STRUCTURAL FIRE ENGINEERING RESEARCH AT THE UNIVERSITY OF SHEFFIELD

Background

Our structural fire engineering research started in 1985, when we were simply attempting to simulate the behaviour of isolated steel elements in furnace tests. We have used several software approaches since then, as the emphasis has shifted from beams and columns in isolation towards the performance of building structures as a whole. A massive stimulus was given to the whole subject by the fire tests on the full-scale composite frame at Cardington during the 1990s.

Our early work was entirely analytical, and the main theme of our research remains in numerical modelling, but several of our major projects have had a substantial experimental component. This was initially done by going into partnership with other institutions with established experimental facilities and expertise, but in more recent work we have developed and used our own purpose-built facilities. The major recent themes have been the robustness of buildings, and the behaviour of thin composite floor slabs, in fire conditions.

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Vulcan Solutions website: http://www.vulcan-solutions.com
Completed Work and the Research Workers Involved

1985-1988 Oyewole Olawale (PhD)

**Steel column behaviour in fire**

Analytical study of uniformly heated steel columns in fire, using finite strip and finite element (INSTAF) approaches. Ramberg-Osgood and bilinear stress-strain-temperature relationships were used. The finite strip analysis included the capability to detect local buckling of flanges.

1986-1989 Jamal El-Rimawi (PhD)

**A secant approach to the analysis of steel beams in fire**

Analytical study of steel beams with uniform and non-uniform temperature profiles. The 2-D secant stiffness software used Ramberg-Osgood material stress-strain-temperature characteristics, and comparisons were made with BS5950 Part 8 predictions and furnace tests.

1987-1990 Hassan Saab (PhD)

**Finite element analysis of plane steel frames in fire**

Development of an existing 2-D finite element inelastic spread-of-yield frame analysis (INSTAF) to include thermal distributions due to fire. Performed pilot studies on multi-storey rigid sway frames with local fires.

1987-1991 Sha’ari Abu (PhD)

**Behaviour of steel frames in fire**

Initial studies for subsequent frame analysis developments, including studies of the relevance of material unloading in zones of strain reversal.

1989-1992 Jamal El-Rimawi (SERC/SCI/BS project)

**The influence of connection behaviour on the performance of steel beams in fire**

Studies of behaviour of steel beams within multi-storey frames. The 2-D secant stiffness frame software (NARR) was developed to include temperature distributions, the effect of the semi-rigidity of simple beam-column connections, axial expansion of members and $P - \Delta$ effects. A range of studies was conducted on subframes and full plane frames, showing that even simple connections can enhance beam survival in fire, but that column stability must also be ensured.

1990-1994 Samer Najjar (PhD)

**Three-dimensional finite element analysis of subframes at high temperatures**

Development of the non-linear finite element frame analysis software previously used by Saab) to full 3-D capability for skeletal steel frames in fire. This was originally intended for use with column subframes, and so far has been used mainly to perform isolated column and subframe studies. It is capable of very high-deflection analysis of 3-D frames, including member buckling, but does not include semi-rigid connections.

1992-1995 Colin Bailey (PhD)

**Further development of 3D frame analysis in fire**

This was a major development from Najjar’s work, which increased the capabilities of the 3-D analysis to include semi-rigid connection characteristics, lateral-torsional buckling and plate elements to represent slab continuity. This was the software used for the EPSRC study referred to below.
**The effects of strain reversal and fire spread on frame behaviour**

*Study of the behaviour of large multi-storey steel frames under the influence of fires restricted to a local compartment or storey, and of the residual effects and repairability of the structure after these have been extinguished. This is the first study that has considered natural rather than standard fire scenarios, and so the software has been developed to be capable of dealing with strain reversal due to cooling of the steelwork.*

1993-1995  Cardington Frame Design Studies (El-Rimawi, Najjar, Bailey)

**Cardington Frame Design Studies**

*As part of the design process for the fire tests on the 8-storey composite frame at Cardington a programme of predictive analyses was carried at several different levels of modelling. Various ways of rationalising the frame and the fire compartments have been used. Studies included the influence of test load level, the effect of column protection, load sharing via the secondary structure and connection stiffness, out-of-plane column failure, and slab continuity over supports.*

1992-1996  Atilla Oven (PhD)  
**Partial interaction in composite beams in fire**

*Study of the behaviour of composite beams with partial interaction between the steel section and the concrete flange through the slip characteristics of the shear connectors. The software was developed to include partial interaction, and the influence on fire survival of various parameters such as beam span, load ratio and degree of interaction between the steel and concrete was examined.*

1995-1997  Windows-based User Interface for Vulcan (Supported by British Steel plc)  

