ABSTRACT

The paper presents a part of the results reached during the Structural integrity fire test in Cardington laboratory January 16, 2003. The work summarises the instrumentation of the experiment and focuses on the measured stresses on columns and on beams, which were instrumented to observe the tie forces in the multistorey building under natural fire. The composite action and joint behaviour play the major role in the structural behaviour under fire on the Cardington frame. The simple rules for the design of the beam may be extended into the catenary action, if the connections are designed to be adequately robust. From the measured forces in columns may be evaluated the horizontal forces in connections. The experiment confirmed all three parts of fire design by Eurocode; the fire modelling by parametric fire curve, the transfer of heat into the structure, and the structural analyses of beams, columns as well as of connections at elevated temperature.

Fig. 1: Fire compartment for sevenths large fire test, structural integrity test, on Cardington frame

1 INTRODUCTION

Reason for carrying out the structural integrity fire test on Cardington frame was to collect data on performance of typical beam-to-column and beam-to-beam frame joints under fire conditions. The structure can resist to exceptional loading, even if beams or columns lose load bearing capacity, see [1]. The resistance of the structure to accidental actions, e.g. fire, is provided by structural integrity, which depends on robustness of members and joints. The robustness is assured by stiffness and resistance of elements and connections, and namely by its deformation capacity. Studies of failure of the WTC on 11th September 2001 show...
excellent behaviour of structures under exceptional loading, see [2], but alerted the engineers to possibility of connection failure, see [3]. Design of connections in exceptional conditions is aimed to prevent progressive collapse of the structure, see [4]. Quantification of tie forces is one of engineering questions at current stage of knowledge.

![Fig. 2: a) Fire load in compartment; b) fire load around column D2; c) protection of internal column E2 after test; d) protection of external column after test](image)

The structural integrity fire test (large test No.7) was carried out in a centrally located compartment of the building, enclosing a plan area of 11 m by 7 m on the 4th floor, see Fig. 1 [5]. The preparatory works took four months. The fire compartment was bounded with walls made of three layers of plasterboard (15 mm + 12.5 mm + 15 mm) with a thermal conductivity between 0.19 - 0.24 W m\(^{-1}\)K\(^{-1}\). In the external wall the plasterboard is fixed to a 0.9 m high brick wall. The opening of 1.27 m high and 9 m length simulated an open window to ventilate the compartment and allow for observation of the element behaviour. The ventilation condition was chosen to produce a fire of the required severity in terms of maximum temperature and overall duration. The columns, external joints and connected beam (about 1.0 m from the joints) were fire protected to prevent global structural instability, see Fig. 2. The fire protection used was 20 mm of Cafo300 vermiculite-cement spray, with a thermal conductivity of 0.078 W m\(^{-1}\)K\(^{-1}\).

The steel exposed structure consists of two secondary beams (section 305x165x40UB, steel S275 measured \(f_y = 303\) MPa; \(f_u = 469\) MPa), an edge beam (section 356x171x51UB), two primary beams (section 336x171x51UB, steel S350 measured \(f_y = 396\) MPa; \(f_u = 544\) MPa) and four columns, (internal column sections are 305x305x198UC and external column sections are 305x305x137UC, steel S350). Flexible end plates were designed for the beam-to-column connections and fin plates for the beam-to-beam connections. In both cases S275 steel and M20, grade 8.8 bolts were used. Composite behaviour was achieved by using 19 mm diameter shear studs (with \(f_u = 350\) MPa) to connect the primary and secondary beams to the
composite floor slab concreted into the profiled metal deck by the light-weight concrete. The geometry and measured material properties of the flooring system are summarised in [6].

The applied load was simulated using 1 100 kg sandbags applied over an area of 18 m by 10.5 m on the floor immediately above the fire compartment. The sandbags represent 100% of the permanent actions, 100% of variable permanent actions and 56% of variable actions. The applied load was designed to fail the floor during fire, based on analytical and FE simulations. Wooden cribs with moisture content 13.6% were used to provide a fire load of 40 kg/m². The stresses in fire protected columns and in beams are summarised further to help to understand the tie forces developed during the natural fire of multi-storey building.

