TEMPERATURE HETEROGENEITY OF TRAVELLING FIRE AND ITS INFLUENCE ON COMPOSITE STEEL-CONCRETE FLOOR

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ABSTRACT

In order to follow modern trends in contemporary building architecture, which is moving off the limits of current fire design models, assumption of homogeneous temperature conditions used for structural fire analysis needs to be revised. In this paper fire dynamics of travelling fire is investigated experimentally by conducting fire test in two-storey experimental building. To evaluate the impact of travelling fire on the mechanical behaviour of a structure, the spatial and temporal evolution of the gas temperature calculated in NIST code FDS, which was validated to experimental measurements, is applied to the composite floor of dimensions 9.0 m by 9.0 m. Mechanical behaviour of the composite slab highly affected by regions of high temperatures and areas with only elevated temperatures is solved in code Vulcan. To highlight the severity of spreading fire causing non-uniform temperature conditions, which after-effects differ from traditional methods, a comparison of both methods is introduced. The calculation of mechanical behaviour of the composite floor is repeated in a series of three different thermal loading cases. Results of all cases are then compared in terms of vertical displacement and axial force in several positions of the composite floor.

KEYWORDS

structural fire design; travelling fire; fire test; non-uniform temperature conditions; CFD; structural response; composite steel-concrete floor

INTRODUCTION

In recent years, traditional design fire methods and their features of realistic description of fire have been criticised. Mainly in buildings with loss of compartmentalization the fire behaviour has been described in different manners. The consequences of larger compartments, evident in several tragic fires as in the World Trade Centre or the Windsor Tower in Madrid, show that fires tend to travel. As flames spread within the floor to consume fuel, regions with high temperatures and regions with elevated temperatures are created. In [1] several studies presenting the experimental evidence of non-uniform temperature across the floor area of a compartment can be found.

In relation to the non-uniform temperature resolution the spatial and temporal evolution of the temperature of the structural elements allowing to determine stresses and deformations within the structure need to be resolved. In order to investigate dynamics of travelling fire with subsequent revision of the effect of the thermal heterogeneities to a structural member, a full-scale fire test was executed in 2011 [2]. To demonstrate the influence of horizontal fire spread on the structural behaviour, a model of composite steel and concrete floor of geometrical and temperature data taken from full-scale fire test is introduced.

CURRENT STAGE

Traditional fire models

The traditional fire design methods widely used in structural fire analysis are based on an assumption of homogeneous temperature conditions in the entire floor area of a compartment. This conservative predication is the result of wide-scale used standard temperature time curve (so called ISO 834 curve) and parametric time temperature curve, design fire models recommended by EN 1991-1-2. Similarly zone models, advance fire models recommended by EN 1991-1-2, leads to homogeneous temperature conditions in horizontal layers across the entire compartment floor. Moving further, advanced design fire model of local fire can be applied in practical use. However the model describes a growth in size as a result of flame spread over the item first ignited, and it also enables to calculate temperature decrease with increasing distance from the central axe of the fire plume in horizontal plane, the flaming core does not move. It remains on the place of origin.

Besides the assumption of homogeneous temperature distribution traditional design fire models have limits in their applicability. Current development of multi-storey buildings uses a number of architecturally unconventional and modern design elements. A spacious atrium, large undivided spaces, high ceilings, connected floors, glass façades and other interesting elements are not according to [3] included in traditional design fire safety methods. A recent study [4] highlights the growing problem in the use of traditional design fire models. It was found that only 8% of the buildings, characterized by modern elements of contemporary architecture, as mentioned connected open spaces and glass façade, falls within the defined area of traditional methods.

Models of travelling fire

Observations of real fires in compartments show that fires tend to travel. It can rarely happen, all combustibles burn simultaneously throughout the whole compartment. Only a part of a floor area is usually involved in a fire. Until all combustibles are burned out, oxygen supply is depleted or fire brigade start extinguishing, flames spread from an ignition core to consume neighbouring fuel. Due to spread of fire, regions of higher and lower temperatures appear.

