1.1 Background to the project

Fire safety engineers are concerned first and foremost with life safety not only of
the occupants of a building but also the fire service. The aim of structural fire engineering design is to ensure that structures do not collapse when subjected to high temperatures in fire. Traditional prescriptive methods of design based on fire resistance testing, require steel elements of construction to stay below a critical temperature, typically 550°C, for the fire resistance period of the structure. This has led to extensive use of passive fire protection to limit the heating of the structural elements (boards, sprays and intumescents) at considerable cost (up to 20% of the total construction cost).

It has been acknowledged for many years that the failure of determinate structures in the fire resistance furnace bears little resemblance to the failure of similar elements as part of a highly redundant frame. However the fire resistance test has a history of safety albeit not based on scientific reasoning.

Design of structures for fire still relies on single element behaviour in the fire resistance test. The future of structural fire design has to be evaluated in terms of the whole performance based design of structures for fire. This should include natural fire exposures, heat transfer calculations and whole frame structural behaviour, recognising the interaction of all elements of the structure in the region of the fire and any cooler elements outside the boundary of the compartment.

The beginnings of change started after evidence from real fires suggested that the contributions of modern steel deck composite floor systems were under utilised when designing for the fire limit state.

On the 23rd June 1990 a fire developed in the partly completed fourteen storey building in the Broadgate development. [115] The fire began in a large contractors hut on the first floor and smoke spread undetected throughout the building. The fire detection and sprinkler system were not yet operational out of working hours.

The fire lasted 4.5 hours including 2 hours where the fire exceeded 1000°C. The direct fire loss was in excess of £25 million however, only a fraction of the cost (£2 million) represented structural frame and floor damage. The major damage was to the building fabric as a result of smoke. Moreover, the structural repairs after the fire took only 30 days. The structure of the building was a steel frame with composite steel deck concrete floors and was only partially protected at this stage of construction. During and after the fire, despite large deflections in the elements exposed to fire, the structure behaved well and there was no collapse of any of the columns, beams or floors. [115] The Broadgate phase 8 fire was the
first opportunity to examine the influence of fire on the structural behaviour of a modern fast track steel framed building with composite construction.

Prompted by the evidence from Broadgate, Building Research Establishment (BRE) built an 8-storey composite steel and lightweight concrete frame at their large scale test facility at Cardington. The frame was subjected to six full-scale fire tests (2 by BRE and 4 by British Steel (now CORUS)) enabling the behaviour of the structure during fire to be observed and recorded. The outputs from these tests were introduced to the public domain. Edinburgh University in collaboration with British Steel and Imperial College carried out a research project (funded by the Department of Environment, Transport and Regions "Partners in Technology" scheme) to model the structural behaviour of the 4 British Steel tests using finite element codes. One aim of the research programme was to develop numerical models capable of predicting the structural behaviour of a modern, multi-storey composite steel frame building during a real compartment fire. The most important outcome however was the explanation and understanding of the structural behaviour in response to fire.

The computer package ABAQUS [101] was used by Edinburgh University and British Steel to develop numerical models of the four tests. ABAQUS is a powerful commercial code capable of modelling the geometric and material nonlinear behaviour of a structure during fire. The models have captured the global structural behaviour and agree with measured data from the tests. The results and understanding gained through the models have highlighted complex behaviour.

1.2 Aims of this research

This PhD project has evolved as a direct result of the modelling of the Cardington frame fire tests. Both the test data and the modelling provided a wealth of new information about whole frame structural behaviour in fire. However the tests were carried out on one building. As a result of the Cardington frame tests and theoretical work by Bailey [23] SCI (Steel Construction Institute) have produced a simple conservative design guide in the form of look-up tables for composite frame structures in fire. The tables are applicable to common buildings. This level one design guide is as a major step forward for structural fire engineering in the UK. However, for detailed design guidance to be produced different buildings of various sizes and configurations should be investigated under contrasting fire scenarios. The primary aim of this project was to use the modelling approach developed and checked against real test data to create generic composite steel frames and fire scenarios. Parametric studies and
sensitivity analyses were conducted on the generic frames. "What-if," scenarios considered included, what-if,

- there is a fire in a corner or edge compartment or over a whole floor level?
- only the columns are protected?
- the fire severity changes?

