Journal of Constructional Steel Research 138 (2017) 380–388

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Simulations on progressive collapse resistance of steel moment frames under localized fire

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ARTICLE INFO

Article history:
Received 26 January 2017
Received in revised form 15 May 2017
Accepted 29 May 2017
Available online xxxx

Keywords:
Steel frame
Progressive collapse
Fire
Simulation
Dynamic effect

ABSTRACT

Based on three steel frame tests conducted by the authors, which explicitly considered dynamic effect caused by column buckling, numerical models were developed to analyse the progressive collapse resistance of steel moment frames under a localized fire. Besides, the effects of damping and strain rate were studied, and the progressive collapse modes of the test frames were studied through amplifying the load applied to the frames. The analysis results match well with test data and show that the influence of damping on progressive collapse of steel frames under a localized fire is negligible in the range of damping ratio from 0 to 10%. However, the effect of strain rate on the structural performance of steel frames under a fire is significant for the cases involving dynamic buckling of the heated column. Besides, the strain rate effect in the heated columns is significant but is negligible in other parts of the test frames. The successful validation of the numerical models paves the way for their application in parametric studies aimed at improved guidance of structural robustness under localized fire conditions.

1. Introduction

Since experiments on global behaviour of building structures are expensive and time-consuming, it is not feasible to conduct a large number of experiments to study the progressive collapse resistance of structures under fire conditions. Besides, the data that could be directly collected from structural experiments is limited, making it difficult to comprehend the structural performance mechanisms just from the test data. Therefore, numerical study is an important alternative way to study structural behaviours under fire conditions. On the other hand, progressive collapse of structures under a fire may involve material deterioration at elevated temperature and geometrical and material nonlinearity, hence, progressive collapse simulation involves potentially complex and interacting phenomena. Therefore, to ensure the accuracy of a numerical simulation, it is important to validate the numerical model against experimental results.

The Cardington fire tests [1,2] have provided very important test data on global behaviour of steel structures in fire conditions. Following these tests, significant numerical research efforts have been made to understand the global performance of steel structures under fire conditions [3–8]. However, in the Cardington fire tests the steel columns were fire protected to prevent global buckling and the test steel structures almost behaved in a static way. Hence, the above analyses were conducted through using static methods, with the dynamic effects typically overlooked.

More recent research has shown that severe dynamic effects may occur during the failure process of steel columns under a localized fire [9,10]. Hence in simulations of progressive collapse resistance of steel structures under fire conditions, dynamic effects need to be considered. During the past two decades, significant dynamic analyses were conducted on the progressive collapse of steel structures under fires [11–14]. These numerical models were carefully verified through comparing with theoretical analyses or relative tests. However, due to the lack of tests which explicitly consider the dynamic effects during the failure of steel columns under fire, there is yet a lack of direct validation for the analysis results of progressive collapse resistance of steel structures under a localized fire.

Tests on progressive collapse resistance of moment steel frames, presented in the paper [15], were conducted by the authors. These tests, in which significant deflections occurred, explicitly considered the dynamic effects in the performance of steel frames under a localized fire. The test results show that global buckling of steel columns in a fire can cause significant dynamic effects on the performance of the whole frame.

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http://dx.doi.org/10.1016/j.jcsr.2017.05.018

