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Fire induced progressive collapse of steel building structures: A review of the mechanisms

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ABSTRACT

In this paper, a literature review of the mechanisms involved in fire induced progressive collapse of steel building structures are presented. Researchers have been investigating progressive collapse of building structures for some time. With the changing political climate around the world highlighted by the events of September 11th, 2001, researchers have begun to further study the mechanisms of fire induced structural collapse of steel building structures. Furthermore, with the use of performance based building codes throughout the world, engineers can now investigate the use of alternative structural fire protection strategies. This summary provides a brief overview of conventional fire protection strategies for steel buildings and then describes current work done by researchers in the area of the mechanisms involved in fire induced progressive collapse of steel building structures. A summary of two possible design methodologies for resistance of fire-induced progressive collapse are presented.

1. Introduction

High-rise building structures are often constructed on a steel skeleton system. While rare, high rise steel framed buildings can be significantly adversely affected by a large fire possibly leading to progressive collapse. The most notable recent case would be the collapse of the World Trade Center 7 office building on September 11, 2001 due to a large uncontrolled fire [1,2]. Progressive collapse of building structures has been defined differently by many authors but the fundamental concept remains the same. Progressive collapse results when an initially localized failure of a structural element propagates to other elements, leading to a broader structural failure [3–9]. Progressive collapse can be initiated by many abnormal loading scenarios such as; blast loads, design errors, construction errors, substandard materials, soil failure, impact loading, seismic forces and extreme environmental loads [6–9]. A great deal of work has been done on progressive collapse of building structures due to abnormal loading over the years [6–8,10–15], and others. Most published articles have focused on collapse resulting from abnormal loading events other than fire. Severe fires can lead to abnormal loading which could be a factor in initiating progressive collapse of a building [1,2,5–9,16]. In the past, structural engineers have relied on thermal barriers to protect a steel structure from temperature increase during a fire [6]. With the emergence of performance based engineering design, it becomes necessary to consider new and innovative passive structural fire protection strategies so that in the rare occurrence of an abnormal loading event of a severe fire, progressive collapse can be avoided.

2. Background

This section presents the necessary background information essential to understanding the vulnerability that building structures face when exposed to fire. The traditional methodology of avoiding fire induced failure of structural members has been by insulating the member from the heat source. Common methods for passive thermal structural fire protection are briefly explained. The use of the passive thermal fire protection is mainly determined by fire resistance tests and their associated ratings. Issues relating to the reliance on fire resistance tests to protect against progressive collapse are discussed at the end of this section.

2.1. Passive thermal structural fire protection

Historically, building codes have addressed the need to protect main structural steel load bearing elements from fire by providing

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a prescriptive solution to restrict the heat flow to structural elements. This can be achieved by applying a covering material to the steel element to protect the steel from exposure to elevated temperature for a specified time duration [17]. The protection is typically prescribed in the form of a gypsum board wrap, a spray applied fiber cementitious coating or an intumescent paint. Gypsum board protection protects the underlying steel by a series of endothermic reactions that occur in the gypsum board as it is heated [18–22]. Many proprietary versions of spray applied fire proofing exist with different component mixtures such as: Portland cement, vermiculite, gypsum and other minerals [23]. However the main premise is the same in that the material bonds to the steel surface and acts as a thermal barrier to the transfer of heat to the substrate [24,25]. Intumescent coatings are typically composed of inorganic compounds within a polymer matrix [26,27]. These compounds react and swell at high temperatures to produce a char layer on the surface to which they are applied and thereby retarding heat transfer to the underlying layer [23,27]. The time assigned to the passive fire protection before the structural member begins to fail is known as the fire resistance rating.

