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Quantitative risk assessment methods of evacuation safety for collapse of large steel structure gymnasium caused by localized fire

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ABSTRACT

A risk assessment method was proposed to evaluate the evacuation safety in the collapse of a large steel-structured gymnasium caused by localized fire. The criterion for safety evacuation was that the available evacuation time was greater than the required evacuation time, which could be determined by a proposed steel-temperature rise model and a proposed evacuation model, respectively. In the proposed steel-temperature rise model, not only the effects of smoke thermal radiation and convection, but also the effects of flame thermal radiation on steel components were considered. In the evacuation model, the required evacuation time was determined mainly by the following factors: distance from the farthest point to the safety exit, personnel evacuation speed, width of evacuation exit, and density of personnel. All these results and experimental data obtained in this study provide valuable references to fire simulation, hazard assessment, and fire protection design.

1. Introduction

With increasing population, increasingly larger gymnasiums have been constructed in cities. These gymnasiums have characteristic wide areas, unique architecture, and steel structures. Although steel structures have good strength at normal atmospheric temperature and pressure, when a fire occurs, the generated heat may significantly affect the properties of steel structural components, e.g., the mechanical properties of steel. In particular, when the temperature of steel structural components exceeds 550 °C, the ordinary structural steel loses most of its strength, causing partial or even complete collapse of the building (Moore and Lennon, 1997). Therefore, evacuation safety in gymnasium fires has become an important research direction for fire engineers, and the fire protection design, hazard assessment, and evacuation safety are investigated in detail. In this study, all the above criteria were investigated, and the available and required times for safe evacuation were compared to estimate the reliability of fire protection design.

The previous studies on fire hazard assessment mainly focused on the temperature rise of the steel structure, instability mechanism, and fire simulation. Many researchers (such as Barthelemy, 1976; Dwaikat and Kodur, 2012; Gardner and Ng, 2006; Ghojel and Wong, 2005; Kay et al., 1996; Shi et al., 2011; Wald et al., 2006) developed temperature rise models and calculation methods for steel components exposed to fire. In the models, the heat received by steel components during fire was divided into two parts: thermal radiation and convection of smoke. In these studies, the classical thermal radiation and convective heat transfer models were used to calculate the heat exchange between steel components and smoke. To elucidate the instability mechanism and fire simulation of a steel structure, Rubert and Schaumann (1986) conducted fire resistance tests on a series of steel frames with different structures, and the destruction temperatures were obtained for various types of steel frames. Wang (2000) analyzed the global structural behavior of an eight-storey steel-framed building at Cardington. Franssen et al. (1995) conducted several numerical simulations on the behavior of a full-size, loaded, two-dimensional, and mainly unprotected steel frame in case of a real fire. Wong (2001) developed an elastic and plastic method for the numerical modeling of steel structures subjected to fire. The elastic method includes the effect of interaction between the thermal loading and static loading. The plastic method is based on the plastic hinge concept for the calculation of critical temperature of frames at collapse.

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In evacuation safety research, studies on occupant evacuation mainly focused on the specific simulation models for evacuation, including the occupants' behavior under emergency situations (Zhao et al., 2009), the effects of complex spatial characteristics on evacuation behavior, evacuation time, and the relationship between density and occupants' evacuation speed. Simulation softwares such as FDS + Evac (Korhonen and Hostikka, 2010), STEPS (Li et al., 2012), and Pathfinder (Thornton et al., 2009) were used in these studies. The three models represent different methods to model the evacuation process. Moreover, in some of the studies, the results were compared to analytical calculations reported in the Society of Fire Protection Engineers (SFPE) Handbook.

Although many studies have been conducted, the casualties caused by a collapsed steel structure in gymnasium fires has been rarely quantitatively assessed (Tavares and Marshall, 2012). The quantitative risk assessment methods for safety evacuation in steel collapse caused by localized fires still lack experimental data. The risk of structure collapse has been rarely discussed in fire hazard assessment, and the existing temperature rise model of steel components does not consider the thermal effects of flame radiation on steel components. When the distance from a fire source to steel components is small, the thermal effect of flame radiation on steel components is clearly significant. Moreover, the evacuation time is still estimated by complex numerical calculations, which is not advantageous to applications and fire protection design. This article reports a quantitative assessment method for the casualties caused by collapsed steel structures in fire. The modified steel-temperature rise model and simplified evacuation model are developed specifically to predict the available and required evacuation times. The research results may have certain significance for safety evacuation in case of a fire and a safe design of gymnasiums.

