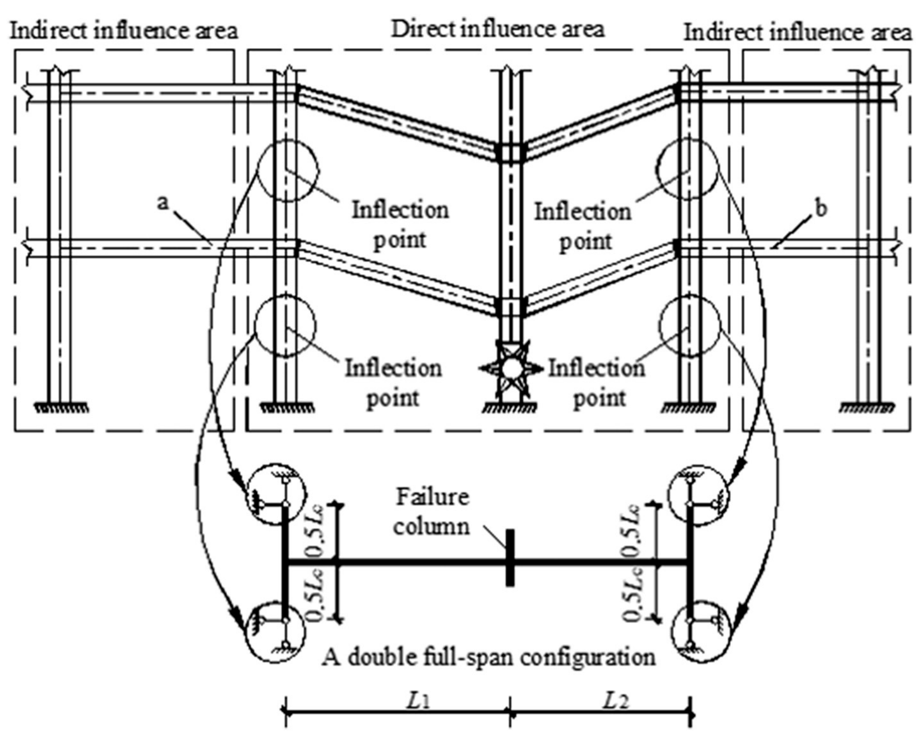

Fig. 1. Beam-to-column assembly extracted from steel frame.