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The fire safety engineering of steel/concrete composite structures

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SYNOPSIS. Careful use of composite action between steel and concrete can lead to space-saving beams and columns having high load carrying capacity and high fire resistance without the need for additional fire protection. British and other European advances in calculation methods coupled with elevated temperature data on material properties allow the fire performance of such structures to be verified by calculation with a minimum of expensive and time consuming fire testing. The paper describes developments in fire safety engineering of composite structures in general, and its particular application to the UK Thor system.

1 INTRODUCTION

The virtue of composite construction is that it permits the optimum positioning of steel and concrete to provide the required room temperature and elevated temperature performances. In flexural elements, reinforcing steel bars embedded in concrete can carry more of the load as other uninsulated parts lose strength with increase of temperature. Composite construction can also lead to important space savings - reduced structural floor depths means that extra storeys can be achieved in multi-storey buildings with height restrictions. In the past the fire performance of beams and columns has been proved by undertaking full scale fire resistance tests. However, the large variety of designs possible in composite construction make this approach untenable. An acceptable alternative is to undertake a small number of fire resistance tests to obtain essential thermal and integrity data, and then calculate the performance of variants having validated the calculation model with the fire test data.

During the last decade there has been rapid progress in the development of analytical methods for the calculation of the behaviour of fire exposed structural elements, especially those constructed of steel or steel/concrete. In several countries, particularly in the EEC and EFTA, these methods are now being used as alternatives to the use of classification tables based on the results of standard fire resistance tests.

The European Convention for Constructional Steelwork (ECCS) published its recommendations [1] for the fire safety of steel structures in 1983. The recommendations give a theory for computing heat transfer to unprotected and protected steel members. However, in the UK, columns with 4-sided fire exposure and beams with 3-sided exposure usually have their thermal responses measured in a package of fire resistance tests so that calculations of thermal response are not normally necessary for such elements. A calculation method may be used, however, where there are sparse or no experimental data. For example, the British Steel Corporation (BSC) has used a finite element program to generate temperature profiles in shelf angle floor beams so that a parametric study of the thermal and structural behaviour of different shelf angle floor beam constructions could be accomplished. Similarly, the Fire Research Station (FRS) and others have been using finite element programs for predicting the thermal and structural response of structural elements.

Composite construction has a respectable history and, indeed, a long history if a reinforced concrete beam is recognised as a composite construction. Fire safety engineering is being increasingly applied to composite construction. UK examples are composite floors [2], and Arbed composite columns [3]. European examples are composite beams and columns [4] and interaction of beams and columns [5].

The new (1990) BSI code of practice for fire resistant design of steel structures, BS 5950: Part 8 [6], adopts the fire safety engineering approach based on limit state design concepts. It introduces new concepts and much new data and a handbook has therefore been produced [7] to assist in the understanding and application of the code.

2 FIRE SAFETY ENGINEERING : GENERAL

2.1 Definition of Fire Safety Engineering

In one sense fire safety engineering means balancing passive and active fire precautions so as to achieve the level of safety implicit in fire regulations for people in and near buildings. There is much current activity in this field, notably within ISO and CIB. Work is also in hand to produce a BSI Code of Practice on the subject which allows probabilistic and deterministic approaches.

Fire Safety Engineering in the context of this paper means the calculation, using numerical models validated by appropriate fire test data, of the thermal and structural response of individual beams and columns exposed to the standard fire resistance test exposure (ISO 834 temperature-time curve). The paper does not cover the fire behaviour of complete frameworks or other standard fire exposures such as the proposed ISO 834 hydrocarbon temperature-time exposure or the wide range of real fire exposures, although numerical models can take account of these different thermal environments.

2.2 Building Regulations

The Building Regulations 1985 applicable in England and Wales specify that 'the building shall be so constructed that, in the event of fire, its stability will be maintained for a reasonable period'. The Approved Document B 'Fire Spread' referred to in the regulations gives guidance on the fire resistance needed which may depend on the height and use of the building and the presence of automatic sprinklers, but it is emphasised that the guidance represents only one way in which the functional regulations can be met. It is open to designers to satisfy the regulations in other ways having comparable safety. For instance it may be possible to show that a period of fire resistance less than that given in the Approved Document is appropriate if, for instance, the fire load density in the building is substantially less than that normally present in buildings of the same nominal occupancy.