The key parameters investigated were the temperature distributions in the structural elements for various compartment fires and the restraint provided by the edge beams (protected or unprotected) or the surrounding cooler structure to the fire compartment. A clear understanding of compartment fire dynamics and heat transfer was necessary to create design fires and compute the heat transfer to the structural elements. Thus a detailed review of the tools available to fire engineers to calculate compartment fire exposures and heat transfer was conducted.

Output from these analyses adds to the information collected as a result of modelling the Cardington frame tests and will help the development of performance based design guidance for fire.

1.3 Outline of thesis chapters

Chapter 2. An overview of structural fire safety design and research.

Traditional and performance based design methods and the history of this field of research will be outlined. Research into the behaviour of single elements of construction in fire and studies of steel frames before the Cardington frame tests will be presented. A summary of the factors affecting structures in fire, for instance degradation of mechanical properties and restraint conditions, will also be given.

Chapter 3. Thermal response of structures to real fires.

Prescriptive fire gradings and design methods based on heating single elements in the fire resistance test over-simplify the whole fire design process. The real problem can be addressed by performance based design methods where possible fire scenarios are investigated and fire temperatures are calculated based on the compartment size, shape, ventilation, assumed fire load and thermal properties of the compartment boundaries. The temperatures achieved by the connected structure can then be determined by heat transfer analysis. This chapter describes and tests some of the methods available to engineers and designers to predict fire temperatures and heat transfer to the structure.
Chapter 4. Whole frame composite steel structures in fire: Research and design developments.

This chapter will review recent experimental work and numerical modelling of whole frame composite steel structures in fire. Design methods developed as a direct result of this research will also be discussed.

Chapter 5. Heat transfer analysis of the Cardington frame fire tests using HADAPT.

This chapter describes heat transfer analysis of the Cardington frame tests. Using the finite element code HADAPT the temperatures achieved by the composite slab and the edge beams were predicted. The results of these analyses are given and discussed. This work was carried out for two reasons. One to supplement the existing Cardington frame data and two to have a reliable method of modelling heat transfer to structural elements for any compartment fire scenario.

Chapter 6. Analytical and numerical analysis of simple beam models in fire.

This chapter describes analytical and numerical analyses on a simple beam to aid our understanding of the behaviour of structures in fire. Thermal bowing and thermal expansion effects were analysed on a simple beam, first individually and then combined. The effect of the beam end restraint conditions were also studied to explain why runaway occurs much earlier in axially unrestrained beams, as tested in the fire resistance test, when compared with axially restrained beams, typical of beams in real structures.

Chapter 7. Structural behaviour in British Steel Test 1 under different heating regimes.

Following the simple studies and understanding of thermal bowing and thermal expansion effects in Chapter 6. A parametric study was conducted on an ABAQUS grillage model of British Steel Test 1 (restrained beam test) to understand the effects on the structure, of systematically changing the temperature regime in the slab. The parametric study and the results are outlined in this chapter.

Chapter 8. Parametric studies on a small generic composite steel frame.

Two generic composite steel frames, different in plan and size from Cardington,
were designed in accordance with Eurocode 4 Part 1.1 [77]. This chapter describes the structural response of a small frame (2x2 bays in plan) to whole floor compartment fires with different ventilation characteristics. Changing the available ventilation and fuel in a compartment leads to fires of short or prolonged post-flashover duration and different thermal responses in the steel and concrete.

The Cardington frame survived several fire tests where all the steel beams were unprotected. The structural behaviour of the small generic frame to three fire protection configurations, 1) the edge and primary beams were protected, 2) only the edge beams were protected and 3) all beams were left unprotected, is also described. In each case the columns were always protected to their full height.

Chapter 9. Parametric studies on a large generic composite steel frame

This chapter describes results from a series of parametric studies on a 9x9 bay generic composite frame. Compartment fire scenarios in the corner and on the side of the building were analysed. The locations provided different boundary restraint conditions to the expanding compartment floor and different deflection and force patterns in the beams and slab. The effect of protecting the edge beams on the structural behaviour of the large frame is also described.

