NUMERICAL SIMULATION OF CARDINGTON FIRE TEST ON STRUCTURAL INTEGRITY

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ABSTRACT. Numerical study of experiment on structural integrity under fire is presented. The research is focused on preparation of fire test on eight-floor multi-storey building in European Large Building Test Facility (LBTF) in Cardington. Beams, columns, slabs, joints and column bases of the frame are modelled at elevated temperature during heating and cooling phases of the fire. The simulation include large deformations, spread of plasticity in beams and columns and semi-rigid behaviour of joints. Required robustness of joints in terms of tie forces is discussed to assure structural integrity under accidental loading for preventing progressive collapse.

1. INTRODUCTION
Reason for carrying out the structural integrity fire test on Cardington frame is 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 conditions, even if beams or columns loose 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 namely by 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] and [5]. Quantification of tie forces is one of engineering questions at current stage of knowledge.

Compartment fire test is in preparation in LBTF in Cardington. Intention of the test is to measure and collect data of temperatures in the fire compartment, on connections, beams and in the composite slab, internal forces in connections and deformations of composite slab in and out of plane. The test provides opportunity to study 3D behaviour, to measure temperature distribution of different types of connections, to monitor changes of internal forces and moments in the connections and composite slab and to determine the mode of failure. The performance of connections in fire depends on restraints of three-dimensional structure, which can be only investigated on natural scale. The frame at LBTF allows such investigation in a closely monitored environment, see [6].

The knowledge of performance of the structure allows application of such restraints in smaller scale tests. Thus, a programme of preparatory and supplementary tests on steel connections (four connections) will be performed at Czech Technical University in Prague. A complementary programme of eight tests on a T-shaped structural assemblage will be carried out in the Structural laboratory at Coimbra University. Observed and measured boundary conditions from the full-scale compartment test will be used in these test programmes in order to impose more
realistic (i.e. three-dimensional) conditions on smaller scale tests. This approach will help to obtain more relevant performance data on variety of steel joints at elevated temperature and to evaluate accuracy of present prediction methods.

2. STRUCTURAL ANALYSIS
Finite element code ANSYS 5.7 was utilized for the numerical simulation. The response of the structure was non-linear with spread of plasticity along the elements, large strains and large deformations. Multi-linear isotropic material with strain hardening was used for mild steel. Temperature dependent stress strain relationship ($\sigma - \varepsilon$) of the steel is based on the latest rules [7].

The structural elements were divided into nine finite elements. Beam element with three degrees of freedom at each node: translation in nodal x and y directions and rotation about nodal z-axis, marked in the ANSYS library as BEAM 23, was used for the beams and columns. This element allows linear temperature distribution along its height and length.

![Diagram](image)

Fig. 1 The compartment for integrity test at Cardington frame, a) b) c) connections in the frame

The solution was divided into three loading steps. In the first step, external forces (dead and live loads) were applied. In the second step, the heating phase was simulated by application of elevated temperature on beam in the fire compartment. The steel temperature $\theta_s$ of the bottom flange of the floor beam at mid span was
related to gas temperature, see [1]. Based on simple modelling of the compartment, the temperature of the structure reached $\theta_s = 720 \, ^\circ C$. Temperature of the top flange was estimated to $\theta_{top} = 0.70 \, \theta_s$. Temperature at the connections was 0.62 $\theta_s$ and 0.80 $\theta_s$ at the top and bottom of the beam respectively. The cooling phase was modelled in the third step applying negative temperature increment to the elements. Load increment with arc length control method was used for the calculation. The structural response from numerical analysis needs to be transferred to time-dependent relationship. Linear depression 10°C per minute was assumed in the cooling phase, see Fig. 2.

![Fig. 2 Predicted temperature curve of compartment and steel elements in heating and cooling phases of the fire](image)

3. JOINT BEHAVIOUR

Modelling of the joints is divided into two steps. In the first step, stiffness and resistance of the joints were obtained by component method [8]. It allows simulation of joint behaviour at high temperatures, see [9] and [10].

![Fig. 3 Joint representation; a) extended end plate joint, b) components of the joint, c) components in tension and compression zones, d) mechanical model of joint, e) modelling of joint in global analysis, f) rotational stiffness, g) translation stiffness](image)
In the second step, moment-rotation and force-deformation characteristics of the joints were modelled in the frame by elements of type COMBIN39, which is non-linear spring element, see [11]. For each joint, two separate elements with one degree of freedom were necessary. One spring was used for transfer of bending moments and the other for axial forces in the beams, see Fig. 3. Transfer of shear forces was modelled by coupling constraints of the connected nodes.

The results for beam with restrained expansion represent the upper boundary of internal forces in the real frame, see Fig. 4. When the beam is exposed to increasing temperature, the axial compressive force caused by thermal expansion increases. This causes high normal stress in the beam, development of plastic hinge at mid-span and buckling of the beam. Rapid increase of vertical deformation leads to drop of axial force. Further increase of temperature is accompanied by degradation of material properties (yield stress and modulus of elasticity) and causes high vertical deformations. At this stage, membrane effect of the deformed beam can be observed. During the cooling phase, the increase of compressive axial force is caused by changing of the material properties. The beam shortening results in tensile force at ambient temperature.

![Graph 4](image4.png)
**Fig. 4** Normal force in beam-to-column joint for beam with restrained expansion representing upper boundary of internal forces in the connection

![Graph 5](image5.png)
**Fig. 5** Normal force in beam-to-column joint for T stub assemblage representing lower boundary of internal forces in the connection
The T-shaped assemblage with external column of the frame represents the lower boundary for developing of internal forces. In this case, free expansion of the beam is modelled. Behaviour of the assemblage is primarily influenced by temperature dependent material properties of the beam. Results for three types of beam-to-column joints are shown in Fig. 5.

4. CONCLUSIONS

The numerical simulation of beams with free and restrained expansion shows influence of restraints on their behaviour. Simulation of the frame will help to predict response of the real structure and to apply adequate mechanical and fire loads. The behaviour of the frame is described in second part of the test project [6]. The large-scale test and its simulation are prepared to improve European practice by establishing rules to ensure structural integrity of buildings. This can be done by introduction of requirements for resistance to tie forces in structural design.

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REFERENCES