*A highly interactive graphical user interface for Vulcan has been developed by consultants, which makes preparation of subframes for analysis less error-prone and much more efficient. On the output side the interface enables rapid selection and plotting of results generated by the program.*

1993-1996  Lee Leston-Jones (PhD, supported by BRE and SERC)  
**Moment-rotation characteristics of end-plate connections in fire**

*A programme of experiments on typical semi-rigid connections used in steel and composite construction has been carried out at BRE Garston. The object of these was to determine how the moment-rotation characteristics of connections degrade with temperature rise; only a few indicative tests had previously been done. The study used mainly small UB and UC sections, and attempted to relate the high-temperature performance to existing data on ambient-temperature behaviour. A general model for connection degradation at high temperatures has been postulated and a sensitivity study has been carried out on the influence of connections on fire survival of frames.*

1995-1998  Paul Rose (PhD, supported by ECSC and British Steel)  
**Modelling of the Cardington full-scale fire tests**

*The six full-scale Cardington fire tests were studied in detail using Vulcan. In the post-test analyses, measured parameter values were used to refine the precision of the modelling, and sensitivity studies were carried out so that the relative importance to the behaviour of a range of aspects could be gauged. This modelling formed part of an integrated series of numerical analyses, together with complementary studies at TNO (Holland), CTICM (France) and British Steel Swinden Technology Centre. The shell elements used to model slabs were developed to a layered model as part of this project.*
1995-1998  Paul Shepherd (PhD, supported by EPSRC)

**The effect of restraint on column performance in fire**

This was a study of the in-fire performance of restrained columns in multi-storey frame construction, carried out in collaboration with an experimental programme at the University of Ulster. The Ulster tests were analysed in detail, and a model of the mechanisms involved in axial restraint to column expansion in fire was developed. The latter gives some insight into the redistribution of internal forces which takes place in the building when fire-affected columns "collapse"; in most cases this redistribution prevents a real structural collapse.

1996-1998  Ahmed Allam (PhD funded by University of Sheffield Bursary)

**Tensile membrane action in slabs at high temperatures**

In full-scale fire tests carried out recently there has been a strong indication that concrete slabs survive to very high fire temperatures, maintaining the vertical compartmentation of a building, due to a self-equilibrating membrane action. This occurs at high deflections and represents the true ultimate condition in the fire Limit State. An improved slab formulation which will assist in the modelling of membrane action, was researched and partially implemented.

1996-1998  Neal Butterworth, (Research Assistant supported by EPSRC under ROPA)

**Fire protection systems for steel columns**

Innovative fire-protection systems for steel columns in multi-storey frame construction were evaluated for thermal and structural effectiveness. It is currently generally accepted that columns must be fire-protected, and this on-site process is both expensive and time-consuming. Systems which offer the prospect of pre-fabrication, cutting out the costly programme delays, were tested computationally first for thermal effectiveness and for structural fire survival. An MPhil has now been awarded.

1998  

**Vulcan**

Our finite element software, which had by now been developed to a massive extent from its origins in INSTAF, was re-named **Vulcan** in 1998 by the research group.

This is not an acronym - Vulcan is the Roman god of fire and the forge, and his statue stands above Sheffield Town Hall, reflecting the city's long tradition of steelmaking and engineering.

1998-1999  Graham Knapp (MSc(Res) Student, funded by EPSRC)

**Design studies based on the Cardington tests**

The full-scale Cardington fire tests were used as a basis for the development of a more enlightened approach to the design of composite multi-storey structures than had previously been possible. The development of design documents for this Fire Engineered approach is envisaged as being phased to co-ordinate with numerical modelling over a wide parametric range. This project performed a series of studies to support the development of a "Level 1" design guide which was published by SCI in 2001.
1996-2000 Khalifa Al-Jabri (PhD, partially supported by BRE & DoE under Partners in Technology)

Moment-rotation characteristics of steel and composite connections in fire

This work extended the experimental programme started by Leston-Jones on the high-temperature properties of bolted steelwork connections, in a series of tests on connections typical of those used on the Cardington full-scale frame. These connect much larger beam and column sections than those previously tested, and provide an opportunity to test the connection modelling principles postulated by Leston-Jones. The properties themselves are being used in post-test Cardington studies, and these will provide a guide to the importance of connection characteristics to fire survival of frames. Initial studies were also made in the development of a component-based method of representing connections for fire resistance.

1996-1999 Young Wong (PhD, supported by Health & Safety Laboratories)

Portal frames in fire

This project studied the collapse behaviour in fire of industrial portal frame structures, commonly used for warehousing of highly inflammable organic substances which produce extremely toxic effluents on burning. In the course of the project portal frames were modelled numerically, and two series of fire tests were carried out at HSL Buxton.

