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Structural Analysis of Multi-Storey Steel Frames Exposed to Travelling Fire & Traditional Design Fires

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Abstract* – *For understanding of building behaviour in fire, most of the time standard and parametric temperature time fire curves are adopted. However, the disadvantages of design fires on the standard parametric curves are based on small scale tests and also idealize the thermal environment as uniform. Thus, they have important disadvantage on their applicability to large enclosures. But in large open-plan compartments, travelling fires have been observed. To analyse such fires, a design tool called Travelling Fires Methodology (TFM) has been developed & used for design. In this paper, the review of study on analysis of multi-storey steel frame in traditional fires & travelling fires studied. The comparison between traditional method through parametric curves & travelling fires studied.

Keywords: Travelling Fires, Finite Element Method, Travelling Fire Methodology

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I. INTRODUCTION

Innovative architectural designs of new high rise structures pose previously unthought-of challenges to architects and engineers. For the design of buildings against fire the European building design code (Eurocode EN1991-1-2) considers a standard fire and parametric time-temperature curves. Standard fires are based on tests in small enclosures and thus have limitations on their applicability to large enclosures (>100 m^2). In addition, the standard fire curves and parametric time-temperature curves are based on the unrealistic assumption of uniform fire conditions in a compartment. While this assumption may be suitable for small enclosures, fires in large open-plan compartments have been observed to travel resulting in highly non-uniform temperature distributions within the enclosure. Examples of such accidental events include the World Trade Centre Buildings 1, 2 & 7 (2001) and Windsor Tower fire in Madrid (2006) and One Meridian Plaza fire in Philadelphia (1991). In all of these accidents, the fires lasted for up to 7 or even 20 hours. Long fire durations like these are not considered in the current design codes.

Non-uniform temperature distributions on structures have been shown to have a significant impact on the failure mechanism and time to failure. In studies on steel, reinforced concrete and post-tensioned concrete frames where a travelling fire was considered, large distortions and a cyclic behaviour of stresses and deflection patterns have been observed. However, to represent a travelling fire the studies, parametric curves were used and shifted from one bay to another after an arbitrary time. As noted by Stern-Gottfried and Rein such representation ignores the basics of fire spread, preheating of structural elements by hot smoke and spatially varying temperatures within the compartment.

Recently, to account for travelling fires a design tool called Travelling Fires Methodology (TFM), has been developed. It considers a family of fires which depend on the fire spread rates and thus the percentage of the total floor area engulfed in flames. In TFM fire is divided into two regions near-field and far-field. Near-field represents the area where flames are directly impinging on the ceiling and far-field represents radially decreasing smoke temperatures further away from the fire. Therefore, TFM unlike parametric fires considers more realistic non-uniform temperature distributions in the compartment.

II. LITERATURE REVIEW

Brief information of the research work done by researchers about topic which will help us to decide about the subject, is as given below. A number of researchers have made important contributions to the development of our understanding of the experimental studies on travelling fires.

Egle Rackauskaite, Panagiotis Kotsovinos, Ann Jeffers, Guillermo Rein (July2017)[1] The aim of the study was to compare computationally the structural response of multi-storey steel frame subjected to both uniform design fires and travelling fires. A two-dimensional 10-storey 5-bay steel frame designed according to ASCE 7-02 was modelled in the general finite element program LS-DYNA. Different fire exposures are investigated. They included travelling fires, Eurocode parametric curves, ISO-834 standard fire and the constant compartment temperature curve from the SFPE standard. These fires were applied to different floors, one at a time, to explore the influence on the structural response, resulted in 80 different scenarios. The development of deflections, axial forces and bending moment was analysed. Uniform fires were found to result in approx.15-55 KN (3-13%) higher compressive axial forces in beams compared to small travelling fires. However, the results show irregular oscillations in member utilization levels in the range of 2-38% for the smallest travelling fire sizes, which were not observed for any of the uniform fires and depend mainly on the fire duration, but the locations in the frame and times when these peak displacements occur were different. The results indicated that travelling fires and uniform fires trigger substantially different structural responses which may be important in the structural design and selection of the critical members.

E. Ellobody, C.G.Bailey (March 2011)[2].This paper highlights the structural performance of a bonded post-tensioned concrete floor subject to fires that travel horizontally between zones within the floor plate. They used the validated finite element model to investigate different horizontal travelling fire scenarios between zones and inter-zone time delays to represent fire travelling time. The study had shown that horizontally travelling fire scenarios and the inter-zone time delay affect the time deflection behaviour considerably the change in heating/cooling scenarios between zones has resulted in a cyclic deflection pattern, which had previously not been considered when designing post-tensioned concrete floors against fire.

