TO SHEAR RESISTANCE OF CASTELLATED BEAM EXPOSED TO FIRE

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Abstract. *The paper presents the comparison of the fire design of the unprotected castellated composite beam to the results of the fire test on administrative building. The transfer of heat into the structure shows a good conservative prediction of the test on real structure. The shear failure modes of the simplified mechanical prediction of the behaviour at elevated temperature are well visible on the load deformation curve as well as on relative deformation of the beam web close to its support.*

1 INTRODUCTION

The main goal of the fire test on a floor of an administrative building was the overall behaviour of the structure, which may not be observed on the separate tests on individual elements. A new building was erected in front of the Czech Technical University in Prague educational centre Joseph gallery in Mokrsko in Central Bohemia. The experiment followed the seven large fire tests in Cardington laboratory on steel frame conducted between 1998 and 2003, see [1]. The structure was design complex to allow a simple as well as advanced modelling of today modern buildings. Except of the three types of flooring systems were tested six wall structures with mineral wool. On one half of the floor was used the composite slab supported by the fire unprotected composite pretty castellated beams with large openings ArcellorMittal Angelina^{TM}, see Figure 1. The experimental structure represents a part of a floor of administrative building of size 18 x 12 m with height 2,68 m, see [2].

Figure 1: Thermocouples located at the midspan on the castellated beams and its connections

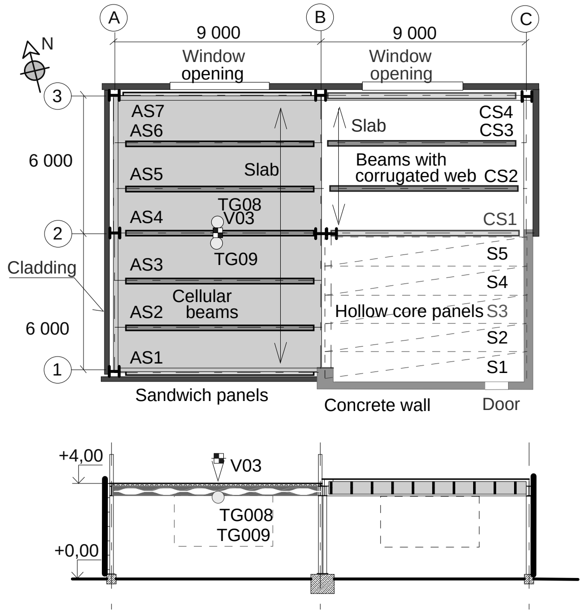

Figure 2: Structure of experimental building for fire test

The composite slab on the castellated beams was designed with a span 9 to 12 m and on beams with corrugated webs with a span 9 to 6 m. The deck was a simple trapezoidal composite slab of thickness 60 mm with the height over the rib 120 mm with sheeting CF60 (Cofraplus 0,75 mm) and concrete of measured cubic strength 34 N/mm^3 in 28 days reinforced by a smooth mesh ø 5 mm 100/100 mm; with strength 500 MPa and coverage 20 mm. The castellated beams with sinusoidal shape openings were made from profile IPE 270 and its web height was 395 mm. The beam has the parameters A_{net} = 3769,5 mm^2 A_{gross} = 5419,5 mm^2; $I_{y,net}$ = 128,8 · 10^6 mm^4; $I_{y,gross}$ = 137,4 · 10^6 mm^4. The connections were design as simple with header plate connection partially encased in the concrete slab.

The test was observed apart from other by more then 300 thermocouples, twenty deflectometers, six flux density meters, two meteorological stations, ten video, and four thermo imagine cameras. The gas temperature round the castellated beam was measured by thermocouples TG08 and TG09 at the level of lower flange, see Figure 1. Round the experimental building was erected the structure from scaffold. The vertical deformations were measured from the twins of timber formwork beams, which were fixed on linear scaffolds and on bridged truss girders 1,5 m above the building floor.