1996-1999 Dr Zhaohui Huang, (Research Associate, supported by EPSRC)

A new slab element for Vulcan

The elevated-temperature concrete failure model originally implemented in Vulcan was rather crude in its assumptions, and there were some circumstances in which it provided an unreasonable representation of the slab behaviour. In this project a new failure model for concrete floor slabs at elevated temperatures was developed, and this was implemented in conjunction with a layered slab element which allows thermal distributions within the slab to be represented and progressive cracking and crushing of the concrete to be modelled. Partial interaction at shear studs in composite construction has recently been included. The Cardington fire tests were used to validate these developments and a number of papers have been written.

1998-2001 Ahmed Allam (Research Assistant + PhD, supported by EPSRC)

The effect of restraint on the behaviour of steel beams in fire

This project, which involved collaboration with the University of Manchester, began in February 1998. It involved examination of the effects of in-plane restraint to the fire compartment by adjacent structure for steel-framed buildings using non-composite precast slabs, with an emphasis on the ultimate development of catenary action in the beam grillage. The work included furnace testing at Manchester and frame modelling at Sheffield.

1998-2000 Craig English (PhD)

Risks to structural stability and life safety in fire

This project compared the risks to life [pre-flashover] and the risks of structural failure [post flashover] in low-rise steel-framed office buildings when the alternative fire resistance options [60mins FR and 30mins FR + sprinkler] in Table A2 of Approved Document B are used. A risk comparison approach, as described in PD7 of BS 7974 was adopted. The study used statistical data, event trees and two separate risk models of the Monte Carlo type to calculate these risks. The findings demonstrated that unclad steel framed buildings which only have sprinkler protection provide a much higher level of life safety and structural fire safety than do structures which are designed simply for 60 minutes' fire resistance [the code recommendation] and that further trade-offs in fire safety measures should be given to increase the financial viability of this design option.
1998-2001 Spyros Spyrou (Research Assistant + PhD, funded by EPSRC)

**A component model for steel end-plate connections in fire**

This project included a programme of furnace tests to identify the degradation of characteristics of the most important parts of typical connections at elevated temperatures, together with detailed finite element studies. These were very successfully used to develop a Component Method to represent the behaviour of steel-to-steel connections at elevated temperature, following the principles used at ambient temperature in Eurocode 3 Annex J. This method allows the connection behaviour in rotation and in thrust to be combined easily in frame modelling.

1998-2002 Jun Cai (Research Student, funded by British Steel/SCI)

**A general beam-column element for Vulcan**

In the course of this project new elements were devised to represent general beam-column member cross-sections in the Vulcan software. These elements were necessary firstly to model reinforced concrete beams and later to represent cross-sections which are asymmetric, hollow, or contain different materials. They are segmented so that temperatures and material properties can vary as required in two dimensions. Studies were also conducted using these elements on the effect of push-out on the survival in fire of columns in multi-storey buildings during fires.

1999-2000 Dr Zhaohui Huang, (Research Associate, internal support)

**A new shell element for Vulcan**

In this six-month bridging project a new 9-noded layered flat-shell element with a geometrically non-linear formulation, which embodies the developments made to the previous 4-noded elements, was developed and introduced into the *Vulcan* software. This was validated wherever possible in a range of comparisons against analytical solutions, independent numerical modelling and test results. This has enabled modelling of the large-deflection behaviour of floor slabs in fire conditions, including both thermal buckling against restraint and tensile membrane action.

1999 Dr Antonio Claret de Gouveia (Visiting Scholar, University of Ouro Preto, Brazil)

**Fire resistance of Brazilian steel sections**

A finite element study was made of the behaviour in fire conditions of welded I-section beams, of the type produced by Brazilian steel manufacturers. The effects of high residual-stress patterns and of partial protection were the main themes of this work.

2000-2003 Dr Zhaohui Huang, (Research Associate, supported by EPSRC)

**Geometrically non-linear analysis of 3-dimensional composite building behaviour in fire**

The major objective of this project is to try to shift the basis of fire resistance design from its present dependence on standard fire testing of isolated members to the performance of real building structures in fire. It will investigate the ultimate integrity of fire compartments in multi-storey composite building frames by wholly (material and geometric) non-linear modelling. The project started in April 2000.

2000-2004 Seng-Kwan Choi (Research Student, funded by Metsec Building Products plc.)

**Behaviour of long-span composite trusses in fire**

In this project the fire resistance of lightweight long-span composite lattice girders was investigated. Such systems are very often used in the United States, to produce commercial multi-storey buildings with column-free beam spans of up to 20m. The systems have so far been rather neglected in the Britain, largely because of the traditional fire protection
requirements necessary to achieve normal fire resistance ratings. A series of parametric studies were performed in this project, to identify the fire engineering design strategies necessary in order to make these systems perform to the expected standards when subjected to fires. The modelling was extended to the composite floor arrangement used in the World Trade Center twin towers in New York, in order to provide some insights about the likely floor system behaviour during the events of 11 September 2001.