Chao Zhang, John L. Gross, Therese P. McAllister (July 2017)[3] The paper investigates the effect of temperature gradients on the lateral torsional buckling behavior of steel wide flange(W) beams in fire conditions. The effects of localized fires and the temperature gradients they produce in steel beams were studied. Laterally unstrained beams of various dimensions were subject to arrange of load ratios. The location of the localized fire was varied to provide different conditions. The standard ISO 834 fire, and a uniform temperature condition in which the steel temperature was ramped linearly were used for comparison. The study shows that temperature gradients within a steel W-beam may have a detrimental effect on the lateral torsional buckling capacity of beams in fire.

Angus Law, Jamie Stern-Gottfried, Martin Gillie, Guillermo Rein (March 2011)[4] The paper applies a novel methodology for defining a family of possible heating regimes to a framed concrete structure using the travelling fires. A finite element model of generic concrete structure is used to study the impact of the family of fires; both relative to one another and in comparison to a conventional codified temperature-time curves. It is found that travelling fires have a significant impact on the performance of the structure and that the current design approaches cannot be assumed to be conservative. Further, it is found that a travelling fire of approximately 25% of the floor plate in size is most severe in terms of structural response. It was concluded that the new approach is simple to implement, provides more realistic fire scenarios, and was more conservative than current design methods.

Chao Zhang, Guo Qiang Li, Asif Usmani (March 2013)[5] The paper numerically investigates the thermal and mechanical behaviours of restrained steel beams exposed to flame impingement from localized fires. Four steel beams with different dimensions and restraints were considered. Both developing and steady burning fires were investigated. The standard ISO 834 fire was also used for comparison. This study found that the temperature distributions within the steel beams subjected to flame impingement are highly non-uniform both across and along the beams. Along the beam length, the temperatures near the fire source may be hundreds of degrees higher than those far from the fire source. Due to different temperature distributions, the deformation mode for restrained steel beam subjected to a standard ISO 834 fire. The failure temperatures for restrained steel beams subjected to localized fires may be higher or lower than those for restrained beams subjected to the standard ISO 834 fire. Reliance on the standard fire may lead to an unconservative design if the potential real fires were localized fires.

Jamie Stern-Gottfried, Guillermo Rein (Part 1 - September 2012)[6] The paper gives literature review of the research on the new topic of travelling fires. The research in quantifying the structural response to travelling fires was also reviewed, demonstrating the benefit of collaboration between fire engineers and structural fire engineers.

Jamie Stern-Gottfried, Guillermo Rein (Part 2 - September 2012)[7] The paper gives details of a new design methodology using travelling fires to produce fires more realistic fire scenarios in large, open-plan compartments than the conventional methods that assumed uniform burning. The methodology considers a range of possible fire sizes and is aimed at producing results consistent with the requirements of structural fire analysis. The methodology was applied to a case study of a generic concrete frame by means of heat transfer calculations to infer structural performance. It was found that fires that were around 10% of the floor area were the most onerous for the structure, producing rebar temperatures equivalent to those reached from exposure to 106 min of the standard fire and approximately 200^0 C hotter than that calculated using the Eurocode 1 parametric temperature-time curve. A detailed sensitivity analysis was presented, concluding that the most sensitive input parameters were related to the building design and its use and not the physical assumptions or numerical implementation of the method.

Egle Rackauskaite, Catherine Hamel, Angus Law, Guillermo Rein (June 2015)[8] In this study, TFM has been improved to account for better fire dynamics. Equations are introduced to reduce the range of possible fire sizes taking into account fire spread rates from real fires. It was found to be mainly dependent on the fire spread rate and the heat release rate. Location of the peak temperature in the compartment mostly occurs towards the end of the fire path.

J.Y. Richard Liewa, L.K. Tanga, Tore Holmaasb, Y.S. Choo (1998)[9]

This paper describes the methodology of an advanced analysis technique for studying the large-displacement inelastic behaviour of building frames subjected to localised fire. The main feature of the proposed analysis is its use of one element per member to model each structural component and thereby obtain a realistic representation of material and geometrical nonlinear behaviour of the overall framework. Both ISO fire and natural fires can be simulated by the analysis model. The transient heat transfer is calculated by using a refined finite element mesh, whereas the structural responses are calculated with a nonlinear finite element technique based on an elasto-plastic beam–column formulation. Numerical studies are carried out on portal frames and multi-storey frames exposed to natural fires. The computed results are compared and contrasted with those from the conventional approach based on ISO standard fire; so that the advantage of using advanced analysis for direct assessment of the performance of steel structures in fire can be highlighted. Effects of fire load and ventilation resulting in localised fires in building frames are studied. The design implication of fire spreading in the storey of a building in which cooling and heating are taking place simultaneously is discussed.