Recently, several models of travelling fire have been introduced. Clifton in [5] developed a model for fire in large compartments in which the assumption of uniform burning cannot be applied. The fire compartment can be divided into a number of design areas in which fully-developed burning occurs before moving to other areas.

More recently, Stern-Gottfried [6] has developed an alternative method for modelling travelling fires in large compartments. They suggest that due to localised burning, the gas temperature consists of near-field (temperature of flames, usually around 1200 °C) and far-field temperatures (temperature of hot gases layer). The far-field temperature T_{ff} varies with the distance from the fire. Its distribution can be determined with aid of computational fluid dynamics models or by hand calculation suggested in [7].

TRAVELLING FIRE SCENARIO

Experimental background

For the purpose of investigation of spreading fire, a full-scale fire test illustrated in *Fig. 2b* was carried out in the Czech Republic. A two-storey composite steel-concrete experimental structure of dimensions 10.4 m x 13.4 m x 9 m was designed. Load-bearing structure is shown in *Fig. 1* and described in detail in [2] and [8]. In the upper floor a natural fire spread was simulated by burning of wooden cribs placed closely together on area of 24 m^2. Total volume of ligneous mass used was 2.52 m^3. A thin-walled channel filled by mineral wool and penetrated by paraffin placed on the south side of the fire compartment served as a linear outbreak of burning, see *Fig. 2a*. The sufficient supply of air needed for burning was ensured by an opening of 10 m^2. The gas temperature in the fire compartment was measured by jacketed thermocouples located mainly in the direction of horizontal fire spread.

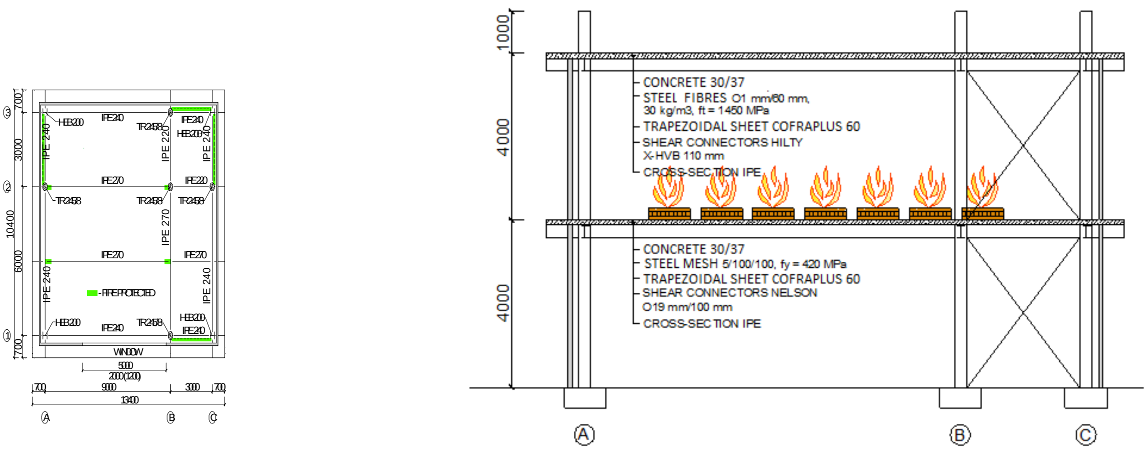

Fig. 1 Experimental two-storey structure scheme

a) b)

Fig. 2 a) Fire load scheme in the upper floor of the experimental building,

b) Photo of the fire test in the upper floor

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Since the scale of experimental enclosure was not large in comparison to the scale of real buildings, high degree of temperature non-uniformity appeared. Between 26 and 30 min., when peak temperatures over 900 °C were reached, the temperature variance of the ceiling layer overgrew 250 °C. The highest degree of gas temperature non-uniformity caused by spreading of flames from the place of ignition to the opposite site of the compartment, appeared at thermocouples placed in the direction of fire spread below the beam 2. However the distance between thermocouples was not large, the difference of 400 °C, which may be observed from temperature contours in *Fig. 3*, was recorded in 15 min.

