Engineering Structures 172 (2018) 483–496

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Progressive collapse triggered by fire induced column loss: Detrimental effect of thermal forces

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ARTICLE INFO

Keywords:
Progressive collapse
Thermal loads
Localized fire
Multi-story buildings
Steel frame
Robustness

ABSTRACT

In progressive collapse analysis, event-independent column loss is commonly used as a design scenario. Yet this scenario does not account for the fire-induced thermal forces that develop in case of a fire. The thermal forces may cause detrimental load redistributions in the structure, notably during the cooling phase. However, as the response of entire structures during the full course of fires until burnout has received little attention, these effects are not well established. The objective of this paper is to analyze the mechanisms of load redistribution in a structural system comprising a column subjected to localized fire, with a focus on the effects of the cooling phase. Numerical simulations by nonlinear finite element method are used, after validation against experimental data. The observed mechanisms result in tension building up in the fire-exposed column and overloading the adjacent columns in compression. Consequently, the damaged vertical member redistributes a force that is larger than the force initially carried. This can lead to failure of vertical members not directly affected by the fire and trigger a progressive collapse. These mechanisms are parametrically studied on a simple system composed of a column and a linear spring. Major parameters influencing the residual tensile force in the fire-exposed column are the maximum reached temperature and the relative stiffness of the remainder of the structure. The analysis of a twenty-story steel frame building under localized fire attacking one ground level perimeter column confirms the development of these mechanisms in a real design. The results have important implications as they question the validity of an event-independent design scenario for capturing the influence of column failure due to fire loading.

1. Introduction

Events such as the Ronan Point Tower partial collapse in 1968 and the World Trade Center collapse in 2001 have highlighted the importance of understanding and preventing the mechanisms of progressive collapse of tall buildings. The key idea is that, in case of an accidental event causing local failure of a structural element, this failure should not spread from element to element eventually resulting in a collapse disproportionate to the original cause [1]. One design approach that can be used to satisfy this requirement is called the alternative load path method [2,3]. This approach to progressive collapse resistance allows local failure to occur when subjected to an extreme load, but ensures that alternative load paths are activated toward a new static equilibrium upon this local failure, therefore preventing the spread of damage and the occurrence of a global collapse. In other words, the structure has enough redundancy to absorb the effect of the loss of one or several structural bearing elements.

The alternative load path method is generally regarded as a threat-independent method. The specific event triggering the local failure is not explicitly considered; instead, one or several key structural elements are removed from the structure and the subsequent ability of the system to bridge over the failed elements and withstand the loads is evaluated [4]. The main advantages of this approach are that, first, it relieves the designer from the necessity to describe the accidental event and the way it will affect the structure and, second, it ensures that, normally, the structure has the ability to survive any accidental event, be it of a foreseeable nature or not. This is why it has been extensively used to investigate progressive collapse of tall buildings due to column loss [5–8].

The loss of a column in a tall building can result from a variety of exceptional events. For instance, the NIST [9] has categorized the potential abnormal load hazards that can trigger progressive collapse as: aircraft impact, design/construction error, fire, gas explosions, accidental overload, hazardous materials, vehicular collision, bomb explosions, etc. Threat-independent sudden column loss has been proven an appropriate design scenario to capture the effect of column failure due

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https://doi.org/10.1016/j.engstruct.2018.06.060
Received 21 November 2017; Received in revised form 14 June 2018; Accepted 16 June 2018

to impact or blast [5]. Researchers have worked toward a simplified method to capture the dynamic effects of a column failure occurring over a relatively short time [10–12]. The United Facilities Criteria provisions by the Department of Defense [3] specify that, for nonlinear static analysis of notional member removal, the structural response must be amplified by a dynamic increase factor to account for dynamic effects. This dynamic increase factor for nonlinear static analysis depends on the structure type and plastic rotation limit with a maximum value of 2. However, fire loading is a specific scenario which may not be adequately captured by this approach. The main issue with fire is related to thermal forces, not to dynamic effects. Fire generates thermal forces in a structure, which may lead to a redistribution of loads that differs from the one evaluated from an alternative load path method that considers the removal of the affected column. This is particularly the case when a localized fire affects only one part of the structure, and even more so during the cooling sequence that occurs in a real fire. The mechanisms at stake are studied in details in this paper, notably to assess whether the case of fire-induced column failure may or may not be properly modeled by notional removal of the column as specified in the alternative load path method [9].

