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Fire tests on full-scale steel portal frames against progressive collapse

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ABSTRACT

This paper presents experimental investigations on the collapse behavior of a full-scale 36 m × 12 m steel portal frame exposed to natural fires. Extensive thermal and structural responses of the frame are measured and presented. The frame collapses after 15-min fire exposure with a critical temperature of about 1100 °C in the heated column. The measured gas temperature history has a short growth period of 3 min, and reaches its peak temperature of 1100 °C within 8 min (400 °C higher than standard fire). It is found that a two-zone model can be assumed with uniform temperature distribution in the lower and upper half region, respectively. The temperature gap of these two zones reaches 200 °C. The gas temperature at top region decreases due to the deformation-induced opening of roof and fire walls. The surface facing the environment has higher gas temperatures than that inside the fire compartment (more than 200 °C). The temperature of rafters beyond the fire compartment reaches 700 °C due to the spread hot smoke. Outward bending of the external unexposed column and pulling out of corner column base are observed, which should be prevented in practical design to mitigate fire spread to adjacent buildings and ensure life safety of fire fighters. Numerical simulation is conducted and compared to experimental results which can be used for calibrating numerical models.

1. Introduction

Traditional structural fire design methods are based on standard fire tests on individual structural members under idealized loading and boundary conditions [6,17]. The standard fire tests cannot take into account the real fire scenarios and restraint from surrounding frame which may significantly affect the behavior of members. Laboratory fire tests [15] and realistic fire events have demonstrated that the fire performance of steel-framed composite buildings is much better than is indicated by standard fire tests conducted on isolated structural members. The unscientific nature of prescriptive approaches has led to accelerating adoption of performance-based design approaches [9], characterized by much greater reliance on numerical modeling technologies [16,18,19,24]. In this case, design fires in terms of natural fire, localized fire and travelling fire can be used to represent the realistic fire scenarios [11,44]. Especially since the collapse of the Word Trade Tower under terrorist attack on September 11, 2001, there has been considerable interest in understanding the progressive collapse of buildings in fire [10,21,22,38,39], which is defined as “the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it” [3]. These events have ignited worldwide attention on the global collapse behavior of structures exposed to fire [32].

The calibration of numerical models against experimental results, for both thermal and structural responses, is essential for an accurate prediction of behavior of structures under fire conditions [20]. However, there is limited experimental results available for calibrating numerical models of fire-induced progressive collapse. Fire tests on structural components [14,26,27,40] cannot fully capture the realistic boundary conditions and interactions as they are in a building. Due to the size effect, small-scale fire tests on sub-assemblies or whole structures [29,31,41] always fail to capture the realistic dynamic behavior which significantly depends on the damping, mass and redundancy of the structure ([23]b). Most previous fire tests on full-scale buildings [12,15,42] focus on investigating the behavior of structural components in a building where no collapse limit state is targeted. Recently, Song et al. [35] conducted field experiments on an existing full-scale building to study its progressive collapse behavior at ambient temperatures. Three-dimensional numerical models were established and it was found that that the 3D model was more accurate in simulating the collapse behavior rather than 2D models, as it can account for the contribution of members in the transverse direction. To obtain a good agreement between the measured and predicted responses of these full-scale structures, a detailed finite element simulation of profiled

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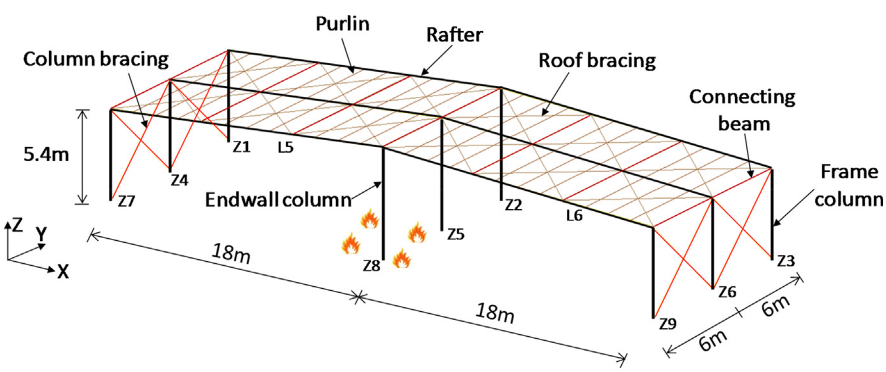
composite slabs and beam-to-column connections is required, which is challenging due to the complex layout of the building and huge computation cost. Thus sub-structure models are always taken to simplify the modeling by assuming grillage of beams, constant thickness of profiled slab, or rigid/pinned connections [8,22,45]. Therefore, it is necessary to conduct fire tests on full-scale structures with a moderate level of complexity which is capable of capturing key issues of the fire-induced collapse mechanisms of structures with minimum modeling cost. A three-bay full-scale steel portal frame was designed and tested by the authors to provide validation data for numerical simulation of progressive collapse of structures, which is one objective of this study.

Steel portal frames are generally low-rise structures, consisting of columns and horizontal or pitched rafters with moment-resisting connections. They are cost effective for enclosing large volumes, and have been widely used in industrial, storage, retail and commercial buildings. Compared to structural members of multi-storey buildings which are required to have fire resistance to prevent structural collapse, single-storey buildings, however, are only required to have fire resistance when fire spread between buildings is of concern [34]. Important factors relevant to limiting fire spread are the presence of fire-resistant external walls and/or the specified spacing between the adjacent buildings. The steel columns and rafters are always permitted to be unprotected and not required to achieve the level of fire-resistance required for the walls. A number of recent fires in industrial structures have drawn attention to a current lack of understanding about the progressive collapse of steel portal frames under fire conditions.

An inward collapse of portal frames is always preferred rather than outward collapse since it helps to prevent fire spread to adjacent buildings, and to ensure life safety of fire fighters who usually extinguish fire outside the frame. In addition, the inward collapse of walls or claddings may contribute to extinguishing fire inside the frame. Efforts have been made to understand the collapse mechanism of steel portal frames in the case of fire. Souza et al. [37] presented a comparative study of 2D and 3D models of a portal frame in fire. It was found that the 2D modeling was unrealistic as it failed to take into account the lateral instability of the members of the portal member. Ali et al. [1] found that a frame could collapse outwards if the fire was localized to the column due to the limited heated portion of the beam and thus insufficient catenary forces to pull columns inwards. It was also found that some level of base fixity should be provided to ensure a favorable inward collapse mode [5,28,36]. The results indicated that the current design method may provide unconservative results. The failure mechanism of a portal frame may be a rotational failure of the roof section [36]. EI-Heweity [7] investigated the failure temperature of steel portal frames exposed to fire. A failure criterion depending on the formation of plastic hinges was proposed. Johnston et al. [25] demonstrated that the joint rigidity and various fire scenarios should be considered to allow for conservative design. Garcia et al. [13] studied the behavior of steel portal frames with fire-resistant steel and intumescent coatings. The results showed that a combination of these two methods was the best choice from both economic and structural views. Balogh and Vigh [4] developed structural optimization framework for steel portal frames. It was concluded that the application of ISO standard fires did not always



(a) schematic of the frame layout

(b) frame on site

Fig. 1. Layout of the tested portal frame.