![Diagram of the floor plan with locations of strain gauges and thermocouples](image)

**Fig. 3**: Location of ambient temperature strain gauges (ijk) on columns and high temperature strain gauges (ijkHT) and relevant thermocouples (ijkC) on beams close to connections

### 2 INSTRUMENTATION

The instrumentation used included thermocouples, strain gauges and displacement transducers. A total of 133 thermocouples monitored the temperature of the connections and beams within the compartment, the temperature distribution through the slab and the atmosphere temperature within the compartment. An additional 14 thermocouples measured the temperature of the protected columns. Two different strain gauge types were used, high temperature and ambient temperature, see Fig. 3. Nine high temperature strain gauges were used in the exposed and un-protected elements (fin plate and end plate - minor axis joint). A total of 47 ambient strain gauges were installed in the protected columns and on the concrete slab. 25 vertical displacement transducers were attached along the 5th floor to measure the deformations of the concrete slab. An additional 12 transducers measure the horizontal movement of the columns and the slab. Ten video cameras and two thermo...
imaging cameras recorded the fire and smoke development, the deformations and temperature distribution.

Table 1: Measured stresses on beam D1.5-E1.5 (D2-E2) by high temperature strain gauges close to fin plate (header plate connection), in MPa, see Fig. 2, $E_\theta$ is modulus of elasticity at elevated temperatures

| Time (min) | Temp. °C | Strain $\mu \varepsilon \cdot 10^{-3}$ | $E_\theta$ Stress MPa | | Time (min) | Temp. °C | Strain $\mu \varepsilon \cdot 10^{-3}$ | $E_\theta$ Stress MPa | | Time (min) | Temp. °C | Strain $\mu \varepsilon \cdot 10^{-3}$ | $E_\theta$ Stress MPa | | Time (min) | Temp. °C | Strain $\mu \varepsilon \cdot 10^{-3}$ | $E_\theta$ Stress MPa |
|------------|---------|--------------------------------|---------------------| |------------|---------|--------------------------------|---------------------| |------------|---------|--------------------------------|---------------------| |------------|---------|--------------------------------|---------------------| |------------|---------|--------------------------------|---------------------| |------------|---------|--------------------------------|---------------------|
| 0          | 18      | 0,000                           | 210000              | | 0          | 18      | 0,000                           | 210000              | | 0          | 18      | 0,000                           | 210000              | | 0          | 18      | 0,000                           | 210000              |
| 5          | 24      | 0,051                           | 210000              | | 11         | 25     | -0,068                          | 210000              | | 14         | 23     | -0,138                          | 210000              | | 10         | 24     | -0,084                          | 210000              | | 10         | 24     | -0,084                          | 210000              |
| 10         | 42      | 0,198                           | 210000              | | 41         | 41     | -0,217                          | 210000              | | 46         | 40     | -0,084                          | 210000              | | 29         | 41     | -0,084                          | 210000              | | 29         | 41     | -0,084                          | 210000              |
| 15         | 66      | 0,248                           | 210000              | | 52         | 71     | 0,325                           | 210000              | | 68         | 71     | 2,574                           | 210000              | | 18         | 71     | 2,574                           | 210000              | | 18         | 71     | 2,574                           | 210000              |
| 20         | 114     | -2,468                          | 207104 -388         | | 126        | 126    | 8,507                           | 204522 -391         | | 131        | 126    | 8,507                           | 204522 -391         | | 18         | 126    | 8,507                           | 204522 -391         | | 18         | 126    | 8,507                           | 204522 -391         |
| 25         | 212     | -2,554                          | 186459 -335         | | 242        | 242    | 8,552                           | 180229 -372         | | 236        | 236    | 8,496                           | 181518 -320         | | 29         | 236    | 8,496                           | 181518 -320         | | 29         | 236    | 8,496                           | 181518 -320         |
| 30         | 331     | -3,598                          | 161468 -298         | | 362        | 362    | 9,519                           | 155035 -359         | | 369        | 369    | 9,519                           | 155035 -359         | | 38         | 369    | 9,519                           | 155035 -359         | | 38         | 369    | 9,519                           | 155035 -359         |
| 45         | 636     | -6,425                          | 51552 -120          | | 669        | 669    | 9,408                           | 39165 -106          | | 692        | 692    | 9,408                           | 39165 -106          | | 69         | 692    | 9,408                           | 39165 -106          | | 69         | 692    | 9,408                           | 39165 -106          |
| 60         | 810     | 0,294                           | 18413 5             | | 888        | 888    | 10,751                          | 14722 -25           | | 899        | 899    | 10,751                          | 14722 -25           | | 90         | 899    | 10,751                          | 14722 -25           | | 90         | 899    | 10,751                          | 14722 -25           |
| 90         | 908     | 0,458                           | 210000 68           | | 893        | 893    | 11,841                          | 210000 46           | | 908        | 908    | 11,841                          | 210000 46           | | 90         | 908    | 11,841                          | 210000 46           | | 90         | 908    | 11,841                          | 210000 46           |

