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, and we intend to extend this capability for properly monitored furnace testing at Sheffield.

The work has always involved complete cooperation between the Architecture and Civil Engineering departments. Although most of the research workers involved have been located in the Department of Civil and Structural Engineering, the group is completely integrated within the two departments.

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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 will be made commercially available to specialist designers as an analytical tool for performance-based fire engineering design of structures. A university spin-off company, Vulcan Solutions Ltd, has been 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.
Current Work and the Research Workers

2003- Florian Block (Research Student, funded by Buro Happold FEDRA)

**Component modelling of end-plate beam-column connections**

This project follows 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 aims to fill in important gaps in the list of components which have already been modelled, so that connections in full structural assemblies can 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 is currently being studied. The ultimate aim is to assemble the major component characteristics into non-linear degrading connection elements within numerical analysis software.

2003- Chaoming Yu (Research Student)

**Fire resistance of bi-steel core-walls**

This project aims to investigate 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 have been studied. In order to investigate the structural behaviour of the bi-steel cross-section under load and temperature distributions, a 3-dimensional brick element has been formulated for Vulcan and this is currently being implemented in the program code.

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

**Performance of fin-plate beam-column connections in fire**

This project is investigating the robustness of fin-plate joints in fire, under catenary tension together with high rotations. The investigation is being performed by modelling using ABAQUS to produce very detailed finite element representations. These are very complex models using contact elements at the bolt/hole interface, and considerable problems with these have been solved in progressing to the current stage where a complete connection can be modelled to very high distortions at ambient temperature. The high temperature behaviour will be investigated next, and it is hoped to use this in comparison with simple and component-based approaches.

2004- Tony Abu (Research Student, part-funded by Corus Ltd and ORS award)

**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.

2005- Xinmeng Yu (Research Student)

**Development of a ribbed-slab element for structural fire modelling**

Slabs are being seen to perform a key role in enabling the survival of composite buildings in fire, and their use is forming the basis of performance-based structural fire engineering design strategies for such buildings. The existing treatments of ribbed slabs in Vulcan tend to neglect the temperature variations between the ribs and troughs. In this project a simplified thermal
model is first being developed for these areas, and this will be followed by the development of a slab element which reflects these temperature variations, as well as the changes of slab depth. This will be followed by studies which investigate the sensitivity of slab behaviour, especially when the slab is using tensile membrane action as the main part of its load-carrying function.

2005-

Yuan Yuan Song (Research Student)

**Dynamic analysis of structures in fire**

The failure of structural components, such as connections, in a fire can cause dynamic effects, including successive impacts and 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. For such analysis it will clearly be necessary to study structural behaviour dynamically, and in this project the prime objective is to provide Vulcan with the capability to perform dynamic analysis as well as high-deflection, high-temperature modelling.

2005-

Dr Hong Xia 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 proigressive collapse, as is already recognised in UK structural design codes for other limit states. The robustness in fire conditions of end-plate connections will be investigated in this project, in which we are collaborating with researchers at the University of Manchester. At both centres the investigation will involve a mixture of experimental and analytical work. In the initial phase at Sheffield we will be concentrating on high-temperature structural behaviour of components and assemblies under combinations of tying and shearing forces, while the Manchester group will focus on the thermal behaviour under different heating regimes.

The project started in October 2005, and will run until 2008.

2005-

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 is to assess how this phenomenon, and concrete creep of other types, affect the buckling resistance of concrete-filled hollow-section columns in fire. This will initially involve a fundamental study of the mechanics of buckling of compression members affected by temperature spread and time-dependent straining.

The project started in October 2005, and will run until 2008.
Group Publications to Date

1988

1989

1990

1991

1992

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Internal Research Report


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1995


1996


Internal Research Reports


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2006


**Internal Research Reports**


**2007**


**Accepted for Publication**