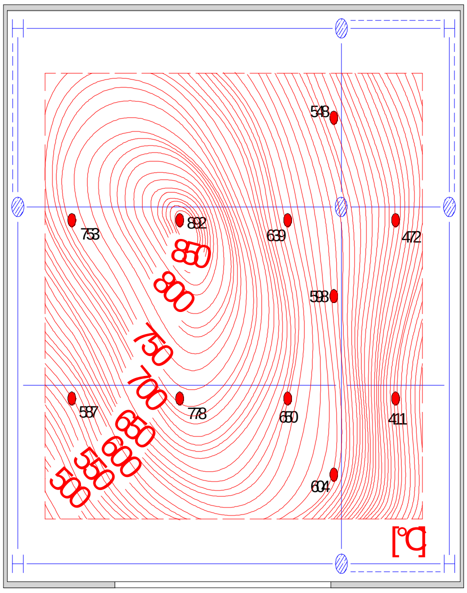
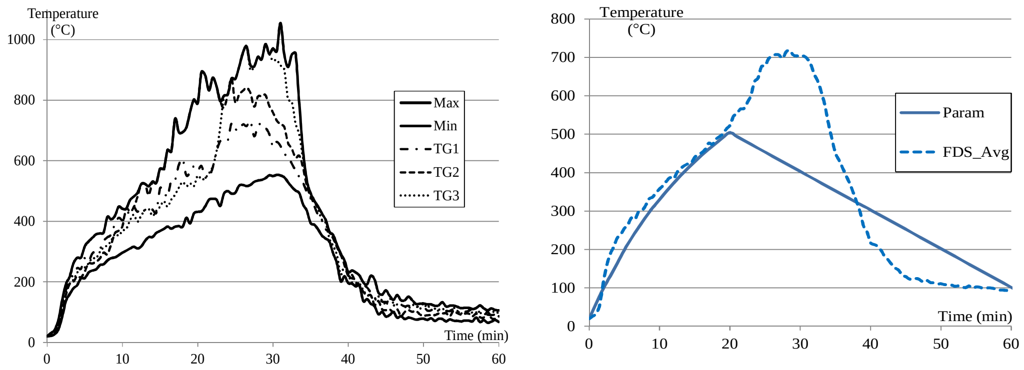


Fig. 3 Gas temperature contours (in °C) recorded in 15 min. of the fire test

Numerical simulation

The spatial and temporal development of gas temperature bellow the steel-concrete floor needed as an input of thermal loading of mechanical behaviour calculation was numerically solved in NIST code FDS 5 [9]. Gas temperature calculated in positions of thermocouples was validated by measurements carried out during the fire test. The simulation confirmed spreading phenomena from the initial outbreak of the fire to the opposite side of fire compartment. However, calculated values were slightly delayed in comparison to the measured values. The numerical model represents the tendency of the measured temperatures mainly in the growing phase, where the highest temperature gradient appeared. Despite the fore-mentioned, results of the numerical simulation are sufficiently applicable to investigate an impact of non-uniform temperature resolution on a structural behaviour. Detailed description of the numerical simulation and its validation can be found in [1].

The range of gas temperature calculated at 18 sensors bellow the composite floor limited by two curves illustrating the maximum and minimum values is shown in *Fig. 4a*. Maximum degree of gas temperature heterogeneity was reached between 20 and 30 min. on sensors below the internal beam 2 and sensors located in the corner of the compartment. Despite the distance between thermocouples being only 4 m, a significant temperature difference of 355 °C was observed in 20 min.



a) *b)*

Fig. 4 a) Calculated gas temperature during travelling fire; b) Average gas temperature from FDS calculation and parametric temperature curve.