2.3 Fire Resistance

Fire resistance is the ability of an element of building construction to fulfil for a stated period of time the required stability, fire integrity and/or thermal insulation in a standard fire resistance test. Fire resistance tests for load-bearing elements are given in BS 476: Parts 20 and 21: 1987. Part 20 states that the specimen has failed the test if it is no longer able to support the test load. To prevent damage to the furnace failure is deemed to occur when the mid-span deflection of a horizontal structural element reaches an absolute value or a given rate. It is widely accepted in the UK and other parts of Europe that it is not necessary to model the deflection-time response of an element: it is sufficient to check that the element can support the load at the fire limit state. This is the approach adopted in BS 5950: Part 8 and the Structural Eurocodes. For a beam this means that the ultimate moment capacity should equal or exceed the applied bending moment. This is justified because predicted fire resistance times are nearly always less than test times, so erring on the safe side.

Stability and insulation are often amenable to calculation but integrity usually is not. However, it will be seen later in this paper that Thor beams and columns can be assumed to have satisfactory fire integrity because of the way in which the materials (steel and concrete) are tied together and, in the case of Thor beams, the way in which the beam ties into the adjoining floor/roof membrane.

2.4 Optimising Fire Resistance

Steel elements can have their fire resistance optimised in several ways:

- by increasing the area of cross-section so as to increase the heat capacity, and reducing the heat-exposed perimeter of the section to reduce the amount of heat entering the section;
- by providing rotational restraint at the ends - beams and columns for example;
- by reducing the load ratio (ratio of applied forces in the fire condition to the ultimate load capacity at room temperature);
- in the case of a hollow steel section column, by cooling with a filling of water or concrete;
- by encasing the element in fire protecting material;
- by protecting part of the element's cross-section, exemplified by the column-in-wall or shelf angle floor beam concept in which one flange is exposed to fire while the other and part of the web is protected by heat absorbing construction.

The effect of providing rotational restraint to the ends of beams or columns is generally to improve the fire resistance - the buckling length of columns is reduced and, in the case of beams, the maximum bending moment at mid span is reduced. Rotational restraint can be provided by rigid or semi-rigid beam-to-column connections, but there have to be safeguards against the development of detrimental high moments induced in the column via the beam. The benefit of moment connections has been investigated [8].

2.5 Calculation of Moment Capacity

The procedure for calculating the ultimate moment capacity of a simply supported composite beam may be summarised as follows:

- Set down design parameters. These will include: required fire resistance, beam span, cross section geometry, nominal strength properties of concrete and steel (reinforcing bars, steel plate and any other steel sections). It will be assumed that strength reduction factors (ie strength at elevated temperature divided by room temperature strength) for all the materials are available from codes (BS 5950: Part 8 or the relevant Structural Eurocode). Note that the use of reinforcing bars gives flexibility in design since their number, size, location, steel grade, and concrete cover be chosen to give the best performance.

- Determine totals for dead and imposed loads, and calculate applied bending moment ($Wl^2/8$ for a simply supported member).

- Determine temperature field in the cross section at the required period of fire resistance. This may require a computer-aided thermal analysis (eg TASEF analysis) or it may be possible to use temperature data for a similar construction from a fire test report or a code (eg BS 5950 : Part 8).

- Discretise the cross section into elements. Relatively large elements can be chosen where the temperature variation along the xy coordinates is small.

- Determine the strength contributions for all of the elements. This is obtained from the product of strength reduction factor, room temperature strength and area of element.

- Determine the position of the neutral axis of the section. This can be done by hand but is tedious due to the iteration needed, and is complicated by the need to ignore elements of concrete below the neutral axis since they cannot transmit tension. This is therefore best done with a computer.

- Take moments about the neutral axis. This gives the ultimate moment capacity.

- Compare the ultimate moment capacity with the applied bending moment to check that it is greater. If it is not, redesign the section and repeat procedure.

2.6 Implications of the Common Market

When implemented the European Commission's Construction Products Directive will have a big impact on the marketing strategy for product manufacturers - it will be possible to market products such as beams and columns in all the member state countries without hindrance if a CE mark is obtained. To obtain a CE mark it will be necessary, amongst other things, to prove compliance with harmonised standards for fire tests and/or harmonised calculation methods. CEN Technical Committee 127 is working on a package of fire resistance test standards while the calculation methods will be covered in the Structural Eurocodes. The work of the European Convention for Constructional Steelwork (ECCS), the European Coal and Steel Community (ECSC) and other forums will increasingly influence the development of harmonised calculation methods for structural elements. The UK has much to gain from this as UK building regulations already provide the freedom to adopt a fire safety engineering approach. It is now necessary to provide easy-to-understand guidance on the subject so that those involved (designers, building control and fire authorities) can be informed to the appropriate level.