2. Criteria for safety evacuation

As shown in Fig. 1, when a gymnasium catches fire, the personnel in the building start to evacuate after fire alarm goes off. When the last person in the building is evacuated to the safety zone, the entire evacuation process is completed. The time taken for complete personnel evacuation is known as the required safety egress time (*RSET*). At the same time, the steel components are gradually heated by the thermal effect. When the temperature of the steel components reaches a critical value, the steel structure cannot anymore support the load of the entire building; therefore, the building is deformed and finally collapses. Moreover, the smoke hazards such as the thermal effect, toxicity, and visibility become more severe as the fire progresses. The duration from the occurrence of fire to the emergence of danger to evacuees is known as the available safe egress time (*ASET*). When *ASET* is more than *RSET*, all the personnel in the building can be evacuated to the safety area before the fire danger emerges. Conversely, when *ASET* is less than *RSET*, some personnel may not be evacuated to the safety area before the fire danger emerges, and casualties may not be avoided. Thus, the criterion for safety evacuation in case of a fire in all gymnasiums is:

$$RSET \leqslant ASET \tag{1}$$

As stated above, when *ASET* is more than *RSET*, all the personnel in the building can be safely evacuated to the outside of the building. Thus, there is no risk of casualties. The surplus safe egress time (*SAFE*) can be expressed as follows:

$$SAFE = RSET - ASET \tag{2}$$

However, when *ASET* is less than *RSET*, some personnel may not be safely evacuated to the outside of the building, and casualties may not be avoided.

3. *ASET*

The main factors affecting personnel safety evacuation in case of a fire are smoke hazards and structure collapse. Smoke hazards mainly include the smoke layer's height, temperature, toxicity, and visibility. We investigated the smoke hazards of fires in dozens of steel-structured gymnasiums and found that for a steel-structured gymnasium, the building's height is relatively high, and the building's volume is relatively large. In case of a fire, the hot gases in fire plume rise directly above the burning fuel and affect the ceiling. The ceiling surface turns the flow of hot gases that then move horizontally under the ceiling to other areas of the building remote from the fire position. The hot gases can be exhausted to the outside of the building using fans or openings. As a result, the gases descend slowly, and the personnel are barely affected by smoke hazards. Taking a gymnasium fire as an example, a fire dynamic simulation conducted using the FDS software was applied to predict the smoke hazards. The FDS software is a certified software set developed by the NIST for fire smoke migration analysis. This software uses the spatial filtering method for a simplified use of Navier–Stokes equations, and the simplified equations have some features of elliptic partial differential equations, thus simulating the flow processes of low-speed fire smoke migration and heat convection. The simulated fire in a circular gymnasium of 100 m diameter and 10 m height was 15 MW. Natural ventilation (the area of ventilation openings was 5% of the circular area) was applied to exhaust the hot smoke. The smoke layer's height, temperature, toxicity, and visibility are shown in Figs. 2–5. The smoke layer's height was 6 m, higher than the critical value for safety evacuation (2 m) as shown in Fig. 2. The smoke influence area

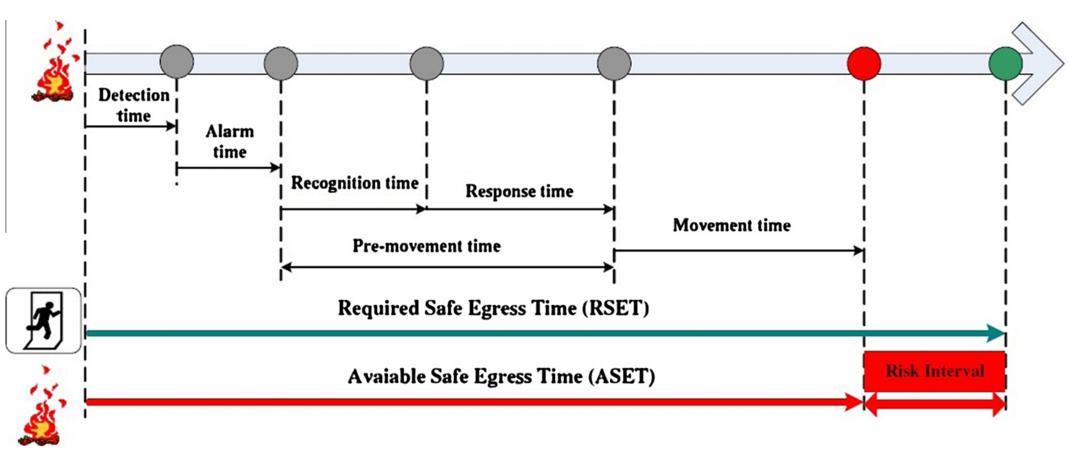

Fig. 1. *RSET* and *ASET*.