STRUCTURAL ANALYSIS

Model of composite steel-concrete floor

The spatial-temporal evolution of gas temperature coming from FDS simulation is applied to a FEM model of the composite floor of dimensions 9.0 m by 9.0 m which represent a part of the experimental floor. The concrete slab composed of trapezoidal sheet and concrete C 30/37 is supported by 3 protected steel beams of profile IPE 240 and 2 unprotected steel beams of profile IPE 270 and IPE 220 forming its perimeter, 2 secondary unprotected steel beams of profile IPE 270 and 6 protected steel columns of profile HE200B. Steel elements are of grade S355. The concrete slab of continuous depth of 70 mm is reinforced by 2 layers of steel bars of area 196 mm^2/m placed 30 mm from the top of the cross-section. Partial interaction between concrete slab and supporting steel beams is ensured by shear connectors of diameter 19 mm of ultimate shear strength 450 N/mm^2 placed in total of 2.11 pieces/m. Data of the floor including geometry, beam cross-sections and mechanical loading employed in the calculation of structural response are illustrated in *Fig. 5*. All structural elements being loaded by respective temperature curves are divided into mesh elements of 1.0 x 1.0 m. Mechanics equations to determine stresses, internal forces and deformations are then solved by code Vulcan.

The computer program Vulcan [14] is a three-dimensional frame analysis program, which has been developed at the University of Sheffield to model the behaviour of structures under fire conditions. In this program steel-framed and composite buildings are modelled as assemblies of finite beam-column, connection and layered floor slab elements. The general continuum mechanics equations for large-displacement/rotation nonlinear analysis are applied. The main assumptions of the elements can be summarized as follows: Cross sections remain plane and undistorted under deformation and there is no slip between segments. They do not necessarily remain normal to their reference axis, as they are originally located, as displacement develops. The “small strain and large deformation” theory is adopted. This means the displacements and rotations can be arbitrarily large but strains remain small enough to obey the normal engineers’ definition. The cross section of a beam-column element is divided into a matrix of segments, each segment can then have its own material, thermal and mechanical properties, and its own temperature, at any stage of an analysis. This allows modelling of different temperature distributions across member’s cross-section and, therefore, the different thermal strains and changes of material properties that accompany different temperatures across the section can also be tracked.

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To compare the impact of fire spread with uniform temperature resolution across the floor area of the fire enclosure the model of the steel and concrete composite floor is subjected to series of three different thermal loading. Thermal load in terms of uniform temperature distributed bellow the composite floor is simulated firstly by parametric temperature curve (case Param) calculated according to Eurocode 1 [10]. Geometry of the fire compartment, fire load density, ventilation and thermal characteristic of surrounding walls are considered the same as it was presented during the fire experiment. Secondly, the uniform temperature distribution bellow the floor is applied by the help of average temperate of all sensors calculated in FDS numerical simulation (case FDS_Avg). Comparison of both temperature curves of thermal loading Param and FDS_Avg is shown in *Fig. 4b*. However the growing phase of both curves corresponds well, the peak temperature of parametric temperature curve is about 200 °C lower comparing to average FDS temperature curve. With the view to investigate the influence of spreading fire scenario on the behaviour of composite steel-concrete floor 18 gas temperature developments coming from FDS calculation are applied to certain parts of the floor similarly to location of sensors in FDS model. In most cases temperature curves are applied to area of 3 x 2 mesh cells. In areas with high temperature heterogeneity - the centre of the floor and bellow the beam 2, temperature resolution is higher.

In the analysis material models of steel, concrete and reinforcement steel at elevated temperatures are referred to Eurocode 2 [11] and Eurocode 3 [12]. The temperature in the cross-section of the main elements forms a non-uniform pattern in which each major element of the section's temperature is a proportion of the heating temperature curve. These proportions vary with time and with the particular heating curve being applied. *Fig. 6* indicates the temperature distribution in cross-sections of protected beams, unprotected beams and floor slab. All columns have temperature factor of 0.7 which is uniform across the entire cross section. Temperature patterns used in the analysis follow recommendation in benchmark study of the software in [13].