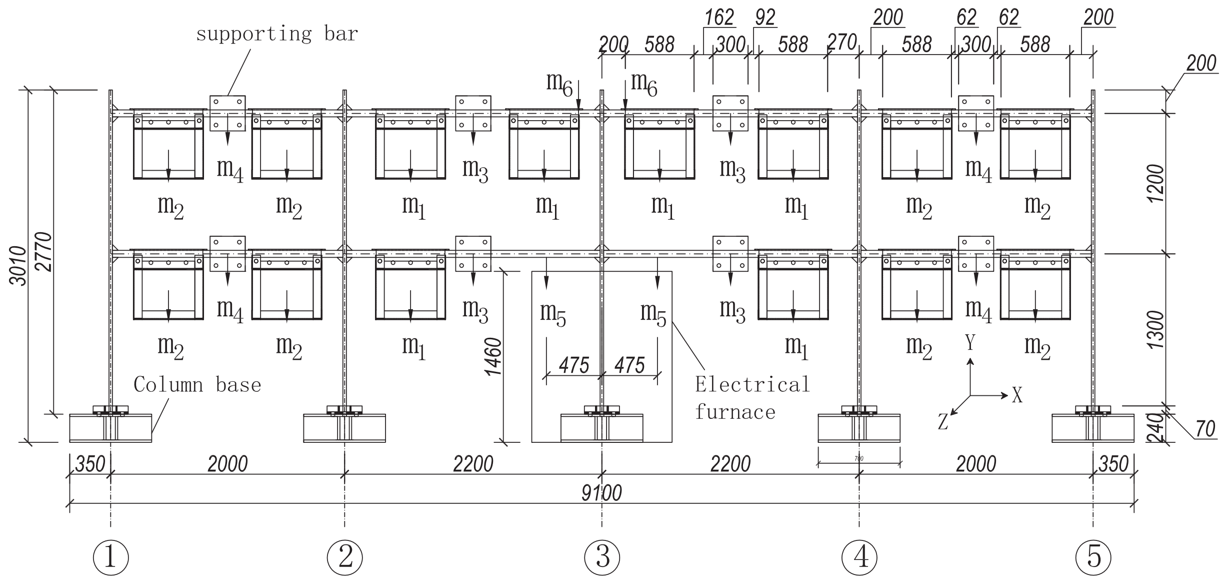

Fig. 1. Test set-up [15].

This paper presents numerical studies of the progressive collapse resistance of steel frames under localized fires, where explicit dynamic analysis was adopted. First, a detailed numerical model, consisting of shell elements, was developed. This developed numerical model was then validated against the tests presented in paper [15]. Besides, the effects of damping and strain rate on performance of steel frames under a localized fire were studied. Furthermore, the progressive collapse modes of the test frames were studied by amplifying the load applied to them. The simulations presented in this paper not only develop a numerical model for further studies aimed at an improved guidance of structural robustness under localized fire conditions, but also bring insights into the progressive collapse resistance of steel frames under such conditions.

2. Brief description of the frame tests

Three steel moment frames were tested in paper [15]. Fig. 1 shows the test set-up and the frame dimensions. Out-of-plane displacement at the middle of each beam was restrained through a supporting bar to make sure the structural performance remains in the frame plane. Sections of the columns and beams of all the test frames were rectangular tubes. Details of the member sections of the test frames are listed in Table 1, where the tubes with sections of 50 × 30 × 3, 60 × 40 × 3.5 and 150 × 50 × 5 are represented by symbols G1, G2 and G3, respectively. Beam-to-column connections were welded connections and were stiffened by triangular plates with dimensions of 50 × 50 × 5 (mm). The Steel grade of the structural tubes is No. 20 and that of the stiffener plates is Q345.

As shown in Fig. 1, the test frames were loaded with gravity loads, with the middle column at the first storey being heated through an electric furnace. Quantities of the weights carried by the test frames are summarized in Table 2. Column bottoms were rigidly connected to the column bases which were fixed on the ground, and the out-of-plane displacement at the middle of each beam was restrained by a supporting bar. In the test, gravity loads were first applied to the test frames, then the column was heated.

Furnace gas temperatures, frame temperatures, displacements and strains at certain locations were measured in the tests. Measured average gas temperatures in the furnace for the three tests are shown in Fig. 2. Locations of sections where frame temperatures were measured are shown in Fig. 3 (a). The thermocouples were located at the middle of each side of column section. The temperature curves of $\bar{T}_{8\sim11}$, $\bar{T}_{16\sim17}$, T_{18} and T_{19} were used to represent the temperatures of the heated column and beam in the simulations of this paper. These test curves are illustrated in Fig. 3 (b).

Table 1
Details of member sections.

Frame no.	Column	Middle bay beam	Side bay beam
Frame 1	50 × 30 × 3 (G1)	150 × 50 × 5 (G3)	60 × 40 × 3.5 (G2)
Frame 2	50 × 30 × 3 (G1)	60 × 40 × 3.5 (G2)	60 × 40 × 3.5 (G2)
Frame 3	50 × 30 × 3 (G1)	60 × 40 × 3.5 (G2)	60 × 40 × 3.5 (G2)

Table 2
Details of weight carried by the test frames.

Frame no.	m_1 (N)	m_2 (N)	m_3 (N)	m_4 (N)	m_5 (N)	m_6 (N)
Frame 1	2910.0	1760.7	701.3	766.0	73.9	74.0
Frame 2	4667.3	2312.4	751.1	766.0	69.7	81.7
Frame 3	7393.5	3716.7	751.1	766.0	69.7	103.7

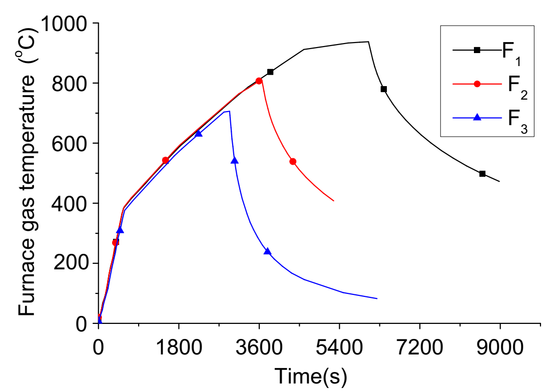

Fig. 2. Furnace gas temperatures [15].