Chapter 10. Conclusions and Further work

Chapter 4.

4.1 Introduction

Since the Broadgate phase 8 fire in the late 8Os and the realisation that composite steel deck floor systems are under utilised when designing for the fire limit state, research into the behaviour of whole frame, composite steel structures in fire has increased considerably. The most notable work in the UK are the Cardington frame fire tests on an 8-storey composite steel frame. Researchers in the UK and Europe have studied and simulated these tests numerically. [20] [108] [187] Subsequently, new design guidance for composite steel structures in fire has been developed. SCI have produced a design guide [70] based on a theoretical analysis by Bailey. [23] New Zealand have also produced a draft design guide [54] based on the Cardington Frame fire tests and work by Wang. [252] The most recent developments in this field will be reviewed in this chapter.

4.2 Case studies
4.2.1 Broadgate Phase 8

The Broadgate fire was introduced in Chapter 1 of this thesis. Structural damage caused by the fire included distortion of a number of trusses and universal beams and axial shortening of five columns by 100mm. The deflection of the trusses produced dishing of the floor of up to 600mm relative to the columns. The concrete floor slab separated from its metal decking in some areas but generally followed the level of its deflected supporting members. Despite large deflections, the structure behaved well and there was no collapse of any of the columns, beams or floors. [115]

The behaviour of the structure and the floor members showed that a steel frame designed to BS 5950 Part 8 is structurally safe when exposed to a severe fire. The study [115] carried out after the Broadgate fire showed that when fire affects only part of a structure (compartmentation) and when the framework acts as a total entity structural stability is improved.

Detailed studies of the material properties at high temperatures were carried out and it was concluded that apart from the concrete to the first floor no material showed significant loss of strength due to the fire. Detailed metallurgical investigations were carried out to assess the temperatures reached by the quenched and tempered bolts recovered from several of the beam to column connections in the areas of the fire which showed most damage. These indicated that the most severe temperatures achieved by the bolts during the fire or during manufacture were limited to 540°C. Similar evidence from a truss indicated that the member had been heated to around 600°C. The principles of BS5950 Part 8 would suggest that these members would transfer load to cooler parts of the structure until temperatures of about 700–800°C but the investigations suggest that the temperatures achieved did not exceed 600°C so an alternative explanation for the deformations observed was needed.

4.2.2 Churchill Plaza building, Basingstoke

In 1991 a fire took hold in the Mercantile Credit Insurance building in Basingstoke. [197] The twelve storey high building was constructed in 1988 and was of composite steel and concrete construction. The columns and the composite floor beams had applied fire protection but the soffit of the floor slab was unprotected. The fire rating of the building was 90 minutes.

The fire started on the 8th floor and spread to the tenth floor as external glazing
failed. The protection materials performed well and there was no permanent
deformation of the steel frame or damage to the protected connections. Similar to
Broadgate the metal deck showed signs of debonding from the concrete floor slab
probably due to the steam from the concrete. Load tests on the most damaged
parts of the slab showed it had adequate strength to be used unrepaired. No
structural repair was required on the protected steel. The cost of repair to the
building was £5 million but most of this was repairing smoke damage.

4.3 Fire tests

4.3.1 BHP William Street fire tests, Melbourne [197]

Built in 1971 in the centre of Melbourne, 140 William street at 41 storeys high
was the tallest building in Australia. This building is also of composite
construction similar to Broadgate and Mercantile centre, with a square plan and
central square inner core. The steelwork around the inner core and the external
columns were protected with concrete whereas the beams and the soffit of the
composite steel deck floors were protected with asbestos based material. In 1990
during a refurbishment programme the decision was made to remove the
hazardous asbestos material. Prior to the refurbishment the fire resistance rating
of the building was 120 minutes. To maintain this level after refurbishment the
regulations at the time required fire protection to the steel beams and the soffit of the
lightly reinforced concrete slab. The light hazard sprinkler system would also
have had to be upgraded. In the 1990s the fire resistance of buildings was a
matter for debate in Australia and the refurbishment of the William street
building provided an opportunity to determine whether these measures were
really necessary.