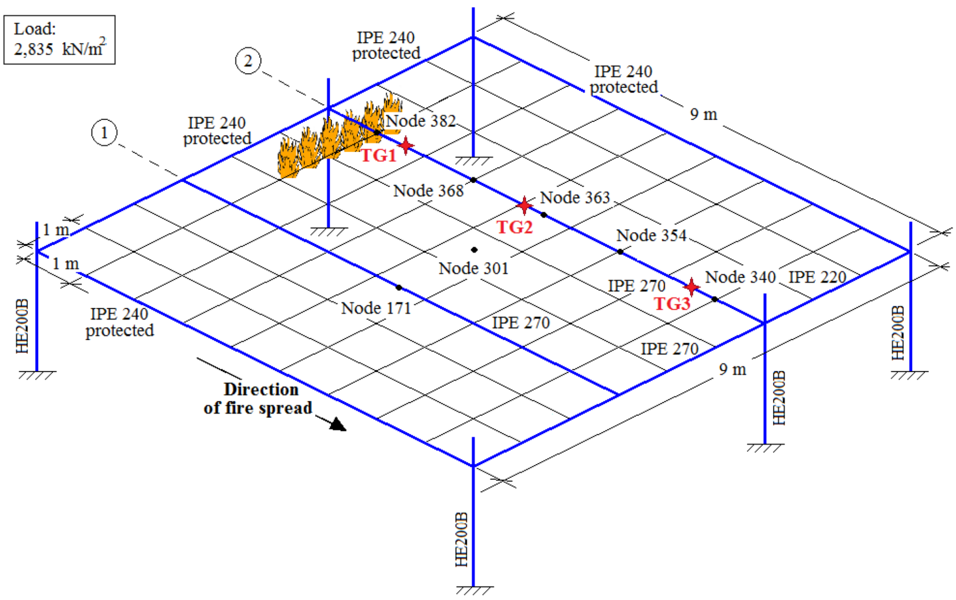

Fig. 5 Model of composite steel-concrete floor

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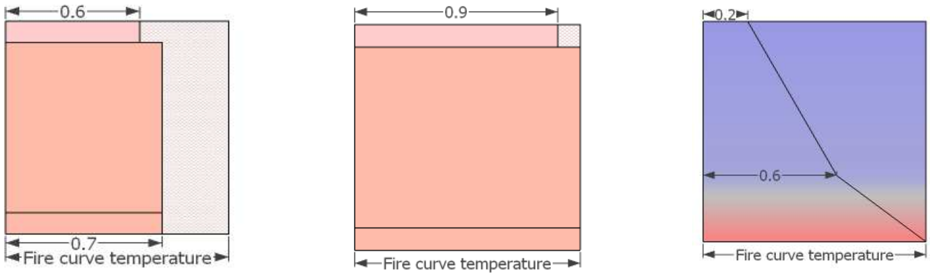


a) b) c)

Fig. 6 Temperature distribution at cross-section of: a) protected beam; b) unprotected beam; c) floor slab

Comparison of results

Mechanical behaviour of steel-concrete composite floor is investigated in terms of displacement in the central point of the floor (Node 301, for location see scheme of the model in *Fig. 5),* vertical displacement and axial force along internal beams. The essential results are summarized in *Figs. 7-9. Fig. 7a* shows the increase of deflection in central point of the floor (Node 301) for all thermal loading cases: parametric temperature and average temperature calculated from FDS results which are uniformly distributed bellow the entire area of the floor, and travelling fire temperatures coming from FDS calculation which represents natural spreading of the fire. As it can be observed from the figure deflection caused by parametric temperature increases slowly from the beginning to reach its maximum value about 150 mm in 20 min. However, both deflection curves caused by travelling fire and average FDS temperature track the previous one during first 20 min. of heating, both start to increase rapidly after 20 min. to reach their peaks in 30 min. The peak value induced by travelling fire is 360 mm, about 35 mm more than the maximum deflection caused by uniformly distributed average FDS temperature. Comparing to deflection incurred by parametric temperature curve the difference is 230 mm. The results demonstrate that the severity of fire spread when temperature of flames and only elevated temperatures act simultaneously in different locations of the floor slab causes more significant mechanical behaviour comparing to uniformly distributed temperature heating.