3 FIRE SAFETY ENGINEERING : THE THOR SYSTEM

Although considerable international effort is being devoted to fire safety engineering in terms of research, code writing and design guidance, the actual transfer to practical structural engineering is more cautious. Whilst accepting the prudence of building control and fire authorities and engineers, the real force to accept fire engineering can only come from education and market requirements.

Over the last five years a Swedish engineer, Dr Jorgen Thor, has developed a system of structural elements whose performance is proved by test [9] and by fire engineering calculations [10]. The development of this system in the UK has benefited from an assessment of the performance at room temperature by Ove Arup and Partners [11] and at elevated temperatures by Fire Research Station [12] which continues to give advice under the BRE Technical Consultancy. Some modelling work has also been undertaken by the Steel Construction Institute and the Department of Civil Engineering, City University.

Fig 1 shows the relationship of the Thor Beam to the floor slab and, when used, the Thor column. The beam and column sections are fabricated in structural steel, erected on site and then filled with concrete to create composite sections. It is worth noting that the success of this structural system in Scandinavia and the UK is as much due to the space saving nature of the elements as to their inherent fire resistance. It is further important to recognise that structural design to a limit state philosophy and the derivation of section strength based on an elastic-plastic analysis, are also fundamental in creating a logical design approach.

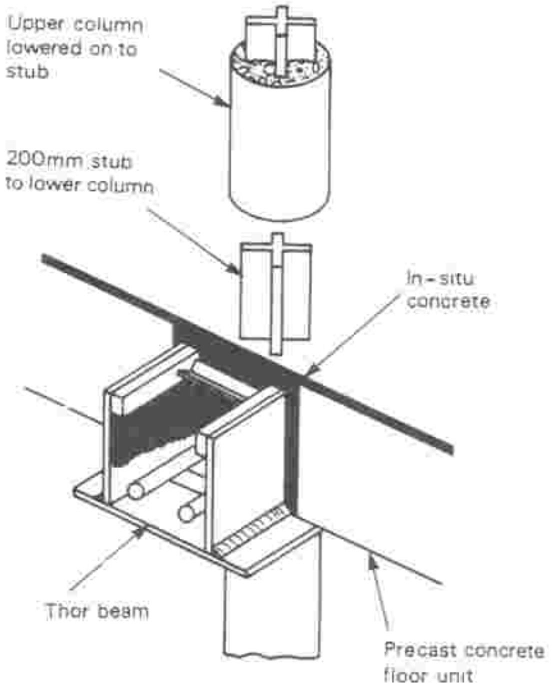

Fig 1 Thor Beam and Thor Column assembly

3.1 The Thor Beam

The Thor Beam may be conceived in several forms but is essentially a steel box section with an open top flange, 100 mm outstands of the lower flange to carry floor units, and, importantly, internal reinforcement which enhances the section strength in fire. The beam may be used in conventional steel, precast, concrete or masonry structures in addition to its use with Thor Columns in the Thor System. Once built into a frame, precast concrete floor units are placed onto the lower flanges of the beam and carried by the steel section alone, Fig 2. The subsequent placing of concrete inside the beams through openings in the top flange creates a composite section, the composite action being generated by shear connectors in the form of angles welded between the components of the top flange at appropriate centres. The in-situ concrete also provides the topping and keys the beam into the adjoining floor units.

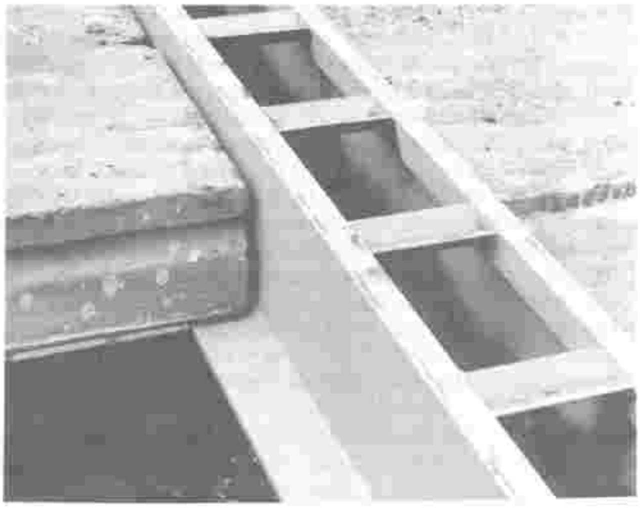

Fig 2 Thor Beam and floor units prior to concreting

Thor Beams are designed to meet four independent criteria which are:

- ambient temperature strength (factored loads)
- ambient temperature serviceability (unfactored loads)
- ambient temperature yield (unfactored loads)
- fire resistance (unfactored loads)

The first two criteria are related to the strength and stiffness of the steel/concrete composite section and take account of the long term material characteristics of the concrete. A requirement of BS 5950: Part 3 is that yield - the third criteria - is avoided in the steel section under service loads. In practice this requires a two stage calculation to assess effects before and after composite action (ie before and after concreting). Fig 3 shows a cross section through a typical Thor Beam and the corresponding plastic stress distribution at room temperature. Note that the neutral axis (position of zero stress) is roughly at mid depth.

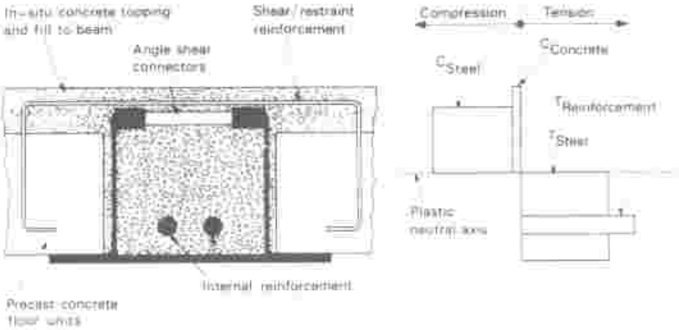

Fig 3 Typical Thor Beam and ambient temperature stress distribution

For the fourth criteria the fire limit state is defined in BS 5950: Part 8. The Standard gives recommendations for load factors, material factors and reduced steel strengths at various elevated temperatures. It also states that a section is deemed to meet the fire limit state when its moment capacity can be demonstrated by calculation to meet the applied loading based on reduced load factors. Using a plastic section design approach, where tension and compression portions of the beam are balanced about a plastic neutral axis, it is possible to calculate a reduced moment capacity, as explained in 2.5.

A simplified finite element mesh for half the section of a typical Thor Beam is shown in Fig 4. Mean element temperatures (ie the mean of four nodal temperatures) are given for a 90 minute standard fire exposure. TASEF adequately models heat sink phenomena. For example it models the reduced lower flange temperature at the point where the web connects showing that the web is conducting heat away from the flange more rapidly than the adjacent concrete, and it also models the higher temperature of the web compared with the reinforcing bar at the same distance from the fire exposed face.

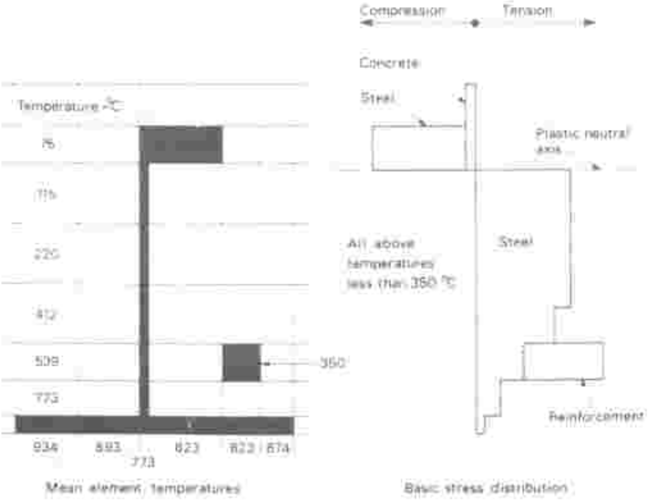

Fig 4 Thor Beam thermal analysis at 90 minutes fire exposure

Fig 4 also shows the plastic stress distribution corresponding to a 90 minute standard fire exposure. Contrast it with Fig 3. The bottom flange has lost most of its strength while the reinforcing bar retains its full strength, being kept below 350°C, and the neutral axis moves up. Because the area of the reinforcing bar is large in relation to the web, and the lever arm is large, the contribution of the reinforcing bar(s) to the total moment capacity becomes large: the reinforcement can contribute 40% of the moment capacity at a 90 minute exposure.

