The Behaviour of Multi-storey Composite Steel Frame Structures in Response to Compartment Fires

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ABSTRACT

This paper presents a summary of the PhD research project “The behaviour of multi-storey composite steel frame structures in response to compartment fires.” The original assumptions, conclusions and suggested further work of the thesis are revisited and newly discussed in the context of structural fire engineering design post 9-11.

The aims of the original PhD research were to extend the understanding of whole frame structural response to fire beyond the research carried out on the Cardington frame fire tests by studying configurations not identical to Cardington, to allow extended application of the at the time new techniques, in real design.

Serious post-flashover fires in real buildings in the 1990s had shown that whole frame response of composite steel structures was significantly better than previously thought and it seemed that the amount of passive fire protection applied to steel was conservative. In addition it was clear our understanding of real structural fire responses including alternative load bearing mechanisms in fire could result in a more robust approach to structural design.

The events of 9-11 and recent tall building fires around the world have meant that fire resistance ratings of tall building structures are being scrutinised again but this time the issue is whether the ratings are adequate or should there be alternative means of engineering structural resilience in fire, especially if total evacuations and extreme events like fire spread to multiple compartment floors are to form the basis of design for tall buildings in the future.

The conclusions of this work are that the beam spans (6-9 m) considered by the PhD research were short in comparison with some modern construction particularly in high rise design. The design fires considered by the sensitivity analysis were severe but could be exceeded if fire spreads via the façade to the compartments above. Conclusions resulting from the sensitivity analyses carried out with regard the effects of different fire scenarios and the effects of different edge restraint on the structural behaviour of a composite floor remain valid.

Runaway failure (a rapid increase in mid-span deflection) was observed in the analyses conducted as part of the PhD research but local cracking and rupture or unzipping of reinforcement could not be modeled. These kind of failure modes were not observed at Cardington and this is a shortfall of the tests in terms of ultimate limit state design. A suggested piece of further work resulting from the PhD was a test to failure of a composite slab. However, there is currently still no experimental evidence to check if

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reinforcement rupture or unzipping type failures in a composite floor should be a concern.

In contrast recent research since 9-11 is beginning to identify potential global progressive collapse mechanisms in different long-span floor systems. Failure mechanisms are being validated against evidence from real fires such as WTC 1, 2 and 7. It is clear that key possible failure mechanisms of composite frame structures in fire are still to be quantified and understood.

KEYWORDS: structural response, structural design, compartment fires

INTRODUCTION

Structural engineers do not traditionally consider fire as a load on the structural frame. This is in contrast to other loads they must consider. Seismic design relies on modelling, risk analysis and changes to the structural stiffness. Wind design relies on additional structural members and wind tunnel tests. Fire design relies on very simple, single element tests and adding insulating material to the frame. Thermal induced forces are generally not calculated or designed for.

Before 9-11 prescriptive fire resistance ratings and the standard furnace test were generally accepted to be conservative. Failure of structures as a result of fire had not been observed.

Research into structural fire engineering especially in the steel industry has generally been aimed at reducing costs because evidence from severe fires in real steel frame buildings indicated that the amount of passive fire protection required by code was overly conservative. This made sense because the furnace test ignores any benefit of load redistribution to adjacent structural members in a redundant frame and therefore formed the basis of the PhD research discussed here.

This assumption has also generally formed the basis for structural fire engineering design. Currently, in performance based fire design the structural response of a frame to a single compartment fire is assessed using computer modeling tools. As there are many alternative load paths available via membrane or catenary load carrying mechanisms in the slab and beams respectively the whole frame analysis predicts better behaviour than the furnace test and some steelwork can normally be left unprotected. This type of fire engineered approach to relatively low rise structures (8-10 storeys high) taking advantage of alternative load carrying mechanisms in fire is proposed to be reasonable in the UK because evacuation times are short and the risk to life and property is low given that buildings of this height will generally be sprinklered. Most importantly the response of the frame to fire is quantified rather than relying on passive fire protection with no understanding of structural performance in fire in particular any potential weaknesses.

In the aftermath of the events of 9-11 there was a heightened awareness of building performance and tall building design from building owners, regulators and other stakeholders but also the public.

Much longer periods of fire resistance were called for with four hours fire resistance a suggestion. This was an understandable emotion driven response but designing a structure with fire as a design load provides a more robust solution. Simply increasing fire proofing thickness without understanding the actual structural response to heat provides no guarantees of increased safety.

The role of structure and its real response to fire, along with the performance of fire proofing materials in real events is important in the overall fire strategy for a building to protect occupants during total evacuation of buildings especially in those buildings designed for a phased evacuation and to protect the fire brigade if fire should spread beyond the compartment of origin.