2003-2004  Dr Paul Shepherd (Buro Happold) and Dr Zhaohui Huang (University of Sheffield)

Vulcan rewriting and re-validation

The structural modelling software Vulcan, developed for many years by the Group in Fortran code, has been completely rewritten in C++, with a completely integrated Windows graphical user interface. The new interface allows practical 3-dimensional subframes of composite buildings to be created very efficiently, including loading and thermal scenarios. It also allows input data and results to be viewed in perspective, with rendered member and slab surfaces, and results to be transferred directly to Excel for creation of reports.

During 2005 this software was made commercially available to designers as a tool for performance-based fire engineering design of structures. A university spin-off company, Vulcan Solutions Ltd, was set up to handle this commercialisation.

2001-2004  Samantha Foster (Research Student, funded by EPSRC and Arup Fire)

Tensile membrane action in concrete slabs

A new fire-resistance design method for composite slabs, proposed by Professor Colin Bailey of Manchester University and embodied in a recent design document, is based on a simplified model of the enhancement to yield-line slab capacity which is caused by tensile membrane action at high deflections. In fire high deflections are acceptable provided that no structural collapse or loss of compartmentation occurs, so that fire spread beyond the compartment of origin is prevented. In this project the proposed method has been investigated with respect to its own formulation, in comparison with numerical modelling, and finally using a large number of experiments. A system was developed initially to carry out a large number of small-scale ambient-temperature experiments, which were not initially envisaged, during the first phase of the project, and the experimental system was developed to conduct loaded high-temperature tests at model-scale. At this scale it has been possible to perform large numbers of tests, which would have been prohibitively expensive at larger scale, and these can be used to test both the simplified method and advanced modelling approaches. The student was also able to perform modelling studies to rationalise the floor slab behaviour of the final (7th) full-scale fire test at Cardington, which was performed in January 2003.

2003-2007  Marwan Sarraj (Research Student, funded by EPSRC)

Performance of fin-plate beam-column connections in fire

This was a computational investigation of the behaviour and robustness of steel fin-plate joints in fire, under catenary tension together with high rotations. The modelling employed ABAQUS to produce very detailed finite element representations. These were very complex models using contact elements at the bolt/hole interface, and considerable problems with these were overcome in progressing to the stage where a complete connection behaviour could be modelled to very high distortions at ambient and elevated temperatures. It was possible, in collaboration with the Czech Technical University, Prague, to compare the model’s predictions with the results of two full-scale fire tests conducted in the Czech Republic. The results of the FE studies were also used as a basis for the development of a simplified component-based approach to be used in global modelling software for performance-based design where fin-plate connections are to be employed.
2003-2007 Florian Block (Research Student, funded by Buro Happold FEDRA)

Component modelling of end-plate beam-column connections

This project followed on from the work of Spyros Spyrou in identifying the degradation of characteristics of the most important components of typical connections at elevated temperatures. The work aimed to fill in important gaps in the list of components which have already been modelled, so that connections in full structural assemblies could be represented properly in numerical modelling. The effect of axial superstructure load on the behaviour of column-web behaviour in the compression zone of an end-plate connection was studied experimentally and analytically. As a final stage in the project a component-based formulation was developed for a steel beam-to-column finite element to be incorporated in global analysis of building structures in fire conditions.

2003-2007 Chaoming Yu (Research Student)

Fire resistance of bi-steel core-walls

This project’s focus was on the possibility of using bi-steel concrete-filled walls in the construction of highly robust fire-resistant service cores for use in medium- to high-rise multi-storey buildings. The temperature distributions generated in the concrete and steel cross-section were initially studied. In order to investigate the structural behaviour of the bi-steel cross-section under load and complex temperature distributions, it was necessary to formulate a new 3-dimensional brick element for the software Vulcan, and to implement it in the program code. General-purpose finite element packages had proved to be very fragile in analysing such problems, but the new brick element performed well. Some studies of the performance of bi-steel wall panels were conducted, and it is hoped to use the new element intensively in future projects investigating steel-concrete composite structural systems in fire conditions.

