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Fire safety assessment of super tall buildings: A case study on Shanghai Tower

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ABSTRACT

Shanghai Tower is an existing super high-rise building composed of mega frame-core-outrigger lateral resisting systems. Its structural safety in fire has been given great attention. This paper presents an independent review of the performance of Shanghai Tower in case of fire. Two fire scenarios: standard fires and parametric fires have been considered. The fire resistance of key component, including the concrete core, mega columns, the composite floor, outrigger trusses and belt trusses were examined first. Their real fire resistance periods proved to be far beyond the design fire resistance. The components with weak fire resistance such as peripheral steel columns and web members of belt trusses were then removed to study the resistance of the residual structure against progressive collapse. The results show that Shanghai Tower has a minimum of 3 h fire resistance against fire-induced progressive collapse. The concrete components have smaller residual displacements compared to the steel components. It is recommended, for the design of other similar structures, that effective fire protection should be provided for the outrigger trusses to guarantee the connection between the core and mega columns.

1. Introduction

Steel–concrete composite structures combine the advantages of steel and concrete structures which makes them particularly suitable for application in high-rise and super tall buildings. However, steel structures are not inherently fire resistant because much of the strength of steel is lost when its temperature reaches 600 °C or above during a fire. Concrete may suffer spalling at high temperature which may cause premature exposure of reinforcement to fire, leading to severe damage of concrete structures. The likelihood of fire incidents is low. However, due to the high-rise nature of such buildings, the probability of them being subjected to longer duration fire is high, e.g., a terrorist attack. When such an incident occurs, despite fire protection, the likelihood of some members losing their local load-bearing capacity is very high due to a combination of feasible reasons such as more severe fire exposure than designed, loss of fire protection due to impact (the case of World Trade Centre) or lack of durability. Should a structure have low resistance against progressive collapse after

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local failure of some components, consequent catastrophic progressive collapse could take place, causing tremendous tragedy as a result of loss of lives and property and immeasurable societal impact.

The progressive collapse of structures 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]. The assessment of collapse performance of structures and measures for the mitigation of disproportionate collapse can be found in various design codes [1–3]. They propose three main design methods such as tie force method, alternate path method and specific local resistance method among which the alternate path method is the most popular one. Progressive collapse is a relatively rare event as it requires both an abnormal loading to initiate the local damage and a structure that lacks adequate continuity, ductility and redundancy to resist the spread of failure. Since the Broadgate Phase 8 fire in London and the subsequent Cardington fire tests, researchers have began to investigate and understand the behavior of whole steel-framed structures in fire. Especially since the collapse of the Word Trade Tower (WTC) under terrorist attack on September 11, 2001, there has been considerable interest in understanding the collapse of tall buildings in fire. Usmani et al. [4–6] carried out a 2D numerical modeling of the WTC tower subjected to fire alone, regardless of the damage caused by the terrorist attack. A possible progressive collapse mechanism for tall frames such as the WTC twin towers was proposed. It showed that the failure of columns played a key role in the collapse of the tower. Ali et al. [7] studied the collapse mode and lateral displacement of single-storey steel-framed buildings exposed to fire. The results showed that the lateral displacement of frames increased with the increase of the spatial extent of fire and roof weight which may affect the minimum clearance between frames and firewalls. Fang et al. [8] conducted a realistic modeling of a multi-storey car park under a vehicle fire scenario. Three failure modes such as single-span failure, double-span failure and shear failure were proposed. Simplified robustness assessment methods of car parks under localized fire were proposed [9,10]. Lange et al. [11] proposed two collapse mechanisms of tall buildings subjected to fire on multiple floors, namely, a weak floor failure mechanism and a strong floor failure mechanism. A simple design assessment methodology was proposed. Sun et al. [12] carried out static-dynamic analyses of progressive collapse of steel structures under fire conditions using Vulcan. The influences of load ratios, beam size and horizontal restraint on the collapse mechanisms were discussed. The same procedure was then used to study the collapse mechanisms of bracing steel frames under fire conditions [13]. Jiang et al. investigated the influence of load ratio, fire scenarios, bracing layout, beam/column stiffness on the resistance of steel framed structures in fire [14–18]. The results showed that the progressive collapse of structures was triggered by buckling of heated columns. The bracing system can effectively enhance the resistance of structures against collapses. Horizontally distributed multi-compartment fires the most dangerous cases.

This paper investigates the performance of the Shanghai Tower against fire-induced progressive collapse. The fire resistance of key components such as the core, mega columns, composite beams and truss systems has been examined in the context of standard and real fire scenarios. The alternative path method is used to study the progressive collapse resistance of residual frame after removing the peripheral steel columns and web members of belt trusses.

2. Structural layout of Shanghai Tower

The Shanghai Tower is a mega-tall skyscraper in Lujiazui, Pudong, Shanghai. The building stands approximately 632 m high (structural height is 580 m) and has 124 stories, with a total floor area of 380,000 m^2. It is composed of a core-outrigger-mega frame lateral system. The tower structure takes the form of nine functional zones including a business zone at the bottom levels, five office zones, two hotel/apartment zones, and sightseeing floors at the top as shown in Fig. 1. The floor plate

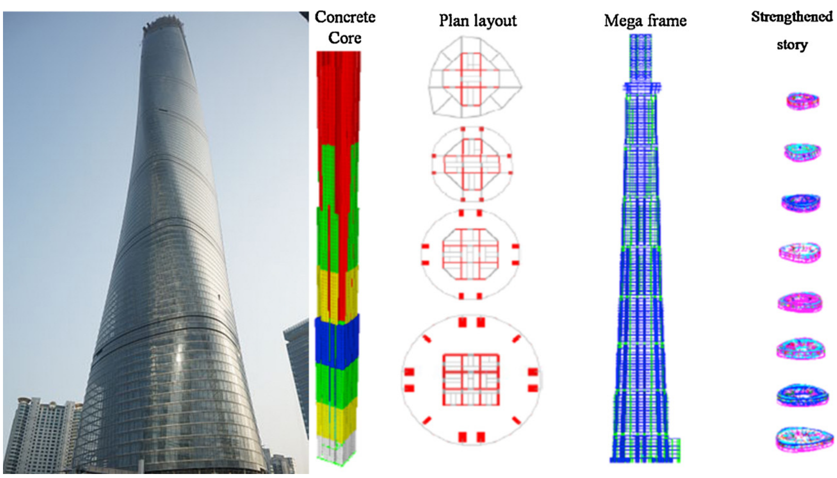

Fig. 1. Layout of Shanghai Tower.