THE BEHAVIOR OF STEEL STRUCTURE EXPOSED TO FIRE: A REVIEW

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ABSTRACT

This paper present an overview of various research works carried out by several researchers on the effects of fire on steel structure. The analysis consist of experimental, analytical and numerical approach. Many steel structure such as beam, column, steel frame, steel girder and bracing frame were analysis using finite element software like Ansys, Abaqus, Safir, Tfield and Vulcan. The behavior of steel structure when exposed to fire depends on many factor including the material properties of the steel, end restraint, the type of fire exposure and the presence of insulation. Under fire conditions, the temperatures in the steel will increase. At higher temperatures, both the yield strength and tensile strength of steel decrease, as does the modulus of elasticity.

Keywords: Steel structure; fire; numerical analysis

A. INTRODUCTION

Steel is widely used due to number of advantages steel offers over other construction materials. These advantages include high strength, ductility, ease of fabrication, and speed of construction. A major drawback of steel construction is that steel structural members possess low fire resistance due high thermal conductivity and low specific heat of steel, as well as faster degradation of strength with temperature . As a result, steel structural members can lose load carrying capacity (strength and stiffness) at a rapid pace under fire conditions.(E. M. Aziz, Kodur, Glassman, & Moreyra Garlock, 2015)(V. Kodur, Dwaikat, & Fike, 2010)

Wang, 2002 explained that the structural effects of a fire on the behaviour of a steel structure are caused by changes in the mechanical properties of steel and concrete where both materials become weaker and more flexible at high temperatures and temperature induced strains.. These changes lead to various phenomena observed in different fire tests. Therefore, to understand the complex behaviour of a steel structure under fire conditions, it is necessary to avail the basic information of material properties at elevated temperatures.

At higher temperatures, both the yield strength and tensile strength of steel decrease, as does the modulus of elasticity. In general, steel retains strength and stiffness approximately equal to 50 percent of its strength and stiffness at ambient conditions at a temperature of 1,100 °F (593 °C). This is comparable to the strength and stiffness reductions for ordinary concrete. At 1,300 °F (704 °C), steel retains about 20 percent strength and stiffness. A near-total deple- tion of strength occurs at approximately 2,200 °F (1,204 °C). (Gewain, Iwankiw, & Farid, 2003)

Usmani, Rotter, Lamont, Sanad, & Gillie, 2001 recognised that contrary to popular belief, composite steel framed structures possess a much larger inherent fire resistance than that apparent from testing single steel members in fire furnaces. It is also accepted that the current prescriptive approaches of designing such structures are overly conservative and not based on rational principles. It is therefore possible to construct these strcutures much more economically, without any loss of fire resistance, by removing or drastically reducing the fire protection of steel members. However, to fully exploit the considerable reserves of strength, it is imperitive that the mechanics of whole steel frame structure behaviour in fire is understood well

B. PRESENT STUDIES AND THEORIES

Jeffers & Sotelino, 2009 introduces a new type of heat transfer finite element that can be used to model the 3D thermal response in structural frames subjected to fire. Because it uses both finite element and finite difference approximations of the governing heat transfer equation, the fiber heat transfer element balances solution accu- racy and computational efficiency in obtaining the transient thermal response of frames subjected to realistic. Results indicate that the element can accurately model temperature distributions in a member with a variety of thermal loads. The solution quickly converges to the exact solution with the use of more fibers over the cross-section and more elements along the length.With as few as four elements along the length, the fiber heat transfer element can provide an accurate prediction of the thermal response in members subjected to the most extreme case of nonuniform heating.

(Crosti, 2009) presented the performance of steel structures under fire loading. For this purpose, the application of nonlinear analysis to the thermo--mechanic behavior of materials and to the structures as a whole, together with the appropriate firemodeling in appropriate scenarios, come together to demonstrate and verify the performance of the structure in terms of resistance to fire during the design phase. All of this focuses on the importance of understanding the behavior of single elements while noting that the fundamental consideration in the structural collapse of a complex structure is the global behavior of the structure itself.

(Hong, Varma, Agarwal, & Prasad, 2008) evaluated the fundamental behavior and stability (collapse potential) of typical steel building structures. The complete 3D structure was modeled using Abaqus. The analytical results indicate that the corner compartment fire will lead to the inelastic buckling failure of the interior gravity column. However, the loads carried by the interior column can be redistributed to the remaining columns through catenary action in the floor system, and the structure remains stable in spite of the interior column failure. When the complete story is exposed to fire, then failure initiates by inelastic buckling of an interior gravity column. This failure propagates further by inelastic buckling of additional interior gravity columns. The overall structural load capacity reduces by about 15% with the failure of each gravity column, and complete story collapse becomes imminent if the loads are maintained constant at the level corresponding to the failure of the first column.