Two risk assessments were conducted. The second was the most interesting. It
assumed no protection to the beams or the soffit of the slab and use of the
existing sprinkler system.

A series of four fire tests were carried out on a purpose built test building at BHP
Research Melbourne Laboratories. The test simulated a 12m x 12m corner bay of
the real building and was furnished to resemble a typical office with a 4m x 4m
small office constructed near the perimeter of the building. Water tanks provided
the imposed loading. The first two tests were concerned with testing the
performance of the existing light hazard sprinkler system. Test 3 was designed to
test the composite slab. The soffit of the slab was left unprotected although a
non-fire-rated suspended ceiling was in place. The supporting beams were
partially protected. The fire was started in the open plan area and allowed to
develop fully. A maximum atmosphere temperature of 1254°C was achieved. The ceiling remained intact during the tests and was beneficial in protecting the slab. In test 4 the ability of the steel beams to withstand a fire without protection was assessed. The fire was started in the small office but unfortunately did not spread to the rest of the compartment and another fire was set in the open plan area. The atmosphere temperature reached 1228°C whilst the steel beams reached temperatures of 632°C. Deflections of 120mm were recorded in one of the beams during the test. The steel beams and slab were shielded by the ceiling resulting in relatively low steel temperatures and small deflections in comparison with Broadgate. The results of the various fire tests concluded that the William street building did not need fire protection on the beams or the underside of the slab and the existing sprinkler system was adequate.

4.3.2 Stuttgart-Vaihingen University fire tests, Germany

In 1985 a fire test was undertaken on a four storey steel-framed demonstration building at the Stuttgart-Vaihingen University in Germany. [197] The building was a test building and as such was constructed from many different types of composite elements including various types of composite floors. The main fire test was conducted on the third floor in a compartment covering approximately one third of the building. The fire load was provided by wooden cribs. The atmosphere temperature exceeded 1000°C whilst the steel temperatures reached 650°C. Investigation of the beams after the test showed spalling of the infilled webs but the behaviour of the beams was very good with no significant permanent deformations after the fire. The composite floor reached deflections of 60mm and retained its integrity.
Figure 4.1: Plan view of the Cardington 8-storey frame showing the 4 British Steel Tests

4.3.3 Cardington frame fire tests

The Broadgate fire provided the greatest insight into the ability of composite structures to resist fire. In all the other case studies and tests there was some form of protection to the steel. In the Chuchill Plaza building the steel frame was completely protected. The tests in Australia provided protection to the slab and beams with an unrated suspended ceiling and in Germany all the steel sections were protected by heat sinks of concrete. The tests at Cardington were much closer to the Broadgate scenario thus fully testing the capacity of the frame.

Over a period of September 1995-June 1996 British Steel (now CORUS) conducted 4 fire tests on the 8-storey composite steel frame structure at BRE’s (Building Research Establishment) large scale test facility at Cardington. BRE carried out two further complementary tests around the same period. Figures 4.1 and 4.2 show the 4 tests conducted by CORUS and the two further tests carried out by BRE respectively. [127] [197]

4.3.3.1 Physical aspects of the tests

4.3.3.1.1 British Steel Test 1: Restrained Beam.

Test 1 illustrated in Figure 4.1 was carried out on the 7th floor of the 8-storey frame and involved a single 305 x 165mm beam and the surrounding concrete floor spanning 9m between a pair of 254 x 254mm columns. The beam was surrounded by a gas fired furnace but the columns and connections were left outside. The furnace was 8m long x 3m wide x 2m high; insulated with mineral wool and ceramic fibre. During the test the beam was heated at between 3-10°C/min until temperatures of 800-900°C were achieved. [37] [128] The test beam and surrounding structure were extensively instrumented to measure temperatures, strains, deflections and rotations. The temperatures in the steel beam were recorded at many points along its length and through the depth. The temperatures through the slabs depth were only recorded at four points on plan (at two points between the beam and furnace wall and two locations over the tested joist). Maximum deflections of 232mm were recorded at 887°C. [6] [197]
Figure 4.2: Plan view of the Cardington 8-storey frame showing the 2 BRE Tests