2004-2008 Xinmeng Yu (Research Student)

Development of a ribbed-slab element for structural fire modelling

Slabs are seen to perform a key role in enabling the survival of composite buildings in fire, and their behaviour forms the basis of performance-based structural fire engineering design strategies for such buildings. Previous treatments of ribbed slabs in Vulcan tended to neglect the temperature variations between the ribs and troughs. In this project a thermal model was developed for these areas, followed by the development of a slab element which reflects these temperature variations, as well as the changes of slab depth. This was followed by studies which investigated the sensitivity of slab behaviour to this and other effects such as concrete spalling. In the final phase of the project an advanced slab element was developed in which the occurrence and development of localised tension cracking was modelled directly. Since failure of slabs is more often associated with integrity failure than with structural collapse, this is an important development. It will be followed-up in subsequent projects in order to establish a method of routinely allowing localised cracking to be represented in performance-based design using global modelling of whole structures or large sub-structures.

2005-2008 Dr Hongxia Yu (Research Associate, funded by EPSRC) and Ying Hu (Project Research Student, funded by EPSRC)

Robustness of steel connections in fire

In the aftermath of the New York twin Towers disaster, robustness (avoidance of progressive collapse emanating from localised failures) has become a major issue in the development of performance-based approaches to structural fire engineering design. In multi-storey buildings failure of connections is one of the main potential sources of progressive collapse, as is already recognised in UK structural design codes for other limit states. The robustness in fire conditions of end-plate connections has been investigated in this project, in which we have
collaborated with researchers at the University of Manchester. At both centres the investigation involved a mixture of experimental and analytical work. In the Sheffield work the focus was on high-temperature structural behaviour of components and assemblies under combinations of tying and shearing forces. A large number of connection tests to destruction under inclined forces have been performed, at temperatures up to 650°C, for four typical beam-column connection types. Modelling using Finite Element analysis has rationalised the test results, and this has subsequently been used to help with the development of simplified component characteristics, to be used in constructing component-based joint elements for global modelling which can feasibly be used in design. Several journal papers have been published; these can be found under Publications. The project’s photos and test data sheets can be downloaded from the Group’s website fire-research.group.shef.ac.uk/downloads/.

The Manchester group initially focused on the thermal behaviour of connection elements under different heating regimes, and in the final phase performed structural subframe testing which will enable modelling which includes component-based connection simulation to be validated.

2005-2009 Ying Hu (Project Research Student, funded by EPSRC)

Robustness of steel connections in fire: Flexible endplate joints

Within the EPSRC project on Robustness of Steel Connections in Fire (see above) this sub-project concerned the failure of flexible (partial-depth) endplate joints under combinations of vertical and tying forces.

2005-09 Yuan Yuan Song (Research Student)

Dynamic analysis of structures in fire

The loss of stability of structural elements in a fire can cause dynamic effects, including successive impacts or progressive collapse scenarios such as those which were observed in the September 11 2001 twin towers collapses. Progressive collapse is clearly a subject which is in need of study under hazard loadings of all kinds. Alternatively, unstable behaviour may be capable of regaining stability after either small or large deformations have occurred; an example of this behaviour is the inversion of the roofs of pitched portal frames, which may lead either to collapse or to re-stabilisation depending on the details of the design, the column base conditions and the fire scenario. In order to analyse these situations it is clearly necessary to study structural behaviour dynamically, and in this project the prime objective has been to provide Vulcan with the capability to perform dynamic analysis as well as quasi-static high-deflection, high-temperature modelling. This has been applied to steel portal frames in fire, for which a UK design process based on rather arbitrary assumptions has been in existence for nearly 30 years. The new procedure has been used to develop a new simplified design approach to calculate the final collapse temperatures for portal frames in fire.

2004-2008 Anthony Abu (Research Student, part-funded by Corus Ltd)

Thermal and structural behaviour of concrete slabs at high temperatures

The work on tensile membrane action initiated by Samantha Foster is being taken further in this project, in which the behaviour of heated and loaded slabs will be studied in detail. In particular, the membrane stresses and cracking mechanisms caused by thermal gradients through the slab thickness, acting alone, will be studied before their combination with externally applied loads. If necessary, more model-scale testing can be done to complete the range of validation results.

A detailed comparative study was made between a current simplified analytical/design method for tensile membrane action and modelling of composite slabs using Vulcan. This has
highlighted particularly the structural failure case in which edge beams eventually fold, limiting the range within which tensile membrane action acts as the main load-bearing mechanism.

2005-2009 Shan Shan Huang (Dorothy Hodgkin Research Student, funded by Corus Group and EPSRC)

**The effects of transient strain on the strength of concrete-filled columns in fire**

Pre-compressed concrete has been observed to acquire a large amount of non-recoverable strain when it is heated, a creep-like effect which seems not to occur when heating precedes the application of compressive stress. The objective of this project was to assess how this phenomenon, and concrete creep of other types, affect the buckling resistance of concrete-filled hollow-section columns, as well as slender RC columns, in fire. A fundamental study of the mechanics of buckling of compression members affected by temperature spread and time-dependent straining was carried out, using the classic Shanley model of inelastic buckling as its basis. Both simplified and finite element models of buckling of columns have been developed, and studies of the effects of pre-compression on columns affected by fire heating have shown that transient strain has the capability to reduce buckling loads compared with those predicted by conventional approaches based only on the degradation of ambient-temperature material characteristics due to heating.