2.2. Fire resistance ratings

The goal of applying a prescribed fire resistance time to structural members is to ensure that occupants have enough time to evacuate the building and to ensure that fire fighting personnel have enough time to safely extinguish the fire and prevent any further fire spread or the initiation of a collapse. Fire resistance ratings are determined based on an established set of guidelines in a standardized test method. These test methods prescribe a pre-determined fire exposure to a structural member or assembly in a specially designed fire testing furnace. The fire exposure is described as a time–temperature curve [28–30]. Once the test begins, the member (or assembly) being tested is exposed to the prescribed time–temperature curve until any one of a set of prescribed failure criteria (as specified in the standard) is violated. This violation ends the test and the time at which the test is ended is recorded as the fire resistance time or fire resistance rating of the member or assembly. The benefit of having a standardized test method for building components is that once tested, the results can be standardized and used in prescriptive codes to assign accepted fire resistance times to structural components and assemblies which make up a building structure. The downside to the standard fire resistance test method for determining the fire performance of an entire building's structural system is twofold. Firstly, the fire that the specimen is being exposed to may not be representative of the actual fire that may take place in situ when the structural member is installed in a building. The explicitly prescribed time–temperature curve eliminates an engineer's ability to apply a more realistic design fire to the structural member to determine the actual temperatures the member may experience in service based on the anticipated fuel load. Secondly, each standard fire resistance test considers only one structural member at a time. In reality, the complexities and redundancies within a building structure provide opportunities for alternate load paths, load sharing, load redistribution, and member stiffening due to the interaction and connection of all the structural members.

2.3. Fire resistance tests and progressive collapse

It is accepted that the behavior of a building structure during a fire is significantly different than the behavior of a single element exposed to a standard temperature curve in the standard prescriptive fire test methodology currently used to assess a structure's resistance to fire attack [1,2,17,31–33]. Given the destructive nature of a fire resistance test and the prohibitive costs involved with such tests, mathematical modeling becomes a feasible alternative to fire testing. With the emergence of performance based building codes, engineers now have the ability to investigate and apply alternative passive fire protection strategies to building structures to ensure occupant and public safety and economy of building construction. Furthermore, the structure's inherent ability to develop alternative load carrying mechanisms can be utilized.

3. Building structure behavior at elevated temperatures

The literature presented in this section is a collection of experimental and numerical data which describes the mechanisms affecting building structures exposed to fire. For brevity, the details of the numerical models have not been included. The reader is encouraged to refer to the appropriate referenced publication for full details about a specific research program and the model employed. The results presented in this section are for unprotected structures (i.e. the passive thermal structural fire protection has failed, has been damaged or does not exist). The robustness of an unprotected steel structure in resisting fire induced progressive collapse is dependent on three characteristics: the thermal effects/restraint conditions, structural stiffness and lateral bracing.

3.1. Thermal effects and restraint

Heating of structural members induces thermal strains (ε_T) within the member,

$$\varepsilon_T = \alpha\, \Delta T,$$

where α represents the material's coefficient of thermal expansion and ΔT represents the change in temperature. Since strain is the ratio of change in length (ΔL) divided by the original length (L), the thermal strain is manifested as elongation due to thermal expansion and curvature depending on the temperature exposure profile. The change in length is therefore,

$$\Delta L = \alpha \Delta T\, L$$

Structural elements without adequate translational restraint will manifest their thermal strain with excessive deflections [34]. Structural members with adequate end rotational restraint experiencing a temperature gradient may develop negative bending moment throughout the length of the member, termed thermal bowing (see Fig. 3.1) [34]. Building structures are connected such that members can be considered to be rotationally and translationally restrained. Therefore, thermal strain is a very important factor when assessing a structure's response to a fire [34].

As a restrained beam experiences an indefinite temperature increase, Usmani et al. [34] showed that it can exhibit a yielding failure, a buckling failure, or a combination of the two depending on the slenderness of the member. Members with a high slenderness ratio tend to experience a buckling type of failure with thermal elongation being manifested in outward deflection, while members with a low slenderness ratio tend to continue to develop internal stresses until the yield stress is reached then the beam continues to yield without any increase in stress [34]. The reduction in mechanical properties with increasing temperature, namely the stiffness, acts to reduce the magnitude of the axial compressive force which develops in a restrained beam which leads to rapid post yielding rise in deflection [34]. Thermal bowing can also be caused in real building structures by a fire in a compartment which heats one side of an element (underside of a beam or floor) while the top surface may not be directly exposed to fire and remain relatively cool. These differences in thermal expansion rates can produce thermal gradients which can induce bending in structural