The aftermath of the test is shown in Figure 4.3. Local buckles in the flange near the connections and folds in the web can be observed. The local buckles are caused by a combination of the high compressions in the highly restrained expanding hot beam and the additional compressions as a result of the high gradient in the composite. The gradient causes a hogging moment, thus increased compressions in the lower part of the beam. The folds in the web may have occurred during cooling. On cooling the beam tries to retract into its original shape. However not all of the deflected shape can be recovered because of plastic straining thus the beam is effectively shorter. Tension folds probably develop in the web as the beam is pulled back into position. This phenomena can be seen in all the British Steel tests. In most cases some bolts or part of the plates forming the connections have failed releasing the tension forces developed during cooling (Figure 4.5).
4.3.3.1.2 British Steel Test 2: Plane frame.

The second test involved heating a series of beams and columns across the full 21m width of the building on the fourth floor using a gas furnace. A furnace 21m long x 3m wide x 4m high was constructed using 190mm lightweight concrete blockwork. It was lined with 50mm thick ceramic fibre blanket to reduce heat losses. Natural gas was supplied to eight industrial burners installed along one side of the furnace. Maximum atmosphere temperatures of 7500°C were achieved. The primary and secondary beams were unprotected. The top 800mm of the columns including the connections were also unprotected. The supporting columns were squashed by 180mm (pictured in Figure 4.4) at unprotected column temperatures of 670°C. As a direct result of this squashing all further tests had protected columns to the underside of the slab. [37] [127] [128] [197]
Figure 4.4: Column squashing in British Steel Test 2: Plane frame test

Figure 4.5: Connection failure in British Steel Test 2: Plane frame test
4.3.3.1.3 British Steel Test 3: Corner fire.

Test 3 was carried out in the South East corner of the 8-storey frame on the first floor in a compartment 10m x 7.5m x 4.0m high. The fire load comprised wood cribs giving a total fire load density of 45kg/m$^2$. The fire was designed using the parametric Equations in EC1 Part 2.2 to achieve atmosphere temperatures greater than 1000°C. The edge beams and columns were protected in this test. [6] [37] [127] [128] The greatest steel temperature (935°C) and deflection (428mm) were recorded in beam EF between gridlines 1 and 2 (See Figure 4.1). The deflection recovered to 296mm after cooling. [197] Protected steel members were placed in the compartment in order to compare protected steel temperatures measured in the test with the time to achieve these temperatures in a standard ISO 834 test. The equivalent time in the fire resistance test was 86 minutes. [197]
4.3.3.1.4 British Steel Test 4: Office Demonstration.

The office fire demonstration was the largest British Steel compartment fire test incorporating a floor space 18m wide and up to 10m deep (135m²). It was conducted on the first floor in the North East corner and simulated a typical open plan office with real office equipment (and some wood cribs) providing a total fire load density of 46kg/m². The area of ventilation was equal to 20% of the floor area. [197] The height of the compartment was 4.0m. In this test only the columns were protected. The unprotected beams achieved temperatures of up to 1150°C. Maximum deflections reached 640mm. Figure 4.7 is a picture of the test in progress. Figures 4.8 and 4.9 show the structure after the fire. As in other tests the flanges of the beams experienced extensive buckling and there were signs tensions developed during cooling (Figure 4.9). The equivalent time of fire exposure in the standard test was shorter than test 3, 74 minutes. No concrete temperatures were measured during this test, hindering accurate numerical modelling of the structural behaviour.
Figure 4.8: Aftermath of the British Steel Test 4: Office demonstration test.
The BRE corner test was conducted on the 2nd floor over an area 54m$^2$. The internal compartment boundaries were steel stud fire resistant board partitions (120 minutes fire resistance with a displacement head of 15mm). All structural steelwork excluding the columns were left unprotected. Twelve timber cribs provided 40kg/m$^2$ fire load. At the start of the test all windows and doors were closed, the fires development was strongly influenced by the lack of oxygen. Atmosphere temperatures of 1051°C were recorded after 102 minutes but in the initial stages the fire died down very quickly and smoldered until after 55 minutes. The fire brigade intervened twice breaking windows to feed the fire with oxygen. The temperature-time history of the fire atmosphere is shown in Figure 4.11 The bottom flange of the central secondary beam achieved a maximum temperature of 903°C after 114 minutes. The max recorded slab deflection (269mm) occurred after 130mins recovering to 160mm after cooling. Unlike the British Steel corner test the compartment walls were directly below the axis of the beams on column lines thus the edge beams experienced high gradients across the width of the cross-section. One of the edge beams
distortionally buckled over its length as a result of these gradients and restraint to thermal expansion. Unlike all the other Cardington frame fire tests there was no local buckling of the beams and no evidence of cooling in the form of failed connections or folds in the web. [197]