The mechanical load was designed for typical administrative building, where the variable action in Czech Republic reached usually from 2,5 to 3,5 kN/m^2. The dead load of the composite slab and beams reached 2,6 kN/m^2. The load was created by bags. The load represents the variable load at ambient temperature 3,0 kN/m^2 and added permanent load 1,0 kN/m^2 in characteristic values. Mechanical load 3,0 kN/m^2 was represented by 78 sand bags; each bag had approximately 900 kg. These sand bags were put on wooden pallets and uniformly distributed on the composite slab and pre-stressed panels.

Two window openings in the front wall with dimension 2.43 x 4.0 m provided air supply into the fire compartment. Fire load was made of rough battens from soft pine wood, total volume of 15 m^3. The usual characteristic value of the fire load for administrative building is 420 MJ/m^2, by the experiment the fire load reached 515 MJ/m^2.

The aim of this paper is to show the accuracy of simplified modelling of the shear behaviour of the composite castellated beam. The prediction of the beam AS4 located between the columns A2 and B2 is presented.

2 HEAT TRANSFER INTO THE CASTELLATED BEAM

In fire, the temperature distribution across a composite member is non-uniform, since the web and bottom flange have thin cross-sections and a greater exposed perimeter than the top flange. The deterioration of the material properties of the web may therefore become an important effect on the overall performance of the member in the event of fire. The former fire resistance studies has been focussed to intumescent protection, see [3], as well as temperature developments in unprotected steel, see [4].

