Engineering Structures 95 (2015) 112–126

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Structural performance of semi-rigid composite frame under column loss

Lanhui Guo [a,b,*], Shan Gao [c], Feng Fu [d]

[a] Key Lab of Structures Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Harbin 150090, China
[b] School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
[c] China Mobile Group Design Institute Co. Ltd. HeBei Branch, Shijiazhuang 050000, China
[d] School of Mathematics, Computer Science & Engineering, Department of Civil Engineering, City University London, London EC1V0HB, United Kingdom

ARTICLE INFO

Article history:
Received 4 November 2014
Revised 23 March 2015
Accepted 24 March 2015
Available online 10 April 2015

Keywords:
Composite frame
Semi-rigid connection
Material fracture
Progressive collapse
Reinforcement

ABSTRACT

The catenary action associated with significant second order effects plays an important role in resisting additional loads when structural column is destroyed under unexpected loads. The capacity and ductility of beam-to-column connection is one of the key factors in the formation and performance of catenary action. To study the behavior of the semi-rigid connection under single column removal scenario, a pseudo-static test of a composite frame with flush-endplate connections (a typical semi-rigid composite connection type) under the loss of middle column was carried out. Also, a FE model using both 3-D elements and 2-D elements was developed and analyzed. The accuracy of FE analysis results is validated by comparing with the experimental results. The analytical results showed that the progressive collapse resistance is sensitive to the properties of bolts. It is also found that increasing the fracture strain of bolts, the progressive collapse resistance of composite frame improves significantly, and increasing the diameter of bolts shank could also increase the loading-capacity and ductility of the connection. Meanwhile, some measures are suggested to improve the behavior of connection in resisting progressive collapse. Among them, a new technique called angle-steel reinforcement method is developed and proved to be a good way to improve the progressive resistance of semi-rigid composite frame.

1. Introduction

The partial collapse of the Roman Point apartment in UK in 1968 is a milestone of the research in the structural integrity of buildings. What is more, many recent catastrophes, such as the terrorist attack of the World Trade Center in 2001, have attracted increasing interest in engineering community on this topic. According to national design codes such as British Standard [1], Eurocode [2] and ACI [3], the structural integrity should be ensured through appropriate measures. After a vertical structural component is destroyed in an exceptional event, the loads on superstructures cannot continue to be transferred downwards due to the loss of the member. Instead, the membrane effect was triggered in the structure systems to carry the additional loads and redistribute the internal force. Based on this phenomenon, a series of design codes, standards and guidelines have been published to provide guidance on preventing the progressive collapse of the structure, such as GSA2003 [4], DoD2009 [5] and ASCE7-05 [6]. In these codes and standards, several methods are proposed, including Alternate Load Path, Tie Force and especially the so called "catenary action".

If a column fails in a structure, the behavior of the beam-to-column connections will play an important role in the formation and performance of catenary action. The connections are withstanding to a combined bending moment and tensile force, as a result of column loss. Compared with bare steel connections and reinforcement concrete (RC) connections, composite connections consisting of steel beams and RC slabs exhibit a higher load resistance and better deformation ability [7–10]. In addition, the steel mesh in the composite slabs are also contributing to "catenary action" while the bare steel connections cannot satisfy the rotation demand for forming catenary action [5].

Many analytical and numerical studies on the behavior of structure under column loss have been performed. A concise methodology for evaluating the predisposition of a structure to progressive collapse was proposed by Buscemi and Marjanishvili [11]. The progressive collapse issue was reduced to a conventional dynamic problem by using the pendulum analogy method. Khandelwal and EI-Tawil [12] performed a computational simulation to investigate

* Corresponding author at: School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China. Tel.: +86 451 86289100.
E-mail address: guolanhui@hit.edu.cn (L. Guo).