(Liu & Jia, 2010) presented a finite element analysis for the calculation of the temperature history of H-section steel columns protected with box-casing insulation under fire conditions. The model proposed in this study is capable of predicting the temperature distribution histories of cross-sections of H-section steel columns with box-casing insulation under fires with fairly good accuracy. The radiative heat transfer in the cavity is of significant influence on the temperature development and as a consequence on the load bearing capacity of the column. The temperature distribution histories generated by TFIELD can be used as temperature input for predicting the structural response of structural members with cavities in fires.

(Cedeno & Gore, 2011) presented analytical approach to model and predict the standard fire behavior of ten composite beam specimens using Abaqus software. It consisted of two sequentially coupled numerical analysis steps. The second step conducted nonlinear stress analysis of the composite beam for the applied mechanical loading and the thermal responses from the first step. The analytical results included the complete structural behavior of the composite beam including the displacements and 3D stresses and strains. The validated analytical approach and finite element models are recommended for modeling and predicting the standard fire behavior of composite beam specimens. They are also recommended for modeling composite beam specimens while conducting: (a) numerical parametric studies, or (b) complete floor system studies under realistic fire loading

(Dwaikat & Kodur, 2011) presented a simplified approach for predicting the fire-induced forces and deflections of restrained steel beams. The proposed approach is verified by comparing the predictions to results from rigorous finite-element analysis carried out using ANSYS. The comparison covers a wide range of beams with varying factors, such as end restraint, connection configuration, load level, slenderness, and thermal gradient.

(E. Aziz & Kodur, 2013; Venkatesh Kodur, Aziz, & Dwaikat, 2013) evaluated the fire response of a steel bridge girder using the FEM computer program Ansys. Thus composite action is to be accounted for properly in the evaluation of the fire resistance of bridge girders. The type of fire exposure and the presence of insulation have a significant influence on the resulting fire resistance of bridge girders. A bridge girder when exposed to external design fire with maximum fire temperature of 680 °C has a residual capacity of about 84% as compared to 70% when exposed to moderate design fire with a maximum fire temperature reaching 800 °C. A steel bridge girder experiences failure under fire conditions when the maximum fire temperature is around 1100 °C, as in the case of typical hydrocarbon fires.

(Lin, Huang, & Fan, 2015) et al presented a comprehensive study was conducted on ageneric three dimensional 45m x45m composite building, with realistic loading conditions and structural layout, under different fire conditions. The end-plate connections were used to connect primary beams to columns. The partial end-plate connections were adopted to connect secondary beams to col- umns, and primary beams to secondary beams, respectively. At high temperatures, the strength and stiffness of unprotected steel beams reduce rapidly. The loads above the fire compart- ment are largely carried by the concrete floor slabs. Hence, the impact of steel reinforcement on the behaviour of floor slabs becomes more significant. Once the connections of protected beams fail, the vertical support for the slab panel would reduce. Therefore, in real performance-based fire resistance design of steel framed composite buildings, the influence of connections needs to be considered carefully.

(Sun, Huang, & Burgess, 2012) investigate the influence of bracing systems on the collapse mechanisms of steel frame in fire. The progressive collapse mechanisms of steel-framed structures with different bracing systems using a static–dynamic procedure was conducted using the computer programme Vulcan. it can be seen that a bracing system can enhance the capacity of a steel frame to resist progressive collapse under fire conditions. The bracing system increases the redundancy of the structure, and provides alternative load-sharing paths after a local instability occurs.

(Payá-Zaforteza & Garlock, 2012) presented numerical investigation of the fire response of a simply supported steelhighway overpass bridge with the finite element (FE) software Abaqus. Results show that restraint to deck expansion coming from an adjacent span or abutment should be considered in the numerical model. In addition, times to collapse are very small when the bridge girders are built with carbon steel (between 8.5 and 18 min) but they can almost double if stainless steel is used for the girders. Therefore, stainless steel is a material to consider for steel girder bridges in a high fire risk situation, especially if the bridge is located in a corrosive environment and its aesthetics deserves special attention.

(Lausova, Skotnicova, & Michalcova, 2015) presented a numerical study of the heat field in the hollow cross sections exposed to fire loading from three side. The finite element method in the commercial software Ansys is used for calculations. Investigated show big differences between temperature of the upper protected flange and the fire exposed sides at the same boundary conditions depending on the size as well as on the thickness of the profile.