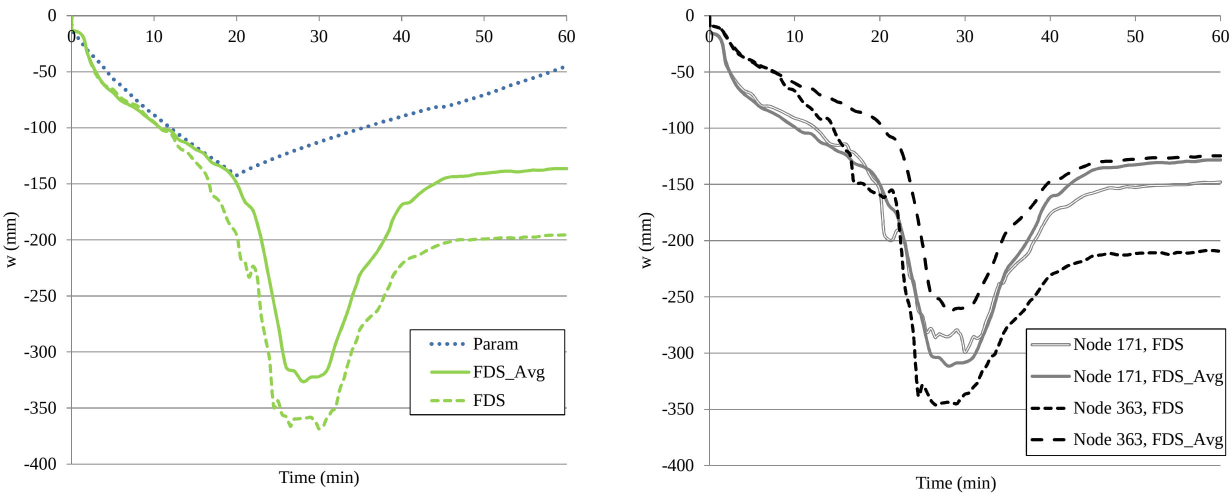
As the fire load was placed asymmetrically in the view of location of both internal beams, vertical displacement of middle point of these beams differs. In *Fig. 7b* a mid-span displacement of beam 2 is described by Node 363, Node 171 illustrates a mid-span displacement of the beam 1 (for location see scheme of the model in *Fig. 5*. The figure demonstrates the difference caused by uniformly distributed heating by FDS_Avg curve and fire spread (load case FDS). Influence of parametrical curve is no longer introduced. It can be observed that maximal displacement is reached during load case FDS at beam 2. In the same node (Node 363) the displacement caused by FDS_Avg is about 90 mm lower. Looking at beam 1, maximal displacement caused by both loading cases are about the same level, with slightly higher values induced by FDS_Avg loading. The variance of results is mainly caused by acting of flames bellow the beam 2 which high temperature is not suppressed within the use of 18 temperature curves coming from FDS, whereas the average FDS temperature is decreased involving corners elevated temperatures. It can be seen that the location of an element considered is an important factor when choosing a type of thermal loading.

Considering a recovery of displacement which occurs when the temperature is reduced, the spreading fire scenario causes the highest final residual displacements. In *Fig. 7a* it can be observed that displacement of the middle point of the slab caused by loading case FDS remains at

200 mm which is about four times higher comparing to uniform heating by parametric temperature curve. Final residual displacement of uniformly distributed FDS_Avg curve stops at 130 mm, which is about 70 mm lower comparing to FDS case. The significant difference in the final residual displacements shows the importance of covering the fire spread scenario into design fire models considered.

To investigate the mechanical behaviour of supporting steel beam 2, where the maximal effects of thermal loading are reached, vertical displacements and axial forces along its length are introduced in *Figs. 8 and 9*. Curves of vertical displacements in time shown in *Fig. 8* are described by the aid of nodes 382, 368 and 354. These nodes are located at beam 2 according to illustration in *Fig. 5*. As it can be expected according to application of temperature curves simulating the fire spread, the maximal deflection of 350 mm is reached in node 354 where the highest temperatures appeared. Vertical displacement of node 368 is about 100 mm lower and displacement of node 382 about 300 mm lower comparing to node 354. The significant difference of displacement along the beam length is caused by high degree of temperature non-uniformity bellow the beam. In contrast, during uniform temperature distribution covering both, parametric temperature and average FDS temperature curve, the maximal deformation occurs in the middle of the beam span.