4.3.3.1.6 BRE Test 2: Large Compartment.

The large compartment test was constructed on the second floor extending over the full width of the building, between gridline A and 0.5m from gridline C see Figure 4.2. The total floor area of the compartment was 340m$^2$. 40kg/m$^2$ fire load was placed in the form of 42 wooden cribs. The compartment was formed by constructing a fire resistant stud partition wall across the width of the building and around the vertical access shafts. Double-glazing was installed on two sides of the building along gridlines 1 and 4. The middle third of the glazing was left open on both sides to allow sufficient ventilation for the fire to develop. All steel beams including the edge beams were left unprotected but the columns were protected.

Rapid ignition resulted in the windows breaking during the early part of the test but the maximum temperature achieved was fairly low at 763°C. The steel reached a maximum temperature of 691°C and a maximum displacement of 557mm was recorded halfway between gridlines 2 to 3 and B to C. The residual displacement after the structure had cooled was 481mm. Overall the structure behaved very well and there were no signs of collapse. Most internal beams showed evidence of local buckling in the lower flange and the web near the connections. In some of the partial depth end plates the plate had fractured down one side and in one instance the web had fractured. The deflection of the slab caused integrity failure of the compartment wall because it was greater than the 15mm allowance.

4.3.3.1.7 Atmosphere temperatures.

The atmosphere temperatures recorded in all six tests are illustrated in Figures 4.10-4.12 for comparison. British Steel test 1 and 2 have very similar heating rates. British Steel test 4 was the shortest duration fire. The BRE corner test achieved the highest temperatures but for a very short time while the BRE large compartment barely reached an average of 700°C during the most intense phase of the fire.
Figure 4.10: Average atmosphere temperatures recorded in the British Steel tests.

Figure 4.11: Average atmosphere temperatures recorded in the BRE corner test. [197]
Figure 4.12: Average atmosphere temperatures recorded in the BRE large compartment test (1/2 floor). [197]

4.4 The PIT Project

In 1995 Edinburgh University in collaboration with CORUS and Imperial College proposed a project to model the 4 British Steel fire tests on the Cardington frame. It was funded by the DETR "Partners in Technology" scheme. The title of the project was

"The behaviour of steel framed structures under fire conditions" and the main objective was described as, "To understand and exploit the results of the large scale fire tests at Cardington so that rational design can be developed for composite steel frameworks at the fire limit state [187]"

The PIT project started in March 1996 running for four years ending in March 2000. Although the main research team consisted of Edinburgh University, CORUS and Imperial College, BRE and SCI also provided valuable input. SCI was primarily responsible for the design output from the project. Sheffield University were part of the steering committee.
Figure 4.13: Steel material behaviour in Eurocode 3 Part 1.276

The numerical models of the tests ranged in complexity from very simple grillage models to detailed shell representations of the beams and slab. The University of Edinburgh and CORUS used the commercial code ABAQUS whilst Imperial College made use of their in-house finite element code ADAPTIC. The output from all the models were comparable and agreed with the measured test data. Conclusions of the project were,

- The Cardington composite steel framed building exhibited very stable behaviour under the various fire scenarios tested because of the nature of its highly redundant structural form.
- The thermo-mechanical phenomena observed (a combination of restrained thermal expansion and thermal bowing) defines the structural behaviour and depends upon the frame layout and the thermal regime of the fire compartment

4.4.1 The numerical models

Rigorous finite element models were developed by all of the three main contributors. The ability to reliably model material and geometrical non-linearities was a key factor in choosing the finite element codes. ABAQUS is a commercially available well accepted package tested rigorously by multiple users modelling a variety of problems. ADAPTIC has been developed over many years
and is also a very reliable research code. All models were thoroughly checked against real test data. The results from corresponding models showed the same structural behaviour reinforcing the individual models results.

