

WHOLE BUILDING BEHAVIOUR – RESULTS FROM A SERIES OF LARGE SCALE TESTS

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Abstract

Structural integrity and stability during and immediately following a fire are traditionally maintained through a reliance on the performance of individual members (beams, columns, walls) subject to idealised loading conditions during a standard fire test. A number of large scale natural fire tests have taken place over the last ten years in a facility purpose built to investigate whole building behaviour. The complex interactions between structural members within a real building subject to a real fire have been investigated using an eight storey steel framed building, a seven storey concrete building and a six storey timber framed building. The tests have shown the importance of whole building behaviour through identification of modes of failure and support mechanisms that are a function of the building rather than the individual members. The horrific events of September 11th 2001 have stimulated discussion on the performance of real buildings subject to real fires. The results from the full scale tests are presented in an attempt to encourage a holistic approach to the subject of fire safety engineering.

The application of performance based codes for fire engineering rely on the availability of accurate source data related to material properties at elevated temperature and aspects of loading and structural performance. The work carried out at BRE goes some way to provide this information for real buildings subject to large natural fires.

Keywords: Tall buildings, Performance-based, Fire resistance, Natural fires, Structural integrity, Robustness

1. Introduction

The purpose of this paper is to describe the structural fire engineering research carried out at over the last ten years at the Building Research Establishment's (BRE) large scale test facility at Cardington in the UK. The need for full scale testing was identified in a report produced by the Institution of Civil Engineers in 1986¹. In response to this demand BRE in collaboration with the UK government and industrial partners developed the Large Building Test Facility inside a disused airship hangar at Cardington near Bedford in the UK. The philosophy behind this initiative is discussed in a paper by Armer and Moore² who set out the principles underpinning the development of the facility and go on to describe the first test building to be erected. Over the last ten years the facility has been used to carry out a wide range of tests on complete buildings constructed from steel, concrete and timber. Although full-scale fire tests have formed a major part of the research undertaken in the facility, tests to investigate vertical and horizontal load carrying capacity, dynamic response, response to blast loading and ability to resist disproportionate collapse have also been carried out. Each of the large buildings within the hangar are illustrated in figures 1 to 3 below:

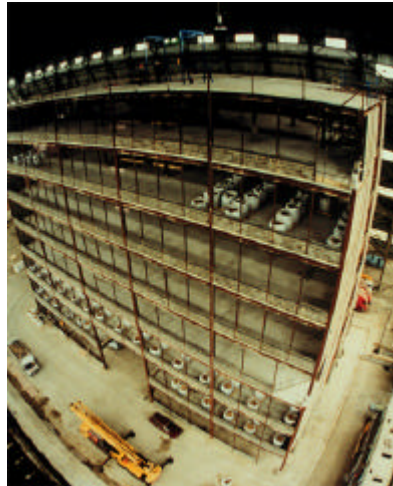


Fig. 1 Steel framed building



Fig.2 Concrete framed building

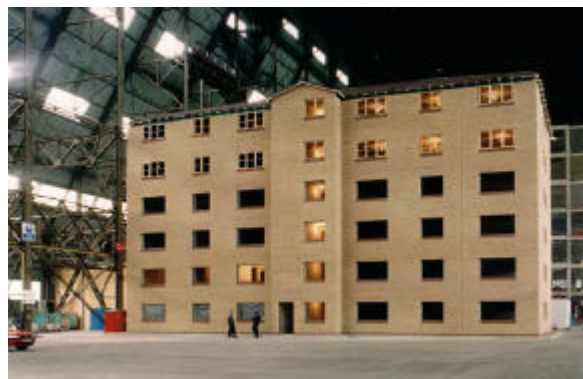


Fig.3 Timber framed building

2. Traditional research and testing

Many structural engineering design codes are based on the results of tests on isolated structural elements (beams, columns, walls, floors). The complex interactions between structural and non-structural members when connected to form a complete building cannot be understood from such tests. Simplifying assumptions are used to model the continuity and restraint present when elements are connected together. The disproportionate collapse of a block of flats in East London in the late 1960s caused many engineers to question this reliance on the performance of individual elements and led to the incorporation of robustness requirements into the UK Building Regulations.