The aims of structural fire research being carried out since 9-11 are to understand

- Whole frame response to multiple floor fires
- Is fire protection effective?
- Why did the WTC towers survive for up to an hour?
- Why did they collapse?
- How will the NIST investigation into the events of 9-11 change design?

The goal is to develop better solutions for fire, without total reliance on passive fire protection, to take advantage of intrinsic design strengths, and attempt to design out any intrinsic design weakness, in the future.

In particular it is important to understand if there are any specific progressive collapse mechanisms in tall structures currently not known or understood as a result of fire.

SUMMARY OF PHD RESEARCH

For many years the ability of highly redundant composite framed structures to resist the effects of fire had not been quantified. The significance of this was first realised when, after a number of real fires in multi-storey composite steel framed structures, structural failure did not occur. The Broadgate Phase 8 fire[1] is probably the most notable. This accidental fire happened during the construction phase when the steel frame was only partially fire protected. Despite very high temperatures during the fully developed phase of the fire and considerable deflections in the composite slab there was no collapse. This initiated construction of an 8-storey composite steel frame at Building Research Establishment's (BRE's) large scale test facility in Cardington [2], UK. Six fire tests were conducted, of varying size and configuration, to observe and ultimately explain why composite steel-framed structures adopt very large deflections during a fire but do not collapse.

Computer modelling of the tests by a number of research groups, including the University of Edinburgh, followed [3-8]. Finite element modeling of these tests provided a wealth of information about the behaviour of whole frame structures in fire. However, despite extensive dissemination of the output, change to design guidance was hindered when the new knowledge was based on analysis of only six tests all conducted on the same structure.

The purpose of the PhD research [9] discussed by this paper was to confirm and extend the conclusions of the Cardington frame fire tests and the subsequent numerical modeling to allow structural fire analysis to be used in design.

Two generic composite steel frames were designed in accordance with EC4 Part 1.1 [10]. Their shape and size in plan were chosen to be significantly different from the Cardington frame.

An investigation of the methods available to model compartment fires was carried out. Comparisons were made between predicted natural fires and atmosphere temperatures measured during experimental compartment fires [9,11]. Heat transfer models were also tested against steel and concrete temperatures recorded during the Cardington tests [9,12]. Using these design tools, natural fire curves were assumed and heat transfer calculations were made, to obtain steel and concrete temperature histories as inputs to structural analyses.

A series of parametric studies was conducted on the two generic frames to investigate the response of the structure if the fire exposure or location changed [9,13-15]. The fire scenarios included compartment fires on the whole floor, at the edge and corners of the structures. By altering the size and location of the compartment, the level of restraint to thermal expansion and thermal bowing of the structural elements changed.

A further set of studies varied the number of beam members with applied fire protection. Three scenarios were tested. Primary and edge beams protected, only edge beams protected and all beams unprotected. In all studies secondary beams were unprotected and columns were protected to their full height.

The tensile membrane behaviour of the slab and alternative load carrying mechanisms observed in the Cardington frame fire tests were confirmed in both generic frames and new phenomena was highlighted [16].

Overall the generic frame structures behaved well and the partially protected composite frame structures were shown to continue to support load under the fire scenarios tested.

AIMS AND ASUMPTIONS OF THE PHD RESEARCH

The aim of the research project was to extend our knowledge of whole frame structural response to fire by conducting a series of sensitivity studies on finite element (FE) models of 2 generic steel frames. These studies were intended to give increased confidence in the use of finite element modeling as a performance based design tool to calculate the amount of passive fire protection required and on what elements.

The research was based on the following assumptions or range of variables:

- Steel beam spans of 6-9 m.
- Concrete slab spans of 3 m.
- Composite steel frame construction.
- Universal steel column and beam sections.
- Single floor fires i.e., floor to floor compartmentation was not breached and flame spread via the façade would not occur.
- In some studies the floor plate would be divided into smaller compartments and the fire was limited to that compartment.
- A post-flashover fire would develop in the compartment.
- Beam to beam and beam to column connections were assumed to be perfect pins.

- Shear studs providing shear interaction between the slab and the beams were perfect rigid elements that remained cold during the fire.
- The anti-crack mesh was represented by a smeared approach in the depth of the concrete slab model.

The assumptions above about fire sizes being confined to the compartment of origin still form the basis of design for structural fire engineering now whether prescriptive or performance based.