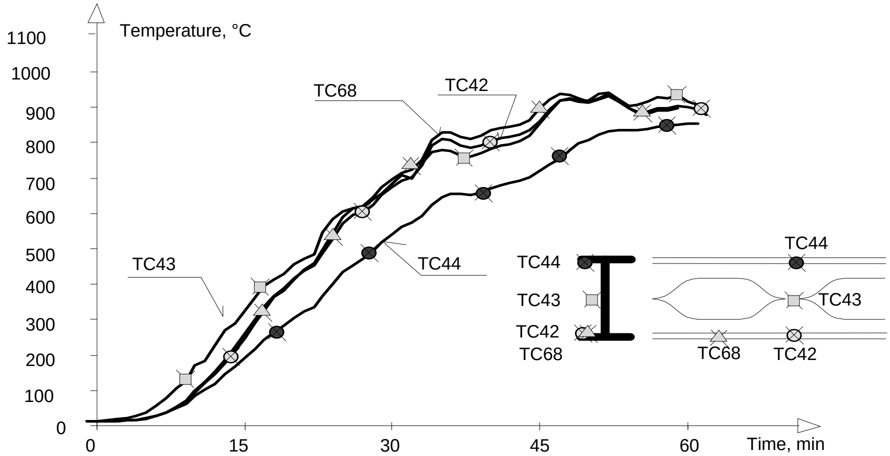

Figure 3 Temperatures measured at the midspan on the castellated beam AS4

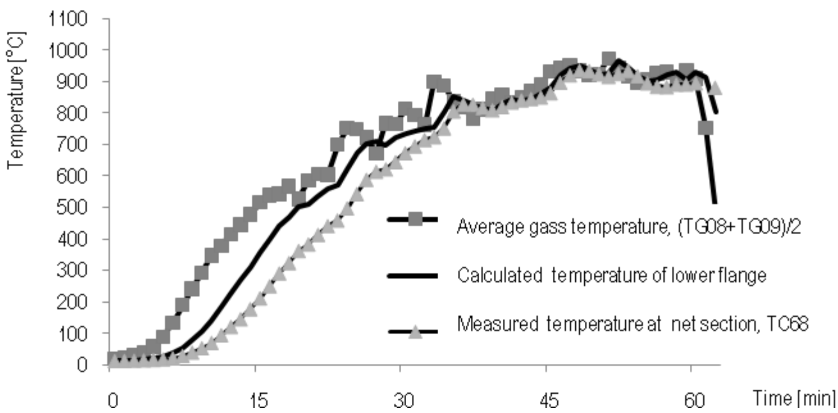

Figure 4: Calculated and measured temperature of the beam lower flange

In the described test was measured the gas temperature round the castellated beam by thermocouples TG08 and TG09 at the level of lower flange. The average gas temperature round the castellated beam was calculated from thermocouples as an average TG08 a TG09, see Figure 3. The step by step procedure according to EN 1993-1-2, see [5] was used to predict the parts of the structure temperature. For the lower flange was calculated the section factor $A_p/V = 232{,}1\ m^{-1}$, for the beam web $303{,}0\ m^{-1}$, for the upper flange exposed from the three sides $156{,}6\ m^{-1}$ and for the net section of the beam $178{,}3\ m^{-1}$. The comparison of this simple prediction to the measured values is shown at Figures 4 and 5.

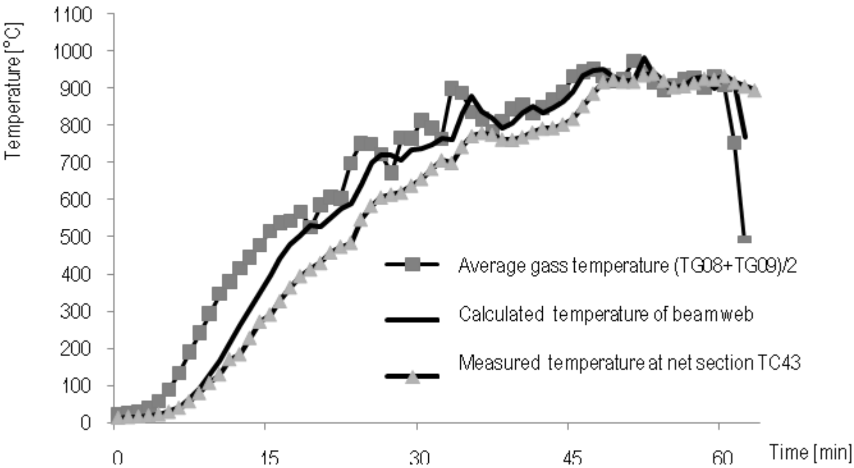

Figure 5: Calculated and measured temperature of the beam web

3 BEAM RESISTANCE

Several investigations into the castellated beams structural behaviour have supported the widespread use of as structural members in steel to concrete composite frames. First studies at ambient temperature concentrated on in plane response in the elastic range and later plastic one as well. Extensive measurements were made of the stress distributions across the cross-section, and these were compared with the predictions of various theoretical studies employing a Vierendeel analogy, finite difference techniques, and a complex variable analytical method. As a result of various series of tests a number of different failure modes have been observed, see [6]. The main failure modes are a Vierendeel collapse mechanism in which plastic hinges form at the section touching the four re-entrant corners of a castellation, buckling of a web-post, and web weld failure. Several prediction of collapse mechanisms have been proposed, see [7], and the lateral buckling of the web-posts has been analysed. Only limited investigations of composite floors using castellated steel beams at ambient temperature have been conducted, see [8]. The beams have been used widely in roof and composite construction without having been rigorously investigated under fire conditions. A composite concrete floor-slab has the effect of significantly increasing the flexural resistance of a steel section. Investigation of the behaviour of composite beams with isolated web openings in otherwise solid webs has shown that the slab significantly increases the shear-carrying capacity beyond that of the steel beam alone. This is due to the enhanced flexural and shear capacity of the upper part of the beam across an opening, although an unsupported webpost is more susceptible to buckling, see [9] and [4]. The simplified model for evaluation of the fire resistance of the beams was developed based on FE modelling approved by two fire tests, see [10].

In the fire test in Mokrsko 2008 were examined beams with large web openings which are sensitive to the shear resistance of the web and flanges. The advanced FE model was prepared to predict the behaviour before and after the fire test au University of Sheffield, see [2]. In the simplified calculation were utilised for the internal forces distribution by the Vierendeel analogy and the adequate failure modes were observed, see [11].