If traditional test methods for evaluating structural performance suffer from a number of drawbacks then there are even greater problems associated with tests at elevated temperature. Despite moves in the last few years towards performance based regulations and performance based design solutions there is still a general reliance on prescriptive methods of demonstrating regulatory requirements. In addition to the problems of simulating complicated structural interactions and loading through the use of idealised boundary conditions and unrealistic loading scenarios there is the added complication of the relationship between a standard fire exposure and a real fire. The structural performance of the buildings involved in the terrorist attacks on the world trade centre has focused attention on whole building behaviour and the

performance of buildings subject to severe fires. There remains an urgent need to carry out full-scale tests to improve our understanding of how buildings respond to extreme events and to enable researchers to develop validated analytical tools for the prediction of structural response subject to such events as fire and explosion. The work carried out at Cardington has improved our understanding of how buildings respond to realistic natural fires. Alternative load carrying mechanisms and alternative modes of failure have been identified from those considered as part of the design process. New design guidance for buildings has been produced as a consequence of the work carried out at Cardington³.

3. Full-Scale Fire Tests

A number of large-scale fire tests to evaluate structural performance have been carried out at the Cardington test facility over the last ten years. These tests are described in the foregoing paragraphs.

3.1 Steel Framed Building

An extensive collaborative programme of fire tests in various locations within the eight storey steel framed building have been carried out. The research projects were funded by the UK government, the UK steel industry and the European Community. Tests ranged from the use of purpose-built furnaces fixed to individual elements through to large-scale natural fires on realistic sized compartments with realistic levels of imposed load and fire load. One such test, the BRE Corner fire test, is illustrated in Figure 4. The extent and nature of the fire testing undertaken on the steel building together with some key results in terms of maximum temperature and deformation are described in Table 1. At the time of writing a final fire test is scheduled to take place in January 2003. This test will investigate the performance of unprotected connections and unprotected beams in a compartment with plan dimensions of 11m by 7m.



Fig. 4 BRE Corner fire test

Table 1. Description of fire tests carried out on the steel framed building

Test Description	Comments
Furnace tests on internal and external columns – ground floor, third floor and seventh floor. Tests took place at different stages in the construction of the building i.e. before and after the concrete floors were cast.	Temperatures limited to 550°C to prevent plastic deformation. Objective of the work was to provide information on the levels of restraint present at various times and at various locations. Used to provide input to boundary conditions to be assumed in numerical models.
Furnace test of restrained beam on 6 th floor of building.	Maximum steel temperature 900°C, time to maximum temperature 170 minutes, maximum deflection 230mm
Furnace test across width of building on 3 rd floor. Natural fire test on 1 st floor of building	Maximum steel temperature 800°C, time to maximum temperature 125 minutes, maximum deflection 445mm Maximum steel temperature 1020°C, time to maximum temperature 75 minutes, maximum floor deflection 425mm
Natural fire test on 2 nd floor of building.	Maximum steel temperature 903°C, time to maximum temperature 114 minutes, maximum deflection 270mm
Natural fire test in large compartment on 2 nd floor. This test involved heating a compartment measuring approximately 21m by 18m in plan. Ventilation was provided on opposite sides.	Maximum steel temperature 691°C, time to maximum temperature 70 minutes, maximum deflection 557mm
Demonstration fire test on 1 st floor. Fuel load provided by office furniture including plastics. Isolated column tests on ground floor.	Maximum steel temperature 1060°C, time to maximum temperature 40 minutes, maximum deflection 610mm Data used for validation of end conditions for German test furnace
Furnace tests on individual beams to investigate influence of thermal expansion of unprotected beams on the stability of protected columns.	
Isolated column tests on ground floor.	Data used for development of numerical model.

3.2 Concrete Building

A large scale fire test was carried out on the ground floor of the seven storey concrete building (Figure 2). The test took place within a compartment measuring 15m by 15m in plan. The purpose of the test was to investigate the response of a modern concrete building to a large-scale natural fire. In particular, the studies concentrated on the influence of restraint from the surrounding cold structure and the impact of spalling on the effectiveness of the load-carrying members. Overall stability was maintained despite significant deformation of the perimeter columns and significant spalling of the underside of the floor slab. The implications from this test are the subject of a current research project. Figure 5 shows the fire being conducted on the concrete building.