However, it may now be considered as a shortcoming of the research. The Telstar fire and the Madrid Torre Windsor fire have shown that if a post-flashover fire develops on one floor fire can spread beyond the floor of origin to multiple floors. In traditional design based on furnace testing the real impact of deforming heated structure cannot be quantified and therefore accounted for in the façade detailing.

Recent research [17-19] is beginning to show that multiple floor fires could result in collapse of structure although it should be remembered that WTC 1 & 2 (see Fig. 1) remained standing for over and hour despite severe impact damage and fire on up to 5 floors. The Madrid Torre Windsor fire (Fig. 2) spread to all floors in a 24 hour period and although must be demolished is still standing except for local structural failure near the top of the tower.

Fig. 1. WTC 1 & 2 on 11th September 2002.

Fig. 2. Aftermath of the Madrid Torre Windsor fire, Madrid, Spain 12th February 2005.

Large modern office floor plates are unlikely to be split into separate smaller fire compartments therefore a post-flashover fire is unlikely to be contained on a fraction of the floor plate as was an assumption of some of the work carried our during the PhD research and the Cardington frame fire tests also. The largest compartment fire tested at Cardington was a half floor [2] therefore there was significant load redistribution to the cooler half which would be limited if the whole floor was on fire unless the fire was at different stages of growth and decay over the floor plate.

The PhD research and the Cardington tests did not consider spans above 9 m when in efficient tall building construction 12-18 m spans are common place. Much longer spans result in much greater expansion therefore very large deflections (1.5-2 m at mid-span) and little stiffness from the deflected floor to support columns if they are pulled in by the floors. Long span cellular beams in particular are common in the UK because they allow efficient structural design with the services integrated in the floor zone and lower floor to floor heights.

Long spans are tested in a similar manner to any other form of construction in that a 4.5 m length of floor is tested in a standard furnace unrestrained and in many cases unloaded. Therefore thermal expansion effects on the long span beam and their effects on the rest of the structure are not considered by testing and therefore not by prescriptive design. The result of this is that the floor system may well pass a 60, 90, 120 minute fire test and therefore can be installed in a 120 minute building but the much longer span of the real case would behave very differently in the real building situation and will generate forces on columns and other surrounding structure that have not been quantified by design.

Arup Fire in collaboration with the University of Edinburgh [17-19] have analysed WTC type structural design (long span truss floor system with closely spaced external columns) in various severe fire scenarios.

This work is not a forensic investigation of the WTC buildings but a series of parametric studies to understand structural response to fire of different long span floor systems subjected to fires on multiple floors.

The aim of the ongoing work is to understand if there are any specific progressive collapse mechanisms in tall structures that are not known or not understood, in the fire limit state and then to design these potential weaknesses out of structural frames without reliance on passive fire protection to achieve this. Figure 3 shows one of the FE models of the WTC type frame with fire on 3 floors.

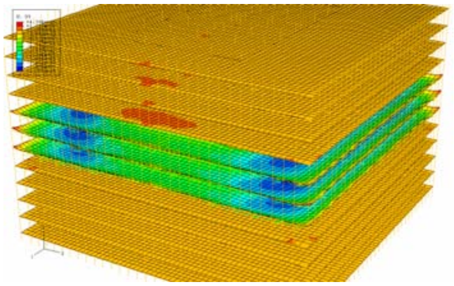

Fig. 3. FE model of a 3 floor fire in a composite truss floor tower
of similar construction to WTC 1 & 2.

CONCLUSIONS OF THE THESIS – A DISCUSSION

In this section of the paper some of the conclusions of the PhD thesis are shown in italics before an appraisal of each in the context of real design and knowledge gained since.

Simple beam analyses showed that an axially unrestrained beam tested in a standard furnace bears little relevance to the behaviour of structural elements as part of highly *indeterminate structures typical of modern, composite steel frame buildings. The test methods are inadequate when the beam is tested as simply supported i.e., no consideration of restraint is made. By including the effect of restraint in a simple beam model the temperature at which "runaway" occurred was greatly increased. The reasons for this are the changing load carrying mechanisms involved as catenary action develops at large deflections.*

Engineers have known for years that the standard furnace test can under predict the failure temperature of a beam when it acts as part of a whole frame. The PhD study simply quantified that [20]. However recent research into long floor spans in fire suggest that failure of an assembly/frame could occur earlier than the traditional 550°C if the columns are unsupported over several floors i.e., fire spreads from floor to floor in a building and the deformed weakened floors do not provide in plane restraint to the columns [17-19].

The 2x2 frame with a whole floor fire was more sensitive to changes in parameters such as fire severity and protected or unprotected edge beams than the large frame with corner and edge compartment fires because the former is a small low redundancy frame and the latter is a large highly redundant frame.