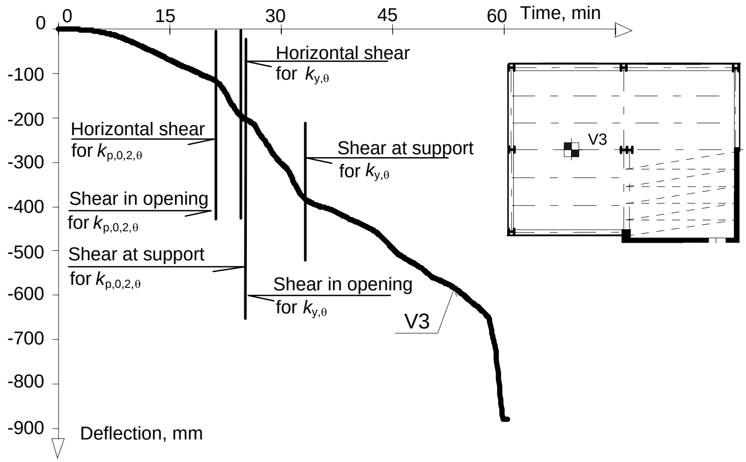

Figure 6: Measured deflection of the castellated beam AS4 with reached shear resistances

The beam was exposed a uniform action $f = 6{,}8 + 2{,}6 = 9{,}4$ kN/m, which creates a bending moment $M = f \cdot l^2/2 = 9{,}4 \cdot 9^2/2 = 95{,}175$ kNm and acting shear force $V = f \cdot l/2 = 9{,}4 \cdot 9/2 = 42{,}3$ kNm. In evaluation of the shear resistance was assumed the shear area at beam support as $395 \cdot 6{,}6 = 2607$ mm^2; the area of the web in opening $0{,}9\,(2 \cdot 72{,}5 \cdot 6{,}6) = 861{,}3$ mm^2; the minimal horizontal shear area is $0{,}9 \cdot 250 \cdot 6{,}6 = 1485$ mm^2. The critical temperature of the shear resistance in support $V_{max} = 42{,}3$ kN may be calculated from the reduction factor of the effective yield stress $k_{y,\theta}$ from $42{,}3 = k_{y,\theta} \cdot 0{,}6 \cdot 235 \quad 2607/10^3$ which is $k_{y,\theta} = 0{,}1151$. Thus the critical temperature is 795,7 °C. The beam web reached this steel temperature in 34 min. From the reduction factor of proportional limit for steel at elevated temperature $k_{p,0,2,\theta}$ the temperature of steel 661,8 °C is derived, which was reached in 25 min.

For the shear resistance in the beam web opening $V_{max} = 36{,}2$ kN may be the reduction factor of the effective yield stress calculated from $36{,}19 = k_{y,\theta} \cdot 0{,}6 \cdot 235 \quad 861{,}3/10^3$ and $k_{y,\theta} = 0{,}2980$. The adequate beam web temperature 673,7 °C will be reached in 25 min. For the effective yield stress it is $k_{p,0,2,\theta}$ it is web temperature 544,5 °C in 21 min.

From the horizontal shear resistance V_h, which is $V_{max} = 54{,}8$ kN may be derived for $54{,}8 = k_{y,\theta} \cdot 0{,}6 \cdot 235 \quad 1484/10^3$ the factor $k_{y,\theta} = 0{,}2620$ and the temperature 686,8 °C, which is reached on 24 min. The proportional limit $k_{p,0,2,\theta} = 0{,}2620$. The reached values of degradation of the beam are shown on Figure 6. No beam weld failure was observed on collapsed structure.