2008-11 Vui Yee Bernice Wong (Research Assistant, funded by EPSRC)

**Performance of cellular composite floor beams under fire conditions**

Despite the current popularity of long-span composite flooring systems, the current structural fire engineering design codes EC3/4 Part 1.2 and BS5950 Part 8 do not contain rules or guidance on the fire resistance of composite floors employing cellular steel beams. The purpose of this project was to investigate the performance and failure mechanisms of composite cellular floor beams at elevated temperatures, including the influences of both flexure and shear. Emphasis will also be placed on examining the development and influence of the additional compression forces caused by axial restraint to thermal expansion from adjacent structure when a beam is heated in a fire. The research was coordinated with a programme of physical model fire tests at Ulster University, which provided carefully monitored data. A configurable finite element model was developed to demonstrate the 3-dimensional behaviour of composite cellular beams, which was validated against the tests to ensure that all types of failure modes are predicted. An extensive parametric study was carried out, extending the scope of the research beyond the limits of the parameters used in the experimental work and investigating the influence of CB behaviour on membrane action of floor slabs in compartment fires. The project also developed a design methodology for such members in fire.

2008-12 Mariati Taib (Research Student, funded by Universiti Sains Malaysia)

**The Performance in Fire of Framed Structures with Fin Plate Connections**

The work of Sarraj in developing realistic FE models for fin plate connections in fire, also enabled the creation of a simple component-based model, allowing only horizontal bolt-hole distortions, for a fin plate connection, which was validated against purely rotational furnace tests by Leston-Jones. In order to make such models capable of dealing properly with the combinations of vertical and horizontal forces, together with high rotation, that are experienced by such connections at the ends of beams in real structural fire scenarios, the component-based approach is in need of major development. Although fin plate joints are generally considered as "simple" their behaviour when the steel is highly ductile is actually very complex compared with other types, including distortions at bolt-holes which are in completely different directions. This project has created an integrated component-based element for fin-plate connections which was implemented in the software *Vulcan*, including
the influence of both vertical and horizontal forces at bolt rows, as well as unloading and cooling properties.

2009-12 Shan Shan Huang (Post-doctoral Research Associate, funded by the European Commission under RFCS)

**COMPFIRE: Robustness of connections to composite columns in fire**

This was a European-funded (RFCS) project in which we worked with teams at Manchester, Coimbra, Lulea and Prague, as well as Tata Steel Ltd. It concerned the behaviour and robustness in fire of practical connections between steel or composite beams and two types of composite column - concrete-filled hollow sections and partially-encased H-sections. Tests were carried out at various scales, accompanied by detailed FE modelling, and a component-based approach has been developed. The Sheffield group conducted a total of 20 tests, in a setup similar to that used for steel-to-steel connections by Yu, at ambient and elevated temperatures, on end-plate connections to partially encased H-columns and on reverse-channel connections to both square and circular concrete-filled hollow-section columns. Reverse-channel connections in particular showed a considerable degree of ductility both in rotation and in push-pull, which offers great potential for their use as robust connections in fire conditions. The tests were used mainly to develop connection component models to enable connection interaction to be modelled in whole-structure modelling.

2008-12 Rui Rui Sun (Research Student)

**A dynamic analysis for structural robustness modelling in fire**

This project forms a significant advance on the work done previously by Song in setting up a dynamic formulation to analyse steel portal frames beyond an initial loss of stability. In this case the emphasis was on developing a general capability to model alternately both the static and dynamic behaviour of steel, concrete and composite buildings during both local and global progressive collapse caused by fire attack. The analysis is intended to follow the structural behaviour from static response through local failure of components. At each stage when an instability is caused by a local fracture the subsequent dynamic behaviour is modelled using an explicit scheme until re-stabilization occurs. This kind of model is necessary in order to determine whether progressive collapse ensues or a re-stabilised state occurs, and will thus allow fire engineering designs to be assessed for robustness. It has been used already with a component-based connection model to track a sequence of local failures leading to a final collapse.