This conclusion holds true and is also the reason that buildings with beams that span from a central core to an edge column creating a column free floor layout are likely to be less robust in fire than conventional frames with many columns over the depth of the floor plate. A column free space can be robust once the structural response to fire is understood and structural detailing is enhanced if required.

The temperature history of a natural fire depends upon the available ventilation, fire load, room geometry and thermal properties of the boundary wall materials. Many fire scenarios exist leading to a range of thermal responses in the structural elements, which are manifested in various combinations of deflections and forces. In composite floor slabs fires of short post-flashover duration result in low concrete temperatures but high temperatures in the steel beams. High gradients exist over the depth of the composite causing thermal bowing behaviour [13,21]. Fires of longer duration allow the concrete to reach much greater temperatures therefore, thermal expansion of the composite is the more dominant behaviour [13,22].

An upper and lower bound of design fires should be assessed when designing structures for fire. This is achieved by conducting a sensitivity study on fire load, compartment size and available ventilation from the building façade when calculating post-flashover design fires. Figure 4 shows the extent of maximum temperature and fire duration that can be achieved when ventilation is changed in a particular compartment. The generic steel frames were tested against both types of design fire defined by the PhD research as “short-hot” and “long-cool” fires [13].

The development of deflections and internal forces in the beam is governed by the interaction of mean temperature increase, through depth thermal gradients and the end restraints governing translation and rotation. The variation of mean temperature and thermal gradients (for various thermal regimes) can produce a large variety of responses [20] from largely compression when thermal expansion is dominant to mainly tension when thermal bowing is dominant. Therefore any state from high compression to high tension can (theoretically) exist in heated structural members. However, in all these *cases large deflections will be present albeit having developed through different mechanisms.*

The above conclusion holds true and highlights the importance of carrying out a sensitivity study on potential fires when analysing structures.

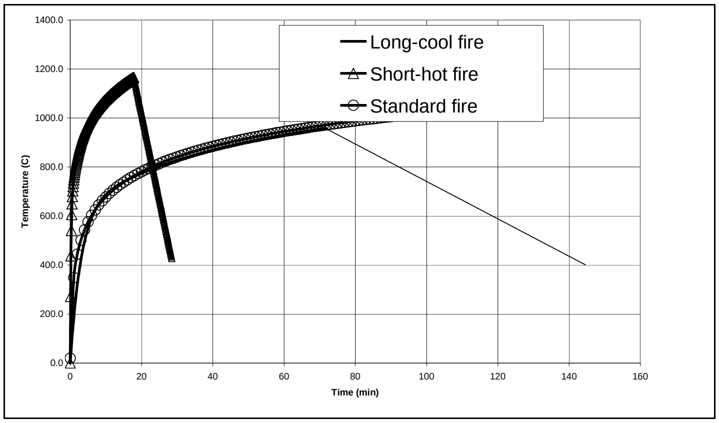

Fig. 4. Example of post-flashover design fires.

The most detrimental fire in terms of the structural response of the generic frames was the "short-hot" fire. Large deflections developed in a very short time. This may result in early compartmentation failure. The slab experienced high mechanical tensile strains at reinforcement level because of the high gradient in the composite.

The "long-cool" fire resulted in higher temperatures in the concrete and the protected steel. This caused greater displacements in the protected structural elements but much later in terms of real time. However, because the concrete slab achieved higher temperatures there was much less tension in the slab with growing compressions towards the end of heating.

Recent studies have shown that although these conclusions are still true failure of the structure is unlikely in a "short-hot" fire because the slab and protected steel stays relatively cool. A "long-cool" fire has been shown to cause runaway failure in longer floor spans (>10 m) with unprotected secondary steel beams [23] because the slab and protected primary steelwork including columns weaken. This weakness can be addressed by increasing the size of the anti-crack mesh or the columns as part of a structural design change rather than adding passive fire protection.

Differences in compartment fire size and location provide various degrees of restraint to an expanding structure. The level and location of restraint is a contributing factor to the patterns of deflections and forces.

This conclusion remains true and when the structural fire behaviour of a frame is quantified in design it is important to test edge conditions where less restraint is available to support deflecting floors but also internal bays where increased restraint will lead to higher deflections.

Protected edge beams allowed the slab to be anchored on all four sides of the frame throughout the heating regime. When the edge beams were unprotected the slab would *tend towards 1D catenary action which is a much weaker load carrying mechanism than 2D tensile membrane action.*

Protected edge beams will allow the structure to survive for a longer period of time.