It is noteworthy that, in structural fire engineering, the prevailing approach has long been prescriptive, considering isolated member behavior rather than system behavior, and continuously heating standard fire exposure rather than real fires with their heating phase followed by a cooling phase. As a result, the understanding of the behavior of entire structures under real fires remains limited. Since the Cardington fire tests, it has been established that system behavior differs dramatically from isolated member behavior, and that the effects of thermal expansion dominate the response of the structure [13–15]. The NIST final report on the collapse of WTC 7 [16] mentions that the factors contributing to the building failure include the thermal expansion effects and a structural system that was not designed to prevent fire-induced progressive collapse. The NIST report highlighted the current knowledge gaps in structural fire response and formulated a number of recommendations, including the “development of methods for prevention of progressive collapse and for reliable prediction of the potential for complex failures in structural systems subjected to multiple hazards” and the “enhancement of the fire resistance of structures by requiring a performance objective that uncontrolled building fires result in burnout without partial or global (total) collapse” [16]. Consequently, recent research has looked at the behavior of structural assemblies under more sophisticated fire scenarios, analyzing for instance the effects of travelling fires on buildings [17,18], of fires with cooling phases on connections [19–21], or of tanker truck fires on bridges [22,23]. Due to the interaction between members under restrained thermal strains, significant load redistributions are known to occur. The development of residual tension axial force in members after fire exposure has been described by several authors, for instance in beams of multi-story frame structures under single bay fires [24], or in connections [21]. Yet, in previous investigations on the issue of fire induced progressive collapse, the focus was mainly on ultimate failure temperature and load redistribution mechanisms during the heating phase [25–28]. Hence, the mechanisms that develop during the cooling phase in an entire structure subject to a localized fire remain still to be fully understood. Meanwhile, numerical studies of isolated members under fires with heating and cooling phases have shown that failure may occur during or even after the cooling phase [29,30]. The hypothesis tested in this research is to assess whether the load redistributions in a structure during the cooling phase of a fire may threaten stability and lead to progressive collapse. Filling this gap is especially essential as delayed structural collapses, which have been observed in real fire events, pose a specific threat to firefighters [31].

In this context, this paper investigates the behavior of a structural system comprising a column subjected to localized fire. The objective is to analyze the mechanisms of load redistributions that develop in a system during the full course of a fire affecting a part of this system, including the eventuality of progressive collapse provoked by load redistributions in the cooling phase. The mechanisms are analyzed using numerical simulations, supported by experimental evidence. The results have significant implications both at the modeling level and at the design level, which are discussed in the paper.

Section 2 discusses the mechanics of a structure response under a localized fire scenario affecting one column of the system. Section 3 presents a parametric analysis of a system composed of a column and a linear elastic spring representing the surrounding structure. Section 4 presents the simulation of an experimental test previously published in the literature which allows validating the modeling approach to capture a structure response under localized fire. Finally, Section 5 studies numerically the behavior of a multi-story moment resisting frame structure subjected to localized fire, while Section 6 presents the conclusions. The numerical analyses are performed with the nonlinear finite element software SAFIR® [32] developed specifically for modeling the behavior of structures in fire.

2. Force redistributions in a structure with a column subjected to localized fire

2.1. Scope of the study

This paper analyzes the behavior of statically indeterminate structures in which one column is subjected to fire. The discussions are illustrated on multi-story steel moment resisting frames (MRF) structures, although the principles are valid generally.

Real fires are considered (as opposed to a standard fire), i.e. fires that comprise a heating phase followed by a cooling down phase, at the end of which the temperatures come back to ambient. A standard fire, in contrast, is primarily defined for furnace testing of building elements, and comprises only a heating phase. Yet as, in a real event, the amount of fuel (and oxygen) present in a compartment is necessarily limited, it is natural to assume that the temperatures eventually come to a peak and then decrease, and it is therefore essential to understand the behavior of fire-exposed structures during the cooling phase as well.

In this paper, the studied scenario assumes that only one column is attacked by the fire. This scenario can result from a localized fire occurring in the immediate vicinity of the column [33,34], or from the specific compartmentation of the building. Localized fires are of particular interest in the analysis of fire-induced forces in structures because of the generated differential thermal elongations between members. As the study focuses on the influence of fire-induced failure of a vertical member on progressive collapse, the heating of the beams adjacent to the column is neglected. It is expected that heating of these beams would lead to additional horizontal forces in the structure (due to restrained thermal elongation) but also to a reduction in the degree of axial restraint for the heated column (due to reduction in stiffness of the heated beams). This latter effect would decrease the amount of (vertical) load redistribution during heating and cooling of the column. Therefore from the progressive collapse analysis perspective, the situation where only the column is heated may be the most dangerous because it considers the highest possible restraint stiffness for the column in the considered building.

2.2. Description of the force redistribution mechanisms during a fire

A schematic discussion is used to illustrate the mechanisms of force redistribution. We consider a four-bay, two-story Moment Resisting Frame (MRF) with its central column exposed to fire on the ground floor. The temperature in the member (thermal response) influences the structural behavior (mechanical response). The following hypotheses are adopted to simplify the discussion: there is no buckling; the thermal strains and yield strengths are reversible with temperature; the temperature is uniform in the section. However, these hypotheses are not required for the mechanisms to develop.