2009-14 Yuan Tian (Research student, funded by Tata Steel Ltd)

**Tensile membrane action in non-rectangular composite slab panels**

The Bailey-BRE design method for composite rectangular slab panels in fire presents a simplified model of tensile membrane action (TMA), the strength enhancements it gives as a function of displacement, and integrity failure by tensile fracture of the slab at a limiting deflection. This project aims to investigate TMA in non-rectangular slab panels, which could directly allow the simplified method to be extended to such slabs, so that performance-based fire engineering design can be used for buildings with irregular column grids. The first task in the project was to implement general boundary conditions linking degrees of freedom of the system. This has been implemented in **Vulcan**, and now allows numerical analysis of panels with local rather than global boundary conditions, which may be necessary either because internal panels need to be subject to credible continuity conditions, or because slabs have non-orthogonal overall shapes. A complete simplified tensile membrane action method is given for triangular slabs at high deflections, and initial work has been done in developing a similar method for trapezoidal slab panels.
2009-16
Gang Dong (Research Assistant/research student, funded part-time by the European Commission under RFCS)

**COMPFIRE: Robustness of connections to composite columns in fire**

This project addresses one of the work packages of COMPFIRE, which is based on the creation of a general-purpose component-based representation of the connections to composite columns, partly using component characteristics which have been developed in previous projects (see Spyrou, Block, Yu, Hu), but also developing new components for the reverse-channel connection type. The objective has been to represent the column-face "connection" zone with an element which has two external nodes but can contain internally any number of rows of components with temperature-dependent properties including both force-reversal and failure. The principles developed are applicable to different connection types and to implementation in different software packages. Within COMPFIRE the component-based element has been informed by tests and detailed FE analysis, which have aided both its development and its validation. When implemented in the static-dynamic development (Sun) of Vulcan, this component-based element has been able to model the progressive collapse process due to the sequential fracture of bolt rows of connections as temperatures increase.

2009-13
Lucy Bull (née Johnson) (Research student, jointly supervised with Engineering Materials, funded through the CDT in Advanced Metallic Systems)

**Microstructural characterisation and performance of steels used in structural bolting assemblies in fire**

Bolted connections are key components which tie structural members together. When a steel structure is subjected to elevated temperatures during a fire the forces applied by highly deflected beam members must be transferred to adjacent cold members through the connection to avoid collapse. During a fire connections are subjected to both compressive and tensile axial forces due to thermal expansion and subsequent contraction of beam members during cooling. Connections are thus subjected to a complex combination of rotation, extension and shear bending and shear. These complex loading conditions, coupled with an insufficient understanding of the mechanical properties of bolts at elevated temperatures means that bolting assemblies can often be the weak link in structural frames in fire. Bolt failure in fire generally occurs as ductile necking in the bolt thread, thread stripping in the nut and bolt or shear failure through the bolt thread or shank. At ambient temperature, bolt failure is designed out; other more ductile modes of failure are designed to be critical, thus ensuring adequate ductility. Recent research has demonstrated that this is not the case in fire situations when the bolt becomes critical. In this project the performance in fire conditions of nuts and bolts will be investigated by looking at the effects of manufacturing processes on their microstructure and thus on the way this affects performance under normal and elevated-temperature conditions.

2011-16
Mohammadali (Danyal) Javaheriafif (Research student)

**Development of a composite slab break-element for the analysis of composite frames in fire**

Large deflections of composite slabs contribute significantly to the robustness of composite steel-framed buildings in fire. Finite element analysis of steel frames in fire often assumes the slab to be continuous, and the inevitable cracking which takes place is accounted for using the smeared cracking approach. At a beam-to-column connection the presence of the slab increases the stiffness and strength of the joint, but existing analysis techniques do not adequately address the effect of fracture of rebar at a discrete crack at this location. In order to investigate the influence of the concrete slab on the joint performance, a method to allow for the development of discrete cracks in the concrete slab, as a result of the hogging bending moment over supporting steel beams and connections, has been developed. In order to avoid
the complexities of generalized discrete cracking analysis, fracture at key locations is represented by the use of “break-elements”. Mathematical equations have been derived, and a simplified mechanical model proposed, to represent the fracture and post-fracture behaviour, of a slab in tension. The model results in a localisation of the yield and ultimate strains in the rebar, enabling the crack width at which it fractures to be represented in terms of the local bond characteristics beyond the crack faces.

Guan Quan (Research student, funded by EPSRC & China Scholarship Council)

Shear buckling in the vicinity of beam-column connections in fire

The Cardington composite frame fire tests indicated that shear buckling of beams, as well as beam bottom flange buckling, in the vicinity of the beam-column joints, is very prevalent under fire conditions. These phenomena can have significant effects on both the force redistribution between the bolt rows at the face of the column and beam deflections at high temperatures.