http://dx.doi.org/10.1016/j.engstruct.2015.03.049
0141-0296/

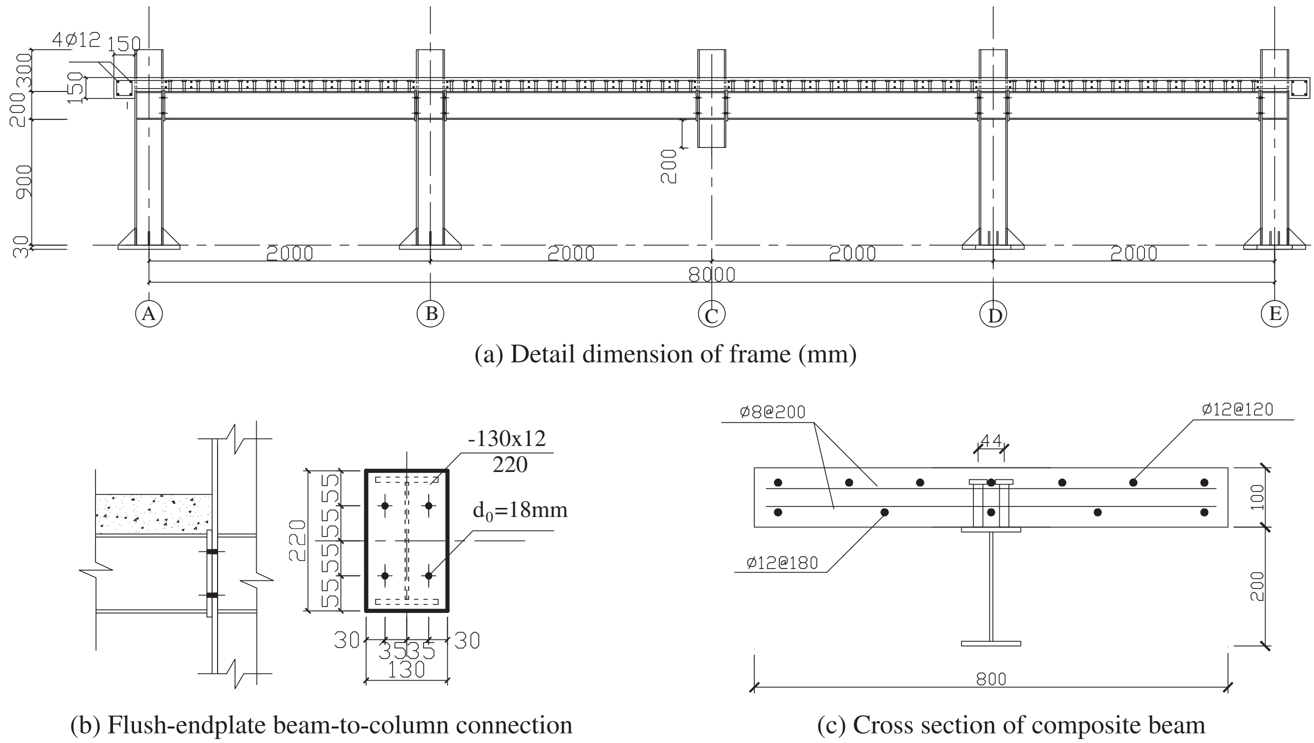

Fig. 1. Details and layout of frame.

Table 1
Mechanical properties of steel.

Se.		f_y (MPa)	f_u (MPa)	E_s (10^5 MPa)
Beam	Flange	269	401	1.96
	Web	275	411	2.09
Column	Flange	247	396	2.00
	Web	276	415	1.98
Reinforcement	∅8	325	487	–
	∅12	331	464	1.95
Grade 10.9 bolt	∅16	1067.4	1186	2.00

catenary action in moment resisting steel frames. Some parameters such as hardening, softening and ductile fracture behavior of steel were considered. Starossek [13] suggested that the progressive collapse of structures could be classified into six types including the pancake, zipper, domino, section, instability and mixed types, and different methods should be used to prevent different types of collapse. A new design-oriented methodology for progressive collapse assessment of multi-storey composite buildings was developed by Izzuddin et al. [14]. Structural robustness at various levels of structural idealization could be easily assessed by using this new methodology which makes progressive collapse assessment more practical. Tsai et al. [15] verified that the dynamic amplification coefficient produced conservative estimation for collapse resistance if the value of the coefficient was set to 2.0. Li and Wang [16] tested steel beam-to-tubular column moment connections under a column removal scenario. Test results demonstrated that the beam-column assemblies resisted the load applied at top the center column primarily by flexural action in the early stage of the response, and the resistance mechanism gradually shifted toward relying on the catenary action as the vertical displacement increased. Fu [17] developed a 3-D finite element model of 20-storey composite building. The numerical results represented the overall behavior of the 20-storey building further to a sudden column loss and provided important information for the assessment of high-rise buildings under column loss in practice.

Some tests of structure under the different scenarios of column loss have also been conducted. A 1/3 scaled progressive collapse test of a 3-story reinforced concrete frame building with 4-bay was conducted by Yi et al. [18]. The experimental results showed that there were 4 phases, through which RC frame under column loss would go. Demonceau et al. [19] conducted a test simulating the loss of a column in a 2-D composite frame. Horizontal brace was used as the lateral restraint of the frame. The catenary action in the frame was observed evidently and the development of membrane force in the beams was confirmed by the experimental results. Yang and Tan [20] conducted seven experimental tests focusing on the performance of bolted steel beam-column connections in catenary action. The extremity of beams in the test was pinned as a simplified boundary condition. The experimental results displayed the behavior and failure modes of different bolted connections, especially their deformation ability in catenary action. The numerical analyses of the response of steel beam-column joints subjected to catenary action were also performed [21]. Oosterhof and Driver [22] conducted a series of tests on steel shear connections under the scenario of middle-column removal. Three types of shear connections were studied in a test set-up which is capable of applying any independent combination of moment, shear and tension. The study indicated the relative performance of three connection types under different combined loads. Guo [23] conducted a 1/3 scaled progressive collapse resistance test of a rigid steel–concrete composite frame. The results showed that the rigid composite frame exhibited good progressive collapse resistance behavior.

Therefore, it can be seen from the above mentioned tests and studies that in the past most of the studies on progressive collapse focused on numerical and theoretical analysis. Although some experimental studies were conducted recently to investigate the performance of the connection under the scenario of column loss,