In accordance to vertical displacement illustrated in *Fig. 8* axial forces in corresponding beam elements are introduced in *Fig. 9*. Beam elements used for description in *Fig. 9* are located subsequently: beam 37 lies between nodes 382 and 368, beam 35 between nodes 368 and 354 and beam 33 lies between node 354 and 340. As the loading temperature is increased compression forces start to decrease by both loading cases. Forces start to turn into tension when the maximal temperature and also deformation is reached. The final residual axial forces remains the highest by loading case of spreading fire, similarly to description of final residual displacements in previous paragraph.



a) *b)*

Fig. 7 Comparison of displacement cause by different thermal loading cases in time: a) in the central point of the floor (Node 301); b) in mid-span of beam 1 (Node 171) and beam 2 (Node 363)

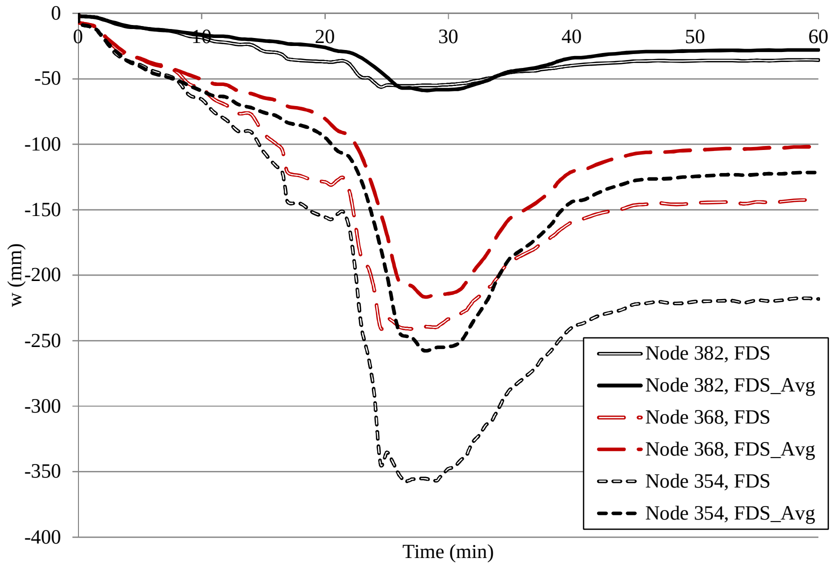


Fig. 8 Vertical displacement in several locations of beam 2

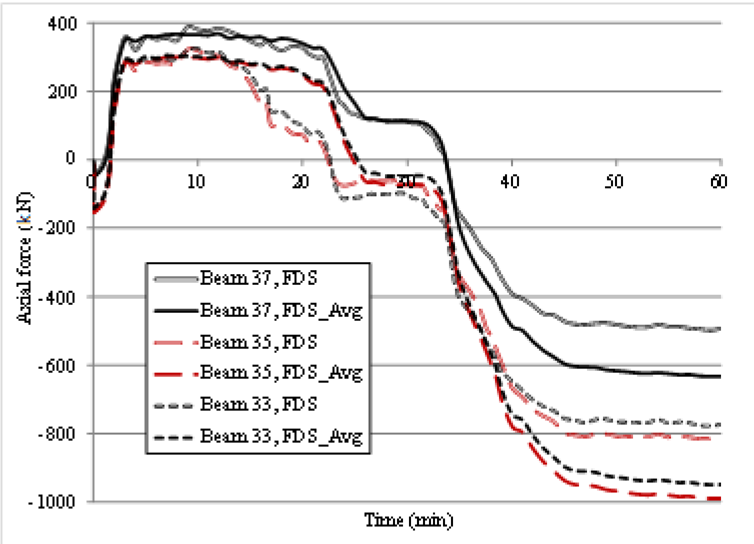


Fig. 9 Axial force along the length of beam 2

SUMMARY

In order to revisit the assumption of homogeneous temperature conditions in compartment fires used for fire design analysis, travelling fire was investigated. Based on the fire experiment executed by Wald [2], numerical simulation of fire dynamics of travelling fire scenario is performed in FDS 5. Numerical results of temperature development during the fire are validated by measurements carried out during the fire test. Since the scale of experimental enclosure was not as large as the scale of real buildings, high degree of temperature non-uniformity appeared. Variations in temperatures of the upper smoke layer up to 400 °C confirm that the homogeneous temperature assumption does not hold in compartment fires.