(E. M. Aziz, Kodur, Glassman, & Moreyra Garlock, 2015) presented experimental and numerical studies on the fire performance of typical steel girders used in bridges. The steel girders were designed according to AASHTO specifications. The numerical model was developed using ANSYS software. Overall, predicted deflections, time to failure, and failure modes from ANSYS compare well with the reported data in fire tests. Typical steel bridge girders can experience failure in about 30 to 40 min under standard fire exposure. The failure time and mode of failure is highly influenced by web slenderness and spacing of stiffeners. The proposed finite element model, developed in Ansys, is capable of tracing the response of steel bridge girders under fire conditions, in the entire range of loading, from preloading stage till failure.

(Zografopoulou & Mistakidis, 2017) presented an integrated approach to the problem of the fire behaviour of steel members with damaged cementitious SFRM coatings is attempted, by modelling numerically both the mechanical damage of the coating applied on a steel member and the impact that this damage has on the structural behaviour of the steel member under ISO-834 thermal loading. On the compression side of the plate, the SFRM coating failed due to separation at the interface between the two materials with minimal damage to the coating itself. Due to the low mechanical strength of the cementitious SFRM coating and the low bonding interfacial strengths, mechanical stressing, e.g. due to an earthquake, can cause considerable damage to the fire protection of a steel structural member, which consequently will cause faster temperature rise, faster and greater deflections and will reduce the time to form plastic deformations from 27% up to 70%, depending on the SFRM damage degree, compared to an undamaged coating. Thus, if such damage is not considered, the fire resistance of a steel member will be overestimated, which can lead to the failure of the member a lot sooner during a fire, with pending risks for the safety of the structure and the rescue teams.

(Petrina, 2016a, 2016b) describes numerical simulations that were conducted on a substructure of the steel building, namely a beam-to-column endplate connection. Simulations were carried out by using Vulcan. From the resulted data it yields that for such a type of connection which is very robust under the normal loading, the fire resistance is low under 30 minutes which is not satisfying for a steel structure made up of elements of the studied type. The need for fire protection for the connection is obvious

(Łukomski, Turkowski, Roszkowski, & Papis, 2017) presented results of fire resistance test of unprotected steel beams, compared with simple and advanced calculation models given in EN 1993-1-2 The average measured steel temperature did not differ by more than 2%. All three methods presented in the paper lead to similar results in terms of beam failure time. Nonetheless, assessment methods given in Eurocode 3 are very efficient at predicting the fire resistance and they are on the safe side. In practice, such beams would have been connected to a reinforced concrete slab, what would cause bigger temperature distribution within the cross-section of the beam. Such elements would also have different mechanical properties.

A numerical study on the temperature distribution of a partially heated steel member using a simple finite difference scheme with parametrically coded generic elements(Wong, 2017). It has been found that themethod gives more accurate results for temperature distribution estimation of steel members than themethod provided by Eurocode3. The results are useful in providing infor- mation on insulation requirements for steel members subject to partial heating in situations such as members passing through multiple fire compartments or subject to localised fires. The concept can be applied to other applications such as partially protected steel connections and partially damaged fire protections.
(Lausova, Kolos, Michalcova, & Skotnicova, 2017) presented a numerical comparative study which is concerned with the behavior of a steel hollow section portal frame exposed to elevated temperatures while considering the effect of both thermal and structural responses incorporating material and geometric nonlinearities. A comparative study between the results of the proposed model from SAFIR software and the results from the software SCIA Engineer. In this study, models in 2D and 3D show similar development of the examined variables, the failure temperature is 600 °C which corresponds with the time t = 19 minutes according to the standard fire curve. The results show different formation of plastic hinges depending on whether the hollow section frame rafter is heated from three sides or from all sides. Thermal analysis is very useful for getting the exact temperature distribution along the height of the section especially at the beginning of the fire when the effect of non-uniform temperature could be more important than in the later stages of the fire.

(Rocha, Albuquerque, Rodrigues, & Laim, 2017) presented the results of numerical simulations performed on some of the columns of the BRE's Cardington Steel Framed Building calibrated with results from experimental tests carried out on this building structure by the third author of the paper. They were compared gas and steel temperatures, strains, displacements and rotations of the columns ends. The results of the experimental tests were used to calibrate a numerical model of the entire building structure. In these numerical simulations, performed with the finite element program Abaqus, was considered the fire at different locations in the building. They were calculated strains and displacements at critical points of the structure. This work allowed to study the influence of the thermal restraining on the behavior of the columns when subjected to a localized fire. It could be observed a redistribution of forces along the structure in such a way that the collapse of a column did not affect the stability of the whole building. However the collapse of more than one important column could lead to the collapse of the entire structure.

C. CONCLUSION

Under fire conditions, the temperatures in the steel will increase, resulting in both thermal expansion of the member and transient deterioration of its mechanical properties. The magnitude of these effects depends upon several factors, including the type of steel and whether it was protected or not. The duration and nature of the fire exposure will affect the temperature distribution in the steel.

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