The use of TASEF was first validated by a fire test undertaken in Sweden on a Thor Beam section [9]. A large number of fire tests have been carried out by BSC on shelf angle beam arrangements and, more recently, slim floor assemblies. These data have also been used to validate TASEF so as to recognise possible differences in heat flux in Swedish and UK fire resistance furnaces.

The UK work on shelf angle beams has been presented in BS 5950: Part 8, Appendix E. The details of thermal analysis and structural analysis are directly applicable to the design of Thor Beam to such an extent that data from Appendix E is used for routine section design without recourse to additional TASEF analysis.

Calculation of section strength after a period of fire takes into account reduced material factors of 1.3 for concrete and 1.0 for steel. Internal reinforcement, fixed inside the section at fabrication stage, is normally given sufficient concrete cover to ensure that its temperature does not exceed 350°C so that its full strength is retained.

3.2 The Thor Column

The Thor Column consists of a relatively thin walled outer steel tube with a centrally placed rolled steel cruciform section with concrete in the void. When used with the Thor Beam the outer tube terminates at the underside of the beam flange whilst the cruciform core section passes through the beam leaving 200 mm projecting above the top of the beam, Fig 1. The beam and column structure for a building can be quickly erected using these elements in such a way that a whole floor level is constructed complete with precast floor units and in-situ concrete before the next lengths of column and beam are erected.

Again, TASEF thermal analyses were carried out to establish the heat flow into various column sections of this type, and ambient temperature strength tests of several cross sections and lengths were made in Stockholm. However, there were no test data to validate the thermal analysis or failure loads at elevated temperatures. A test was therefore carried out at the Loss Prevention Council, Borehamwood in October 1990 on a 300 mm outside diameter column section 3.15 m long. A view of the test specimen before the two halves of the furnace were closed prior to the test is shown in Fig 5. Fifteen thermocouples were fixed to the 180 x 24 steel cruciform core section and five thermocouples set on supports at various radii in the concrete at mid length. Further thermocouples were fixed to the outer surface of the tube. Hence comprehensive thermal data were obtained. A preload of 1,600 KN was applied and the furnace run for 90 minutes whereupon the axial load was increased until buckling failure at 2,950 KN. The furnace was run for a further 30 minutes so that 2 hours of heat flow information were recorded.

Fig 5 Thor Column prior to fire testing at LPC

The results of this test [13] showed that the TASEF analysis over estimated the steel temperature and followed closely the thermal gradient through the concrete, Fig 6.

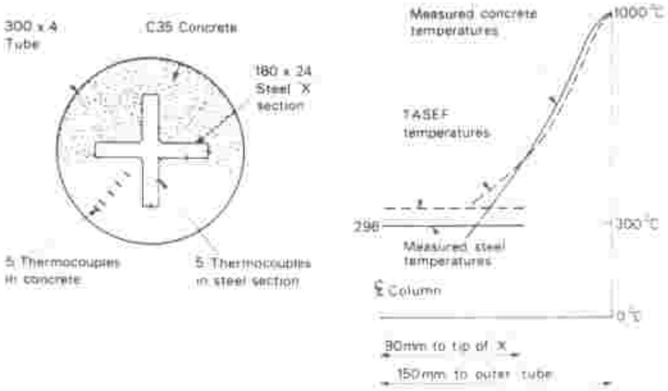

Fig 6 Thor Column temperatures at 120 minutes fire exposure

Using measured material properties established by independent tests, a close correlation was found with the buckling load calculated using a structural model based on Eurocode 4. This design model [14], developed by Dr Thor, takes account of reduced strength in fire by replicating the heated section with reduced cross sectional areas of tube, concrete and cruciform section core. The proportion of each material 'remaining' after a particular period of fire exposure is based on the reduced strength and is represented by a reduced cross sectional area of material still at full strength. In practical terms the Thor Column is designed so that the outer tube and concrete provide the additional strength and stiffness required by ambient temperature loading and then, in a fire, the residual stiffness required to stabilise the core. The outer tube is therefore relatively thin walled, typically 5 mm, as there is no advantage in having a greater thickness of steel directly exposed to fire and reduced to very low yield stresses. Nevertheless, whilst the axial load carrying capacity of the tube has been removed, it still provides the important functions of reflecting heat, containing the concrete, preventing spalling, and reducing the rate of evaporation of moisture in the concrete which delays the rate of heating of the steel core.

4 CONCLUSIONS

Composite construction is now commonly used within the UK and other parts of Europe. Its fire behaviour can be predicted using calculation methods validated by fire test data. The paper has indicated how one particular composite construction system has been developed by a fire safety engineering approach.

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