S. Lamont, A.S. Usmani, M. Gillie (JAN 2004)[10]

This paper describes the results of finite element analyses on a small generic composite steel and lightweight concrete frame. It compares the structural behaviour of the frame during two different single floor compartment fires. The fire scenarios are modelled using Pettersson's (Fire Engineering design of Steel Structures, Swedish Institute of Steel Construction, Publication 50, Stockholm, 1976) post-flashover temperature-time curves assuming a fire load density typical of offices and opening factors of 0.02 and 0:08 m1=2: With an opening factor of 0:08 m1=2 the model fire is characterised by high temperatures but a relatively short post-flashover duration (''short-hot fire''). In contrast an opening factor of 0:02 m1=2 provides less ventilation leading to a post-flashover fire with lower maximum atmosphere temperatures but a longer post-flashover duration (''long-cool'' fire). The two fire scenarios create contrasting structural behaviour because the duration of the fire dictates the gradient through the depth of the composite slab. In the ''short-hot'' fire the steel beams achieve high temperatures but only the exposed face of the concrete begins to respond to heating. The rest of the slab depth stays cool. In the ''long-cool'' fire an extended post-flashover duration allows heat to penetrate further through the thickness of the slab. The slab has a higher mean temperature, thus the gradient through the composite is lower. During the analyses the columns and edge beams were protected to provide 60 min fire resistance, primary and secondary beams were unprotected.

B. R. Kirby (July 1996)[11]

This review outlines some of the major developments that have occurred in structural fire engineering design during recent years. The general principles used in fire engineering are discussed together with the various approaches that can be adopted by an architect or engineer to design a structure capable of withstanding the attack of fire without collapsing, using scientific concepts as a basis for determining the fire resistance and protection requirements. Details are provided of recent full-scale tests and research work either completed or in hand with the aim of producing design concepts and information which the fire engineer may use. Examples are discussed to show how structural fire engineering has been utilised in both large and small buildings to precisely define the fire resistance and protection requirements of steel frameworks. In some instances, estimates of the financial savings realised in following this type of approach are also given.

Egle Rackauskaite, Panagiotis Kotsovinos, Guillermo Reina (2017)[12]

This paper aims at benchmarking the explicit dynamic solver of LS-DYNA for structural fire analysis against other static numerical codes and experiments. A parameter sensitivity study is carried out to study the effects of various numerical parameters on the convergence to quasi-static solutions. Four canonical problems that encompass a range of thermal and mechanical behaviours in fire are simulated. In addition, two different modelling approaches of composite action between the concrete slab and the steel beams are investigated. In general, the results confirm that when numerical parameters are carefully considered such as to not induce excessive inertia forces in the system, explicit dynamic analyses using LS-DYNA provide good predictions of the key variables of structural response during fire.

Angus Law, Panagiotis Kosovinos Neal Butterworth (June 2015)[13]

This paper demonstrates the need for structural fire engineering in the design and specification of unusual structural arrangements. It was found that the required fire resistance of a structure cannot necessarily be achieved by considering only the fire resistance of individual elements of structure. A case study of columns that have a change of direction over their height (geometrically bi-linear columns) was used to illustrate how unusual arrangements may lead to early failure of key structural elements even where design guidance was followed. These arrangements were parameterised to allow the relative importance of a number of key variables to be studied. A methodology was developed to estimate the required limiting temperature for the governing elements of the assembly in order to deliver the required performance.

M.M.S. Dwaikat, V.K.R. Kodur (September 2010)[14]

In this study, a performance based approach was developed for assessing the fire resistance of restrained beams. The proposed approach, based on equilibrium and compatibility principles, took into consideration the influence of many factors including fire scenario, end restraints, connection configuration (location of axial restraint force), thermal gradient, load level, beam geometry, and failure criteria in evaluating fire resistance. The validity of the approach was established by comparing the predictions from the proposed approach with results obtained from rigorous finite element analysis. The applicability and rationality of the proposed approach to practical design situations was illustrated through a numerical example.

