Journal of Constructional Steel Research 112 (2015) 293–304

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental study of through diaphragm connection types under a column removal scenario

Xi Qin [a,b], Wei Wang [a,b,*], Yiyi Chen [a,b], Yihai Bao [c]

[a] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
[b] Department of Structural Engineering, Tongji University, Shanghai 200092, China
[c] Department of Civil and Environmental Engineering, University of California-Davis, Davis, CA 95616, USA

ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form 17 May 2015
Accepted 30 May 2015
Available online 9 June 2015

Keywords:
Steel structures
Progressive collapse
Through diaphragm connections
Connection detailing
Structural robustness

ABSTRACT

The beam-to-column connection has been identified as a key element for steel frame structures to maintain structural integrity under progressive collapse loading conditions. This paper presents full-scale laboratory tests of two steel frame assemblies with different connection details under a column removal scenario. One adopts a traditional field-welded through diaphragm connection, and the other uses a modified bolted through diaphragm connection. Test results demonstrate that the modified bolted connection can delay the fracture occurrence at the bottom flange; therefore the catenary action can be fully developed without completely losing the flexural resistance. For that reason, the beam-to-column assemblies can provide greater vertical resistance owing to combined flexural action with catenary action under large deformations. In this respect, the modified bolted through diaphragm connection is proved to have a better load-carrying capacity than the traditional field-welded connection and can be used to enhance the collapse resistance of steel frame structures.

1. Introduction

The phenomenon whereby the failure of one or more load-resisting structural members due to an unexpected load leads to the collapse of the entire structure or a significant portion of it is commonly called progressive collapse [1]. Since the Alfred P. Murrah Federal Building Bombing in 1995 and the WTC collapse in 2001, research on progressive collapse has become a hot topic. During the past decade, many experimental and computational works have been done in an effort to mitigate the risk of progressive collapse of structures. A series of design specifications and guidelines [1–4] provide specific design requirements to resist progressive collapse for US federal buildings and all Department of Defence (DoD) projects. Currently, ASCE has formed a standard committee to develop the new standard on progressive collapse mitigation. Preventing progressive collapse of buildings has been recognized as an important design consideration. An important design approach of a structure against progressive collapse is the alternative load path method (APM) [2,3], in which structural integrity is evaluated by removing critical gravity load-bearing elements. If a major load-carrying column is destroyed, the beams connected to the destroyed column can carry the vertical load and transfer the load to adjacent columns. An alternative load path is formed and the structure can bridge over the removed column. Under a column removal scenario, the frame structure resists the vertical load by flexural action at first, whereas in the stage of large deformation, the resistance mechanism gradually shifts towards relying on catenary action, provided that sufficient tension anchorage can be developed [5].

The beam-to-column connection has been identified as a key element of steel frame structures to maintain structural integrity under progressive collapse loading conditions. Experimental and computational studies on the behavior of steel frame structures under column removal scenarios have been reported by many researchers. Khandelwal and EI-Tawil [6] carried out computational simulation to investigate catenary action in moment resisting steel frames. Rölle and Kuhlmann [7] did experimental and numerical investigations of steel and composite joints and adjusted their components to ensure a higher deformation capacity during pure bending as well as combined bending and tension exposure. Karns et al. [8] examined the blast resistance and overall structural performance of selected steel frame beam-to-column moment connection configurations when subjected to direct air blast attract. Lee et al. [9] proposed a parallel axial–flexural hinge model capable of representing post-yielding flexural behavior and considering interaction effects of axial force and moment for a simplified nonlinear progressive collapse analysis of welded steel moment frames. Sadek et al. [5,10] conducted an experimental and analytical assessment on the performance of steel assemblies with two types of moment-resisting connections under monotonic vertical displacement of a center column. Yang and Tan [11–13] investigated the mechanism behavior of bolted-angle beam-to-column joints under a middle column removal scenario. Li et al. [14,15] conducted a series of tests to investigate the

* Corresponding author at: State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China.
E-mail address: weiwang@tongji.edu.cn (W. Wang).

http://dx.doi.org/10.1016/j.jcsr.2015.05.022
0143-974X/

behavior of Circular Hollow Section (CHS) column to H-beam connections and Rectangular Hollow Section (RHS) column to H-beam connections. All the results from previous research demonstrated that connection failure modes controlled the final collapse. The bottom beam flanges at the ends connected to the removed column are subjected to tension when the beams are in bending. However, the bottom flanges frequently fracture under a relatively small deformation (as seen in Fig. 1), which can seriously weaken the vertical resistance provided by flexural action and prevent the beam from fully developing axial force. Even though some connections with special configurations already have their advantages in the progress of developing catenary action [16], more enhanced vertical resistance can be achieved in the future. For crucial components in the buildings with high progressive collapse risk, enhancement on connection design may not necessarily cost more compared to other methods to meet the requirements for progressive collapse prevention, such as increasing sizes of structural members. In fact, it maximizes the material efficiency in the structural members by providing greater rotational capacity.

