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Quantitative evaluation of progressive collapse process of steel portal frames in fire

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ABSTRACT

This paper presents quantitative investigations on the collapse behavior of steel portal frames exposed to standard fires. The complete collapse process is divided into safe, alert, dangerous and collapse stages. These four stages are to warn firefighters to make timely reactions to stay, ready to evacuate, and must evacuate, respectively. Numerical models are established and validated against fire tests on a full-scale steel portal frame. Based on the key displacements of the heated columns and rafters, the four stages are quantitatively determined in terms of visible phenomena and warning times. It is found that one should be ready to evacuate when the heated rafter shows large deflections, and must evacuate when the heated column moves back to its initial position. The 1 h, 2 h, 3 h fire rating of protected steel portal frames can be used to estimate the ready-evacuate, must-evacuate and collapse warning time, respectively. The findings from this preliminary study aim to provide references for firefighters to make wise decisions to evacuate timely and safety from the fire scene.

1. Introduction

The collapse of Word Trade Center under terrorist attack on September 11, 2001 has ignited growing interest in understanding the progressive collapse of buildings in fire. The term “progress collapse” 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" [1]. This indicates that large displacements (even failure) of individual structural members are acceptable provided that global collapse is prevented. Approaches for assessing collapse performance of structures and measures for mitigating progressive collapse can be found in various design codes [1–3]. Among them an Alternate Path (AP) method has been widely used which requires that the structure be capable of bridging over a missing structural element in the event of a localized damage. However, this methodology is more applicable to blast or impact actions than to fire since it helps to estimate whether and how a structure collapses, rather than when it collapses [4]. For structural analysis under fire conditions, the collapse time, defined as the time when the structure collapses, is of essential concern for guiding evacuation of occupants and ensuring life safety of firefighters. This is to say how long the structure can resist progressive collapse is of great importance since the failure time of the heated members in the fire compartment should be taken into account. On the other hand, the beneficial effect of fire protection measures on the collapse time cannot be considered in the AP method.

The fire-induced collapse of buildings may most likely endanger the life safety of firefighters since few occupants are still present in the building after hours' development of fire before collapse. The collapse time is a key parameter to warn firefighters to evacuate the fire site in time. However, most previous research focuses on evaluating the robustness of structures against progressive collapse and on predicting the collapse mode [5–8], rather than estimating the collapse time and the whole collapse process. The objective of this paper is to quantitatively evaluate the whole collapse process of structures, which can be used to make a warning for timely and safe evacuation of firefighters. This is motivated by a survey on firefighter deaths for the past two decades as presented in Section2. Usmani etal. [9] investigated the stability of Word Trade Center and the results showed that the tower might still collapse under the fire condition alone due to the degradation of lateral support of columns provided by the composite truss floor system. Two collapse mechanisms, namely a weak floor failure mechanism and a strong floor failure mechanism were proposed [10]. The collapse behaviour of braced steel frames exposed to fire was investigated [11,12], and it was found that using hat trusses on the top of the frame facilitated the load redistribution to columns, but failed to resist the lateral drift of columns leading to globally downward collapse. The effect of fire scenarios on the collapse mechanism of steel frames was also studied [13–15], and various downward and lateral collapse modes were found.

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More recently, there is growing interest to quantitatively evaluate the safety of structures exposed to fire [16–23]. Gernay and Franssen [16] applied duration of the heating phase as an indicator to predict the potential collapse of structures in the cooling phase. Sun and Burgess [18] presented an analytical prediction of ductility demand of steel connections in fire. Rush and Lane [20] quantified the damage stages of concrete columns based on the temperature distribution in the cross section. Molkens etal. [22] proposed a reliability-based method to assess the residual capacity of concrete slabs after exposure to fire. Kodur etal. [23] proposed an approach to quantify the fire risk in bridges, and to develop strategies for overcoming fire hazards.