Close to connections was the beam instrumented with strain gauges for high temperatures to assume the shear stress across the web during the fire test. The application of the free-filament high-temperature strain gauges, which are sandwiched between two thin ceramics cement layers, allow to measure up to a temperature of 1150 °C. The accuracy of the measurement is 3 % till the 5000 μm, which limits the positioning of the strain gauges. Two strain gauges were applied in the middle third of the web height of castellated beam, see Figure 7. The stress at elevated temperature σ_θ was derived from the measured strain using Young´s modulus of elasticity at elevated temperature $E_{a,\theta} = k_{E\theta}\, E$ and the corresponding temperature recorded by the thermocouples

$$\sigma_\theta = \min\,(k_{E,\theta}\, E\, \varepsilon_\theta;\; k_{y,\theta}\, f_y) \tag{1}$$

where $k_{E,\theta}$ is the reduction factor for the slope of the linear elastic range at the steel temperature, see [5], E is the elastic modulus of steel; ε_θ is the strain at elevated temperature; $k_{y,\theta}$ is the reduction factor for the yield strength of steel at the steel temperature, see [5]; f_y is the yield strength at ambient temperature, 355 MPa. Figure 8 documents the strain development the predicted loss of the shear resistance.

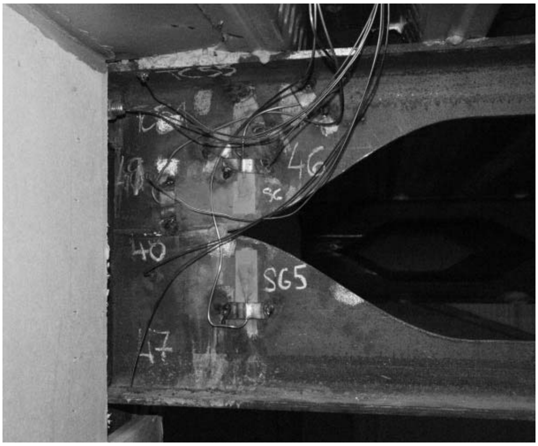

Figure 7: Strain gauges on the web of the castellated beam

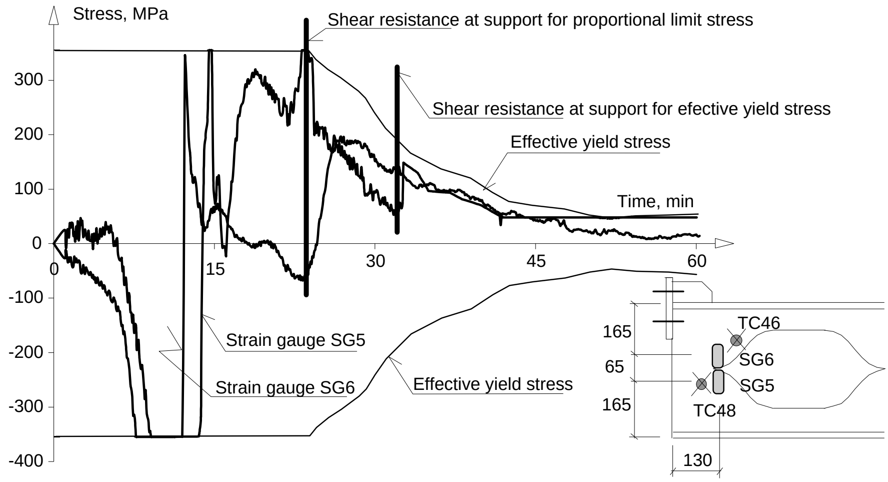

Figure 8: The measured stresses on the web of the castellated beam and predicted shear resistance

4 CONCLUSION

The fire test approved a good fire resistance of composite slab with unprotected castellated beams, which is higher compare to the separate composite beam resistance, see Figure 9. The slab resistance, designed for R60, was reached at 62 min and the beam shear resistance in 21 min.

The experimental data confirms a reasonable accuracy of prediction just by a simple model, even though the stresses of beam in structure are highly influenced be elements elongation/shortening.

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Figure 9: The deformed beams in the 35 min of the fire test

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