Fig. 5 Concrete building fire test

3.3 Timber Frame Building

A number of tests have been carried out on the timber frame building constructed as part of the TF2000 research project. TF2000 is a unique collaborative project between the UK government, BRE, TRADA Technology Ltd and the UK timber industry, focused on exploiting the UK's potential to become world leader in the provision of medium-rise timber frame buildings. This project differed from the work described above in that the timber building was designed for residential accommodation where the steel and composite buildings were designed as offices. For this reason life safety issues formed an important part of the programme of work. The most significant test involved a full-scale natural fire within one apartment on the second floor of the building. The purpose of the test was to show that a modern timber frame building could meet the requirements of the regulations in terms of fire performance and maintain the integrity of the means of escape for fire fighters and occupants. In particular the effectiveness of compartmentation between the fire flat and the adjacent occupancies and common areas was investigated. The main fire-related research projects are described in Table 2 below. The compartment fire test is illustrated in Figure 6.



Fig. 6 TF2000 Compartment fire test

Table 2 Description of fire-related projects undertaken on timber frame building

Test description	Comments
Compartment fire test on 2 nd floor. Objectives were to consider fire spread outside the room of origin and to investigate tenability conditions for means of escape.	Atmosphere temperatures in excess of 1000°C inside compartment. No fire spread outside compartment of origin for duration of the test.
Reinstatement of fire damaged timber building.	Project to look at tools and techniques for inspection and repair of fire damaged timber frame buildings. Design guidance produced for engineers, surveyors and approved inspectors.
Understanding fire risks in combustible cavities	Programme of work to investigate concealed fire spread within cavities. Produced guidance for the industry on the correct procedures for the installation of fire stopping and cavity barriers. Also provided training for the Fire Service on tools and techniques needed to locate fires within concealed spaces. Provided training exercises for Fire Crews.

3.4 Other Full Scale Tests

The work described briefly above has stimulated interest in the response of complete structures to fire and in the behaviour of fully developed, post-flashover natural fires. A number of tests have been carried out on realistic structures subject to natural fires. These include precast concrete flooring units, composite steel-concrete flooring systems, temporary site accommodation and lightweight steel residential units. As part of a collaborative European research project called the Natural Fire Safety Concept a number of fully developed fire tests were carried out in a purpose built compartment measuring 12m by 12m in plan. The tests investigated the impact of the parameters that influence fully developed fire behaviour within a large

compartment. A typical test is illustrated in Figure 7. Some of the significant test results are summarized in Table 3.



Fig. 7 Natural Fire Safety Concept Test

Table 3 Significant results from various full-scale fire tests

Hollow core slabs	Maximum compartment temperature of 1130°C, time to maximum temperature 21 minutes, maximum deflection of floor slab of 115mm
Steel frame housing	Maximum compartment temperature of 1119°C, time to maximum temperature 31 minutes
Natural Fire Safety Concept	Series of 8 full-scale tests with maximum temperature of 1227°C

4. Discussion

The work described briefly in this paper has done much to improve our understanding of the complex interaction between structural elements at the fire limit state and to stimulate interest in the subject of structural fire engineering. Initially, the early fire tests were designed to provide validation and the identification of the relevant boundary conditions for numerical models attempting to predict the response of individual structural elements to a fire situation. As our understanding of the interaction between structural elements at elevated temperature improved the test scenarios became more complex. The tests have identified alternative load carrying mechanisms at the fire limit state. The identification of tensile membrane action in thin slabs at large deflections has enabled new design guidance to be issued based on the observed behaviour. It is hoped that this concept can be extended to incorporate guidance on compressive membrane action in reinforced concrete structures in the near future. The full-scale tests have also identified modes of failure which are a function of the structure rather than the individual elements.

Lennon

The tragic circumstances of September 11th have confirmed how important it is to understand how the various strands of fire safety engineering are dependent on each other. Evacuation can only be achieved safely if structural stability is maintained for the required period.

5. Conclusions

It is clear that current prescriptive regulations do not address fundamental aspects of combustion behaviour or fundamental aspects of whole building performance. The new generation of performance based codes for fire engineering represent an improvement in the design philosophy with solutions tailored to the individual requirements of the project. However, performance based approaches rely on the availability of accurate source data for material properties and aspects of loading. Great advances in the understanding of whole building behaviour have been achieved over the last ten years due in part to the work carried out at BRE. This work should be continued as the terrorist threat does not apply to individual beams, columns, slabs or walls but to complex buildings where the interaction of fire protection, detection and suppression systems impact on the structural response of the building and, ultimately on global structural stability.

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