The conclusions about edge beams are significant and need to be extended to include the importance of columns. Inward and outward movements of the columns as a result of the floor slabs expanding and bowing was not shown to cause failure in the PhD research but if beam spans are longer, columns are slender or multiple floors are on fire simultaneously this could be the case.

Removing applied fire protection from all steel beams leads to greater deflections of the composite floor. However, relative displacements between an unprotected edge beam and the centre of the fire compartment may be reduced causing a reduction in the tensions experienced by the slab at high deflections. Providing applied fire protection to steel beams in composite structures may not be necessary although the impact of large deflections on compartment breach should be considered.

It is generally accepted in design that primary structure connected directly to columns should be protected because this allows a cooler edge condition to structural bays allowing "pockets" of tensile membrane action to develop and be anchored at the boundary. This design approach was adopted at Plantation Place South [23], London UK (see Fig. 5). The building is an 8-storey composite frame office building where the fire resistance of the frame was calculated using FE analysis allowing all secondary steel beams to be left unprotected because the loads in fire were shown to be supported by tensile membrane action.

It should be noted that passive fire protection does not stop heat passing into the steel frame it merely delays it. Finite element models of the Plantation Place South building were analysed to show the client and insurer that the amount of damage to the frame in a post-flashover fire was very similar whether the secondary steel beams are protected or not. Predicted maximum deflections and mechanical strains in the slab were very similar. This was of particular interest to the building insurer because the performance based design solution was no worse than the prescriptive case in terms of the amount of structure that may have to be replaced after a fire.

Fig. 5. Unprotected secondary steel beams at Plantation Place South, London as a result of FE analysis of the frame in fire.

Compatibility played a significant role in the behaviour of the rectangular 2x2 frame but less of a role in the large square frame. Compatibility in the 2x2 frame caused greater mechanical strains (tensions) in the slab.

This conclusion will not change and is something to consider when choosing representative parts of a floor plate to model in design.

SUGGESTED FURTHER WORK RESULTING FROM THE THESIS

Some further work suggested by the thesis was as follows:

- In very large spaces of varying fire load it is unlikely that the whole compartment will achieve flashover at the same time. The influence of spreading fires on structure should be investigated.
- The most important future fire test is that which will define structural failure of a composite frame in fire so that structural fire engineering can be based on limit state design principles.

The investigation by NIST of the collapse of WTC 1, 2 and 7 has meant that spreading fires and the consequent structural response is being analysed as part of their forensic investigation. The effect on the structural load paths before collapse will be interesting.

At the time of this research the most important form of failure to be quantified was considered to be failure of the rebar as it was known to provide the capacity for tensile membrane action. Compartmentation breach as a result of cracking of the concrete slab was also a concern.

Traditional structural failure criteria i.e., large deflections are misleading in the fire case. Large displacements in composite floor slabs enable tensile membrane action to develop and carry the load. They also absorb thermal expansions and reduce thermally induced mechanical strains. The test to structural failure has not been conducted as yet and the debate about sensible failure criteria for structural fire design continues. It will also become more interesting as potential progressive collapse mechanisms in fire are now also of concern.

CONCLUSION

The conclusions of this appraisal are as follows:

- The beam spans (6-9 m) considered by the research were short in comparison with modern construction.
- The design fires considered by the sensitivity analysis were severe but could be exceeded if fire spreads via the façade to the compartments above.
- Major failure mechanisms of composite frame structures in fire are still to be quantified.
- Failure of the Cardington frame was not observed. Runaway failure (a rapid increase in mid-span deflection) was observed in the analyses conducted as part of the generic frame research but local cracking and rupture of reinforcement cannot be modeled. There is no experimental evidence to validate failure criteria of this type for ultimate limit state design.

- Potential progressive collapse mechanisms are beginning to be identified by modelling of different long-span floor systems [15-17]. Failure mechanisms are being validated against evidence from real fires such as WTC 1, 2 and 7.
- Conclusions in the PhD about the effects of different fire scenarios on the structural behaviour and the effects of different edge restraint levels are valid.
- Structural elements and assemblies need to be sized accordingly and joined to together in such a way as to form a robust frame with limited reliance on passive fire protection. Removing fire protection should not be considered as the main benefit of this work as was the intent of the original PhD research but a robust structural solution for fire resistance reliant on the structural assembly and not fire protection coatings.
- Currently the level of structural design and analysis for fire described by this paper is carried out on a case by case basis on projects where clients have demanded a better understanding of their buildings response to extreme events including fire. In the future it is hoped that structural engineering of buildings for fire will become common practice on all structures.

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