The majority of beam-to-column connections for moment resisting frames use rigid full-strength connections for seismic design. In order to develop full moment capacity, transverse column stiffeners are usually required to transfer axial loads in the beam flanges. The stiffener can be either a through diaphragm, internal diaphragm or external diaphragm. If an internal diaphragm is used, the column has to be cut only once at each connection, which considerably saves fabrication costs. However, welding of the diaphragm has to be done from the end of the column and weld defects were frequently observed at corner regions. The use of external diaphragm is convenient for fabrication. But the axial force cannot transfer from the beam flange to the column web directly. The through diaphragm type of connection is fabricated by first cutting the steel tube into three pieces and then welding them together with two diaphragms. The use of through diaphragm is convenient for fabrication as well. Moreover, the through diaphragm is perhaps the most efficient form for the axial force transferring from the beam flange to the column web [17]. Although the through diaphragm type of connection has been widely studied under seismic loads, no study has been reported on its performance under column loss scenarios.

In this paper, an experimental study on the behavior of RHS column to H-beam connections with through diaphragm under large deformations associated with the loss of an interior column is presented. Field-welded connection can be an economical and common type of rigid full-strength connection using through diaphragm. As can be imagined, it still has the aforementioned drawbacks (as seen in Fig. 1) under a column removal scenario. In order to postpone the fracture of the bottom beam flanges, a modified bolted connection is proposed. For comparing and analyzing the influence of the connection detailing, two full-scale beam-to-column assemblies, with a traditional field-welded connection and a modified bolted connection respectively, were constructed and tested under monotonically increased vertical displacement at the unsupported center column location, simulating a column removal scenario. The tests were fully instrumented such that all necessary measurements were available for a comprehensive evaluation of the responses throughout the entire process. The two specimens exhibited two distinctive resistance development paths and final failure mechanisms, thus providing significant information for the assessment of the influence of the through diaphragm connection detailing on the behavior and the resistance of the beam-to-column assemblies in a column removal scenario.

2. Experimental program

2.1. Test setup

As shown in Fig. 2, assuming that the end joints are performing as fixed ends, the internal force and deflection of the double-span beam-to-column assembly are symmetric about the short column at the center after the removal of the interior column. Thus, the inflection points are located at the middle of the beam span during the deflection process. Therefore, a beam-joint-beam (B-J-B) assembly composed with only half of the beam span on both sides was extracted from the prototype steel building frame using pin condition at the inflection points [6].

Fig. 3 shows the test setup. To consider the restraint from surrounding structural elements, horizontal restraint was provided by a horizontally self-balanced support frame system. The specimens were pin-supported at the two horizontal support frames. In order to consider the rotational restraint to beam-to-column assemblies from the continuous column of upper storeys, the test set-up included a rotational restraint system at mid-span. The center column was guided at the bottom end using a sliding support so that only vertical movement was possible. A displacement-controlled point load was applied to the column using an actuator to simulate the column removal scenario, and was balanced by a vertical reaction frame mounted on the strong floor. The maximum range of the vertical displacement of the setup was about 450 mm. Load was applied at a rate less than 7 mm/min during the tests.

2.2. Test specimens

Two RHS column to H-beam assemblies of B-J-B pattern, namely Specimen ST-WB and Specimen ST-B were designed to represent two moment resisting connection details. The main difference between the two test specimens lies in the connection details between the beam flanges and the diaphragms. For specimen ST-WB, complete

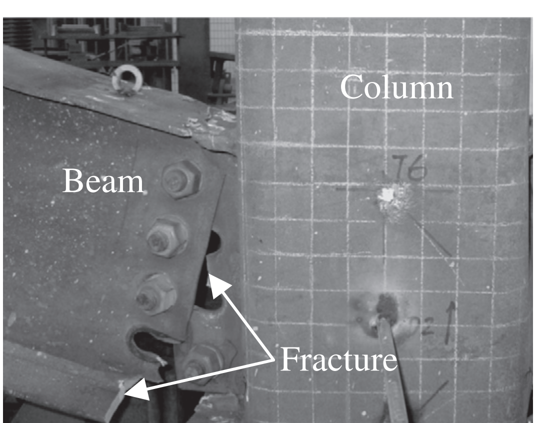

Fig. 1. Failure modes of the RHS column to H-beam joint [15].

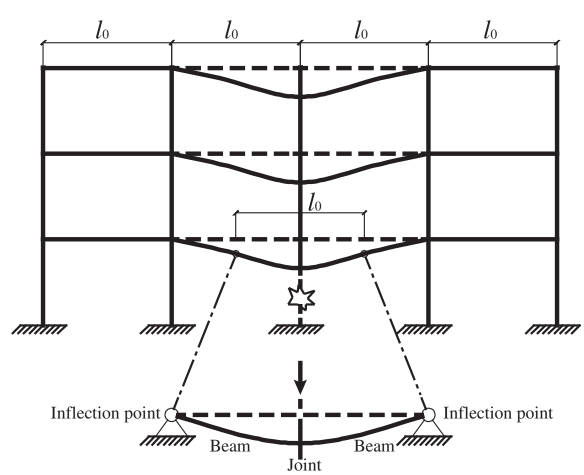

Fig. 2. A beam-joint-beam assembly extracted from a frame structure.