The findings from the above-mentioned studies apply to multi-storey and tall buildings, but their application to long-span structures is questionable. Compared to multi-storey buildings, long-span structures have a lower level of redundancy and a higher level of fire loads that make them more prone to collapse in case of fire. Efforts have been taken to investigate the fire-induced behaviour of steel portal frames which is one of the most common structural form of long-span structures used in industrial, storage, retail and commercial buildings. In fact, 50% of constructional steel used in UK is in portal frame construction. Compared to structural members of multi-storey buildings which are required to have fire resistance to prevent structural collapse, steel portal frames are only required to prevent fire spread from the fire-exposed building to the adjacent buildings by specifying minimum spacing between them [24]. Fire resistance is normally specified for external walls alone, while the steel members are always permitted to be unprotected and are 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 (Fig.1a) rather than outward collapse (Fig.1b) since it helps to prevent fire spread to adjacent buildings, and to ensure life safety of firefighters who extinguish fire outside the frame. Efforts have been made to understand the collapse mechanism of steel portal frames in the event of fire. Souza Junior etal. [25] found that 2D modeling was unrealistic as it failed to account for the lateral instability of the structural members. Ali etal. [26] stated 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 column base fixity should be provided to ensure a favorable inward collapse mode [27–29]. Garcia etal. [30] 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. However, all these studies focus on numerical modeling, while experimental studies are lacking. The existing experiments are based on either small-scale (1:5) portal frames [31] or cold-formed frames [32] where limited information on the thermal and structural responses of frames is available. Therefore, it is necessary to conduct full-scale fire tests on hot-rolled steel portal frames (the most common form) to investigate their fire-induce progressive collapse behavior, and to provide validation references for numerical simulations, which is another objective of this study.

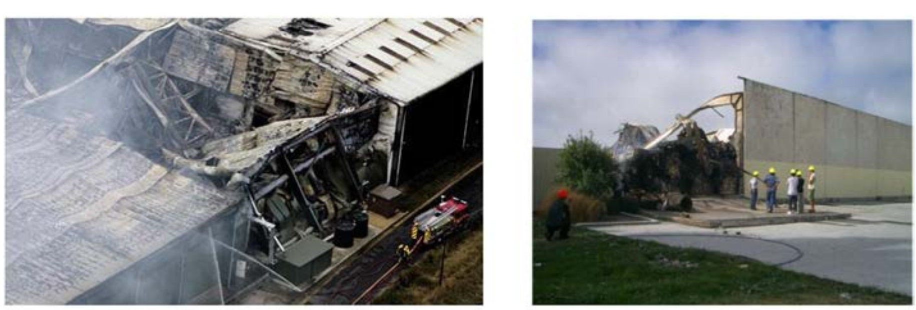
This paper quantitatively investigated the collapse behavior of steel portal frames exposed to fire. A survey on the historical firefighter death was first conducted to highlight the motivation of this study. Based on the key displacements of fire-exposed columns and beams, a four-stage collapse process was proposed including safe, ready-evacuate, must-evacuate and collapse stages. Numerical models were established and validated against fire tests on a full-scale steel portal frame. The key warning times for these four stages were numerically determined.

2. Survey on firefighter fatalities in the past twenty years

The life-saving of firefighters in case of fire-induced collapse of portal frames has received growing attention. This is probably attributed to the fact that most fires appear to develop after hours when there are no or few occupants still present in the building. Statistic data shows that an average of 20 firefighters sacrificed each year in China [33], and construction collapse is deemed to be one of the most primary reasons. NFPA [34] reported that 15 firefighters sacrificed at fire scenes among a total of 69 deaths in the United States in 2016. Among them 7 deaths are in the fire events involving steel portal frames such as dwellings and stores. The NFPA report also mentions that fires in non-residential structures such as manufacturing and storage properties are more hazardous to firefighters than residential structure fires. There were 13 fireground deaths per 100,000 non-residential structure fires from 2011 through 2015, compared to 2.9 deaths per 100,000 residential structure fires [34]. In UK, the annually average number of firefighter deaths is at least 4 for the last 30 years [35]. Table1 lists a survey on the deadest firefighter events over the past twenty years. Allfatalities are due to the collapse of the fire-exposed buildings. Themulti-storey buildings (No. 3, 4, 6)and portal frames (No. 5 and No. 8)exposed to fire are more prone to collapse, accounting for the largest shares of firefighter fatalities. To ensure life safety of firefighters, it is necessary to quantitatively determine

Table1
List of deadest firefighter disasters in the past two decades.

No.	Building	Place	Year	No. of storey	Fire duration before collapse	Deaths of firefighters
1	Word Trade Center	USA	2001	110	60 min	343
2	Store building	Iran	2017	17	Several hours	30
3	Hengyang building	China	2003	8	4 h	20
4	Sofa super store	USA	2007	6	40 min	9
5	Bowling house	Taiwan	2015	2	60 min	6
6	Storage/warehouse	USA	1999	6	–	6
7	Supermarket	China	2015	11	9 h	5
8	Warehouse	UK	2007	1	–	4



(a) (b)

Fig.1. Different collapse modes of steel portal frames: (a)inward collapse of Warwickshire warehouse at UK, 2007 (acceptable); (B)outward collapse of external walls (unacceptable) [29]