4.4.1.1 Material models

The stress-strain material definitions in EC2 Part 1.2 and EC3 Part 1.2 were assumed for concrete and steel respectively. The steel material model is elasto-plastic and includes enhancement from strain hardening above 400°C. The steel model may be conservative as was discussed in Chapter 2. Both sets of properties include degradation with increasing temperature and are illustrated in Figures 4.13 and 4.14.

![Stress-strain material behaviour in Eurocode 2 Part 1.2](image)

**Figure 4.14:** Compressive concrete material behaviour in Eurocode 2 Part 1.2 [75]

4.4.1.2 The University of Edinburgh Numerical Models

The University of Edinburgh modelled British Steel test 1 and test 3 using ABAQUS. Both grillage [223] and shell models were developed. [87]
Integration techniques are normally used to model materially non-linear plate structures using plate or shell finite elements. Stresses are calculated at integration points through the depth of the elements and section forces are obtained by integration of these stresses.

Several attempts were made to model the Cardington tests using the ABAQUS concrete model and this approach. Convergence of the problem was never achieved. Thus a Stress-resultant approach was tried. Stress-resultants enable the geometry of the plate and the material behaviour to be described by one set of equations. Forces and moments per unit width of the plate are calculated based on the strain, curvature and temperature of the plates reference surface. Gradients can also be incorporated. However results are in terms of stress resultants only so the variation of stress over the depth of the plate is not given. Both the grillage and shell representations developed by Edinburgh adopt a stress-resultant approach.

For ABAQUS to model plates using a stress resultant approach an additional user defined sub-routine is required. Hence Gillie [87] developed a suite of programs called FEAST. FEAST is used in the research presented in this thesis to model generic composite steel frames. Therefore an understanding of the code and its assumptions are stated here.

4.4.1.2.1 Development of FEAST [87]

FEAST (Finite Element Analysis of Shells at High Temperatures) enables analysis of generic composite plates like the Cardington floor slab at high temperatures.

The FEAST suite consists of 3 programs,

1. SRAS - Stress Resultant Analysis of Shells. The program defines the force-strain and moment-curvature relationship for user defined plates over a given range of stress-strain-temperature states
2. FEAI - Finite Element Analysis Interface. This program allows stress resultant based calculations for user defined plates to be undertaken by ABAQUS
3. MFDU - Moment-Force Diagram Utility. This program produces moment-force interaction diagrams for plates analysed by SRAS

All three programs are described in detail by Gillie. [87] The first two will be described briefly here. The code was written in FORTRAN 77 for any general
plate. There are no limitations on the number of layers modelled or the number of materials incorporated. SRAS needs an input file which splits the plates cross-section into a number of layers. Each layer is defined by its area, material and distance from the plates reference surface. The file also contains user defined information about the range of reference surface strain, curvature and temperature values over which the stress resultants are to be calculated and also the intervals between these values. Stress-strain-temperature data files are read for each material. The strain in a given layer is calculated by Equation 4.1 assuming plane sections remain plane after bending.

\[(4.1) \quad \varepsilon_l = \varepsilon_r + z_l \phi\]

where,
\begin{align*}
\varepsilon_l & = \text{average strain in the layer} \\
\varepsilon_r & = \text{reference surface strain} \\
z_l & = \text{distance of the centre of a layer from the reference surface} \\
\phi & = \text{curvature of the reference surface}
\end{align*}

The temperature in the layer depends upon the reference surface T and the thermal gradient through the depth of the plate.

SRAS allows polynomials to describe the gradient through the depth, over a number of reference surface temperature ranges. The layers of the plate may also be separated