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To demonstrate the influence of horizontal fire spread on the mechanical behaviour of three-dimensional structure subjected to more realistic temperature loading, a model of the composite steel and concrete floor of temperature data validated to full-scale fire test is investigated in this paper. To highlight the severity of travelling fire, which after-effects differ from traditional methods, the calculation of mechanical behaviour of the composite floor is repeated applying uniform gas temperature distribution in the entire compartment and compared to the effects of travelling fire. The introduced results demonstrate that regions with high temperatures and areas with elevated temperatures which act during travelling fire cause more severe mechanical behaviour of the composite steel-concrete floor. In given case the central-point deflection was 11 % higher comparing to average FDS temperature and 157 % higher comparing to effect of parametric temperature curve.

By the results described in the paper authors would like to show that a methodology allowing to describe the temperature environment in an enclosure more realistic is crucial for examination of structural response to fire.

6. References

[1] Horová et al, 2013: Horová, K., Wald, F., Jána, T., Temperature heterogeneity during travelling fire on experimental building, In: *Advances in Engineering Software*. 2013, vol. 62-63, no. 62-63, p. 119-130. ISSN 0965-9978, http://dx.doi.org/10.1016/j.advengsoft.2013.05.001

[2] Wald et al, 2011: Wald, F., Jána, T., Horová, K., Design of joints to composite columns for improved fire robustness to demonstration fire tests, Česká technika – nakladatelství ČVUT, 2011.

[3] Stern-Gottfried, 2010: Stern-Gottfried J., Rein G., Bisby L.A., Torero J.L., Experimental

[4] Jonsdottir, A., Rein, G. 2009. Out of Range. Fire Risk Management. 2009. review of the homogeneous temperature assumption in post-flashover compartment fires,*Fire Safety Journal*

[5] Clifton C.: Fire Models for Large Firecells, *Hera Report R4-83, Heavy Engineering Research Association*, Auckland, 2006.

[6] Stern-Gottfried and Rein, 2012b: Stern-Gottfried, J. and Rein, G., Travelling fires for structural desing- Part II: Design methodology. *Fire Safety Journal*. 2012, 54.

[7] Stern-Gottfried and Rein, 2012a: Stern-Gottfried, J. and Rein, G., Travellling fires for structural design- Part I: Literature review. *Fire Safety Journal*. 2012a, 54.

[8] Jána et al, 2011: Jána, T., Wald, F., Jirků, J., Zíma, P., Fire test on experimental bulding, in Czech Požární zkoušky na dvoupodlažní experimentální budově, *Konstrukce,* roč. 2011, č. 6, s. 57-59.

[9] McGrattan et al, 2010: McGrattan K., Hostikka S., Floyd J., Fire Dynamics Simulator (Version 5) Users Guide, *NIST Special Publication 1019-5*, Baltimore, 2010., 45, 249.

[10] Eurocode 1. Actions on structures, Part 1.2: General actions – Action on structures exposed to fire. Europena Committee for Standardization, 2002.

[11] Eurocode 2. Design of concrete structures, Part 1.2: Structural fire design. Europena Committee for Standardization, 2004.

[12] Eurocode 3. Design of steel structures, Part 1.2: Structural fire design. Europena Committee for Standardization, 2004.

[13] Wald et al, 2014: Wald, F., Burgess, I., Kwasniewski, L., Horová, K., Caldová, E., Benchmark Studies, Verification of numerical models in fire engineering, CTU Publishing House, 2014.

[14] Vulcan – A software for Structural Fire Engineering, Vulcan Solutions Ltd – A company of Sheffield University Enterprises Limited, Sheffield, UK. Available from http://www.vulcan-solutions.com/index.html.