A.S. Usmani, J.M. Rotter, S. Lamont, A.M. Sanad, M. Gillie (March 2001)[15]

This paper presents theoretical descriptions of the key phenomena that govern the behaviour of composite framed structures in fire. These descriptions have been developed in parallel with large scale computational work undertaken as a part of a research project (The DETR-PIT Project, Behaviour of steel framed structures under fire conditions) to model the full-scale fire tests on a composite steel framed structure at Cardington (UK). Behaviour of composite structures in fire has long been understood to be dominated by the effects of strength loss caused by thermal degradation, and that large deflections and runaway resulting from the action of imposed loading on a 'weakened' structure. Thus 'strength' and 'loads' are quite generally believed to be the key factors determining structural response (fundamentally no different from ambient behaviour). The new understanding produced from the aforementioned project is that, composite framed structures of the type tested at Cardington possess enormous reserves of strength through adopting large displacement configurations. Furthermore, it is the thermally induced forces and displacements, and not material degradation that govern the structural response in fire. Degradation (such as steel yielding and buckling) can even be helpful in developing the large displacement load carrying modes safely. This, of course, is only true until just before failure when material degradation and loads begin to dominate the behaviour once again. However, because no clear failures of composite structures such as the Cardington frame have been seen, it is not clear how far these structures are from failure in a given fire. This paper attempts to lay down some of the most important and fundamental principles that govern the behaviour of composite frame structures in fire in a simple and comprehensible manner. This is based upon the analysis of the response of single structural elements under a combination of thermal actions and end restraints representing the surrounding structure.

V.K.R. Kodur, M.M.S. Dwaikat (October 2008)[16]

In this study when steel beams exposed to fire develop significant restraint forces and often behave as beam-columns. The response of such restrained steel beams under fire depends on many factors including fire scenario, load level, degree of restraint at the supports, and high-temperature properties of steel. A set of numerical studies, using finite element computer program ANSYS, is carried out to study the fire response of steel beam-columns under realistic fire, load and restraint scenarios. The finite element model was validated against experimental data. The results from parametric studies indicate that fire scenario, load level, degree of restraint at the supports, and high-temperature creep had significant influence on the behaviour of beams under fire conditions.

Y.Z. Yin, Y.C. Wang (September 2003)[17]

This paper presents the results of a numerical study, using ABAQUS, of the large deflection behaviour of steel beams at elevated temperatures with different elastic axial and rotational restraints at the ends. A particular emphasis of this paper is the behaviour of axially restrained steel beams in catenary action. Although studies in the area of structural fire engineering has moved beyond the consideration of isolated elements to structural interactions in complete frames, catenary action in steel beams is an important aspect of structural interactions and is receiving considerable attention from researchers. After validating the capability of ABAQUS against available experimental results of fire tests on restrained steel beams, this paper describes the results of a numerical parametric study. The parameters investigated include beam span, uniform and non-uniform temperature distributions, different levels of applied load, and different levels of axial and rotational spring stiffness at the beam ends and the effect of lateral torsional buckling. It is concluded that the large deflection behaviour of steel beams can significantly affect their survival temperature in fire. Indeed, if a realistic amount of axial restraint stiffness is available at the beam ends and fire engineering design is not concerned with the amount of large deflection in a beam, it is possible that the beam can have virtually unlimited survival temperature. Clearly, fire engineering design will need to consider the effect of axial forces in the beam on the adjacent structure, including the connections.

Farshad Hashemi Rezvani, Hamid R. Ronagh (September 2016)[18]

In this study, structural response of a seismically designed steel moment-resisting frame subjected to travelling fire is investigated. This is to determine the structural strength of a generic frame designed for an extreme load when subjected to fire as another extreme load in addition to quantifying the effect of travelling fire size on its collapse behaviour. In this study, using the concept of travelling fire, and calculating the thermal field applied to structural elements, a generic frame was examined against a family of fires travelling across its first floor. In this regard, the resolved far-field gas temperatures dependent on the distance to the centre of fire were considered in order to calculate the temperature at the unprotected steel members. Analysis results revealed that fire size can deeply affect the total collapse time of a frame so that by reducing the fire size to a half or a quarter, collapse time increases by 19% and 62%, respectively. It was also suggested that columns of such structures should be designed against travelling fire considering the effect of load redistribution by which axial forces of columns might be doubled compared to the nominal loads applied to them prior to fire.

C.G. Bailey, I. W. Burgess & R. J. Plank

(March 1996)[19]

In this paper, it is shown that some of the distortions caused by the fire are increased by progressive fire spread, as compared with simultaneous burning across the same range of compartments.