This research investigated the local buckling behaviour in the vicinity of beam-column joints at elevated temperature. The behaviour studied included shear buckling of the beam, local buckling of the bottom flange of the beam and shear buckling of the column. Theoretical models were created for the three buckling zones at elevated temperature. On this basis, three corresponding component-based models were created and implemented in the software Vulcan, and their influences on the behaviour of the whole structure, and particularly on its progressive collapse in fire, were studied. In general the influences of shear and local buckling were not found to be detrimental to the survival of the connection zone under fire conditions.
Development of a kinematically consistent approach to analysis of tensile membrane action of composite floor slabs in fire

It is widely recognized that composite floor slabs experiencing large displacement develop a central zone of hydrostatic membrane tension, surrounded and equilibrated by a ring of membrane compression around the periphery. This mechanism, known as tensile membrane action, can greatly enhance the load-bearing capacity of a slab compared with that defined by yield line analysis. This is a very useful effect in cases where large deflections can be accepted, particularly in fire-resistance design of composite slabs, since the strength enhancement permits some beams to be left unprotected. Studies of TMA in the 1960s led to the development of several methods to define slab load capacity under large displacement. The method due to Hayes has become the most widely accepted, and was adopted in developing the BRE method for fire-safe design of composite floors. Based on observations from the Cardington fire tests and on assumptions concerning yield line patterns and membrane stresses, it calculates the load-carrying enhancement of a slab as a function of its deflection. It also postulates a deflection limit at which the maximum acceptable strain in the rebar is reached. On close examination, however, several hypotheses, such as the assumed failure mechanisms, seem illogical.

A new simplified method, which re-examines the mechanics of tensile membrane action in weakly reinforced thin slabs at high deflections, based on the principles of large-deflection plastic yield-line analysis, has been launched at Sheffield in the past few years. The initial applications of this approach have addressed plain flat slabs, both isolated and continuous. Starting with the optimal yield-line pattern, the method relates a slab’s load capacity to its deflection, allowing for the effects of change of shape of the concrete stress blocks and progressive fracture of the reinforcing mesh. These have been compared with the existing procedure, showing very different behaviour in many cases. The application of tensile membrane action in structural fire engineering is usually for slabs designed as arrays of parallel composite beams, with wide concrete upper flanges connected to downstand steel beam sections by shear studs. The strength of the steel reduces with temperature, and since the applied load intensity is constant the analysis now needs to calculate the steel temperatures at which a yield-line mechanism is created and at which the panel loses stability. The new method has been extended to analyse composite slabs with unprotected steel beams at high temperatures. It monitors small-deflection yield-line patterns, of which the optimum continuously changes as the strength of the steel sections degrades. When the optimal mechanism’s load capacity degrades to the applied load the mechanism for large-deflection enhancement is established. Tensile membrane action can then allow further growth in steel temperature until a maximum is reached. Since integrity failure is also important in fire-resistant design, it is notable that the method provides the internal forces needed to calculate the maximum mean tensile stress in the concrete cross-section. In this project the new kinematically consistent method will be developed to take into account the different mechanisms through which a rectangular composite slab can fail and its different modes of failure. It needs to predict where the reinforcement fractures, and at which temperatures and deflections. The intended outcome is to develop a mechanically justifiable design procedure for performance-based fire-resistant design of composite slab panels.

Ductile Connections to Improve Structural Robustness in Fire

Connection failures observed in the collapse of the World Trade Centre and some of the Cardington full-scale fire tests have indicated that connections are more vulnerable in fire conditions than conventional assumptions in prescriptive codes indicate. To maintain structural integrity and prevent progressive collapse, connections are particularly important.
as the key components tying structural members together. However, current commonly-used connection types lack the axial ductility required to accommodate compressive deformation due to thermal expansion of long-span beams in the early stages of a fire, leading to large compressive forces being applied to surrounding structural members. They are also incapable of allowing tensile deformation of beam-ends at high temperatures, in order to reduce the catenary forces in beams to levels that can be resisted.

In order to improve the performance of connections, and therefore to enhance the robustness of entire structures against fire, a novel ductile connection is proposed. This novel connection consists of two identical parts, each of which can be manufactured by deforming a steel plate, and takes the form of a fin-plate which is bolted to the beam web, an end-plate which is bolted to either the column web or flange, with a semi-cylindrical section between the fin-plate and end-plate. The function of the semi-cylindrical section is the key to providing the additional axial push-pull ductility which is necessary in fire, by allowing the fin-plate to move towards and away from the end-plate. Analytical models of this ductile connection, based on plastic theory, have been developed and tested against Abaqus simulations and experiments, and the component-based model of the novel connection, which will be implemented into the fire engineering software Vulcan, has also been proposed.
Group Publications to Date

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Internal Research Reports


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Internal Research Reports


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**Internal Research Reports**


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2003


2004


2005


2006


Internal Research Reports


2007


2009


2010


2011


2012


2014

257. Quan, G., Huang, S.-S. and Burgess, I.W., 'Shear panel component in the vicinity of beam-column connections in fire', Structures in Fire conference, Shanghai, 2014.


2015


2016


2017


2018


2019


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