3 MEASURED STRESSES

The beams close to connections were instrumented by high temperature strain gauges to measure the forces in the steel part of the connection during fire. The high temperature strain gauges allow to measure form the stresses till temperature of 1200 °C. The reported elongations were recalculated to stresses using the modulus of elasticity $E_\theta$, adequate to the recorded temperature by the relevant thermocouples as shown in Tabs 1 and 2. The results of the measurements are shown on Figs 4 and 5. The stressed documents the behaviour of the restrained composite beam during fire, see [7]. It is visible a high influence of the local buckling of the flange due to compressive forces from thermal elongation of the beam as well as from restraints of the beam by increasing of the influence of the connection stiffness due to decreasing of the bending rigidity of beam, see [8]. The beam ends yields in 17 min. of fire. The measurements confirm indirectly the assumption of the effective yield stress instead of the proportional limit 0,2 used in the European design.

The external columns were equipped by the strain gauges 20 mm from the section edge, see Fig. 3. Low temperature of the fire protected columns allowed recording the strains using ambient temperature strain gauges at 3rd floor till the 60 min. of the fire and at 4th floor during the whole experiment. The strains were transformed to the stresses using modulus of elasticity
210 000 MPa. Selection of results is presented at Figs 6 and 7. The tables of reached temperatures and stresses may be found in [9].

![Graph showing normal stress vs. time](image)

Fig. 4: The stresses in secondary beam close to beam to beam connections

![Graph showing stress vs. time](image)

Fig. 5: The stresses in secondary beam close to beam to column connection D2 (E2)

5 TIE FORCES

The columns were instrumented by stain gauges to learn the horizontal forces in connections during the natural fire. From the column stresses were calculated the bending moments, see Fig. 8. The measured stresses in both columns, D and E, confirm the force distribution. From the bending moments at level d are derived the shear forces and the horizontal forces in the connections during accidental action by natural fire, the tie forces, based on the continuous beam model, see Fig. 8. The maximal horizontal force at third floor was tension, \( F_{t,3} = +344 \text{ kN} \) and \(-65 \text{ kN} \), at fourth floor compression \( F_{t,4} = -462 \text{ kN} \) and \(+88 \text{kN} \).
global structural analysis verify qualitatively and quantitatively the findings using the 2D FE non-linear analysis, including the plasticity of the beam elements, large strains and large deformations, linear temperature distribution, composite action and non-linear response of the composite joints, see [10].

The tie forces may be predicted by a simple model presented in [10] and [11]. For the Cardington frame the asked horizontal tying may be calculated as

\[
F_I = \text{MIN} \left[ 0.5 \left( 1.4 g_k + 1.6 q_k \right) s_t \cdot L \right] = 289.2 \text{ kN} \quad (1)
\]

where \( g_k \) is the characteristic value of permanent action, \( q_k \) is the characteristic value of variable action, \( L \) is the beam span, and \( s_t \) is the mean transverse spacing of the ties adjacent to that being checked.
The forces developed under heating are transferred by steel and concrete part of the connection. During the cooling is majority of the horizontal forces carried by slab due to the higher stiffness of the composite slab compared to the stiffness of the steel frame.

**Fig. 8:** Measured bending moments in columns during fire

**Fig. 9:** Tie forces calculated from the measured bending moments by beam theory

### 8 SUMMARY

During the test we did not succeed to collapse of structure or its parts with the fire load of 40 kg/m², together with a mechanical load representing 100% of the permanent actions, 100% of variable permanent actions and 56% of live actions. The acting load was 6.1 kN/m² and the calculated slab resistance under reached temperatures during fire by a catenary model 4.07 kN/m².

The structure showed good structural integrity. The normal forces in beam to column connection due to natural fire reached in compression 462 kN and in tension 344 kN based on the calculations from the stresses measured in columns. The test in Cardington January 16, 2003 confirmed the simple rules for the design of the structural element in the temperature as well as stress domain and verified the concept of unprotected beams and protected columns as a viable system for composite floors.
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REFERENCES


KEYWORDS

Fire test, Large scale test, Natural fire, Structural integrity, Tie forces, Column behaviour, Global analysis, Composite action.