III. METHODOLOGY

3.1.1 TFM- TRAVELLING FIRE METHODOLOGY

The Travelling Fires Methodology (TFM) framework (Stern-Gottfried & Rein 2012 Stern- Gottfried & Rein 2012) aims to incorporate the effect of non-uniform fires in large open-plan spaces. It does not supersede traditional design methods, but can be used in addition to them, and provides a range of possible fire dynamics. TFM provides an approach for generation of gas temperature-time curves at the ceiling at any location in the compartment. It considers design fires to be composed of two moving regions: the near field (flames) and the far-field (smoke). The near field represents the flames directly impinging on the ceiling and assumes the peak flame temperatures. The far-field model represents cooler smoke temperatures which decrease with radial distance away from the fire due to heat transfer and incremental mixing of hot gases with fresh air. Any structural element will experience cool far-field temperatures which correspond to pre-heating or cooling for much longer duration than the short hot near field.

3.1.1 Mtfm- Modified Travelling Fire Methodology

TFM is flexible in a way that, unlike Eurocodes, it is not limited to one fire type. It covers a wide range of fire sizes depending on the coverage of the total floor area from 1% to 100%. The latter represents the whole compartment under uniform fire. The total fire duration depends on the fire size (Stern-Gottfried & Rein 2012). However, it is unlikely that a very thin line fire across the whole width of the compartment or a whole floor fire (e.g. 2500 m^2) in large compartments will occur. The reason for that may be the physical fire limitations such as available fuel load, fire spread rate and burning rate. The aim in the present study is to provide a more realistic representation of possible range of fire sizes which were not accounted for in the previous versions of TFM. This is necessary to reduce the family of fires passed to structural analysis, reduce computational time and neglect unrealistic results. In the methodology a fire is assumed to be fuel controlled. Therefore, fuel load density and heat release rate are used as main design variables. Based on these values a local burning time needed for an area involved in fire to burn out completely is calculated (e.g. 19min) in Eq1. Local burning time multiplied by fire spread rate gives the distance the trailing edge of the fire would travel until the burn out at the ignition point. If the limits of the realistic fire spread rates (i.e. trailing edge) are known these can be used to compute the limiting sizes of possible fires as in Eq2:

$t_b = q_f/Q''$ ...Eq1

$L_{f,min/max} = S_{min/max} \times t_b$ ...Eq2

Where,

t_b = local burning time (s)

q_f = fuel load density (KJ /m^2)

Q'' = heat release rate (KW /m^2)

$L_{f,min/ma}$ =minimum and maximum possible fire size in terms of length along the fire path (m)

$S_{min/max}$ = minimum and maximum realistic fire spread rates in building fires (m/s)

IV. ADVANTAGES OF STUDY

1. New approach towards the design gives precise building behaviour exposed to travelling fires.

2. Fundamental to the new approach is the idea of the travelling fire that has consistently been observed in real accidental fires. Also key to this approach is the requirement for the fire engineer and the structural fire engineer to work together to create the most appropriate design fire.

3. In the context of finite-element modelling, this relies on a relatively small proportion of the available information about the structure. For example, temperatures at certain locations are used to diagnose the performance of the entire structure. Utilization is frequently used in elastic design to determine how efficiently a structure is designed, and where improvements can be made.

V. APPLICATIONS

5.1. Steel Structures application

In steel structures the temperature of columns or beams is often used as an indication of failure. A limiting temperature is given and if the steel rises above this temperature, failure is said to have occurred. This, binary approach to structural performance (either failed, or not failed) does not adequately capture the processes that occur in real structures. Single elements failure is often a complex process, and when the possibility of load redistribution is introduced, limiting temperature in one location does not necessarily correspond to collapse. So to overcome these and capture the real condition of structure new approach is preferable.

5.2. Concrete structure application

For concrete structures, the temperature of the tension reinforcement is often used as an indication of failure. In concrete structures or slabs, the rupture strain in steel reinforcement is often used as a basis for a failure criterion. Typically this measure is better suited to the numerical analysis of structures rather than fire tests because of the difficulties associated with instrumentation of rebar.

VI. CONCLUSION

Travelling Fires Methodology has been developed to account for the travelling nature of fires. This indicate that in order to ensure a safe building design a range of different fires including both travelling fires and Eurocode fires need to be considered. While uniform fires might lead to higher axial forces travelling fires might result in larger displacements and either of them can lead to failure.

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