MEASUREMENTS AND MODELLING OF FIRE SMOKE AND TOXICITY

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Performance based design for life safety in residential and commercial buildings is based on ensuring a safe evacuation from the building before the fire or its products can cause them any harm. In fire engineering technical terminology, the Available Egress Time (ASET) must exceed the Required Safe Egress Time (RSET) with an appropriate margin of safety. RSET depends on the interaction between people and layout of the building, while ASET depends on the interaction between development of fire and the layout of the building. Fire can harm the safety of life by thermal effect, reduction of visibility and toxicity (asphyxiant and irritant gas effects). Fire products are most likely to compromise the escape of the occupants before flames reach them, recently published fire statistics in Great Britain show that in 2011 the most dominant cause of death in fire incidents was being overcome by smoke and toxic products (which is the same conclusion for the past few decades).

Quantifying the smoke products and their effects on people is a challenging task. Because every fire is different; fuel type, layout of fuel, ignition location, size of compartment and ventilation mechanism. Some fire dynamics correlations partially address these factors and are able to give some guiding quantitative approximation for limited and simplistic fire scenarios. Most of the available smoke toxicity measurements are based on fully ventilated fire conditions and therefore are not representative of many real compartment fire scenarios.

Full scale experiment is the ultimate simulation of a fire that would produce reliable measurements, however the high financial and time cost of conducting such experiments limits the amount and speed at which such data can be obtained.

The main objective of the project is to develop and validate a suitable bench-scale test setup (based on the popular apparatus Cone Calorimeter) as a method for evaluating toxicity of materials in enclosed air starved compartment fires. Such setup would enable the fast production of detailed toxicity data in relevant and varied fire scenarios.

As part of this project eight real scale experiments have already been conducted in Jersey, Channel Islands and these would form the main validation bench mark for the bench scale testing method.

The project involves 3 distinct phases

- Design (with the aid of CFD modelling) and implement changes to the cone calorimeter that would variable ventilation toxicity measurements to be carried out reliably.
- Carry out full scale tests and compare these toxicity measurements (and others in the literature) to the modified Cone data
- Develop suitable correlations of toxicity data that could feed into modelling tools such as zone and field models.

Modifications to the standard cone equipment included enclosing the heater in an enclosure with controlled air supply and adding a chimney to prevent/minimise post flame oxidation and to allow sampling of raw fire effluents without air dilution (as is the usual practice).

Examples of specific challenges and solution approaches:

There was uncertainty on the induced flow patterns of these modifications and CFD was utilised to understand the flow dynamics and adjust the design.

As a test of the occurrence of post-flame oxidation two thermocouples were added to the cone chimney, one next to the sampling point and the other at the chimney exit at an adjustable height. Significant changes/differences in temperature between the two thermocouples would indicate that post-oxidation occurred.

BEHAVIOUR OF COLD-FORMED BEAM-COLUMNS IN CASE OF FIRE

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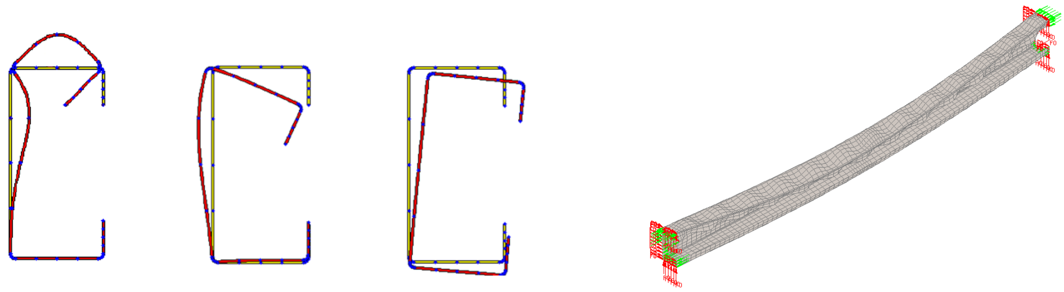
The cold-formed steel profiles can be applied to almost all existing buildings typologies. These elements are common in buildings due to their lightness and ability to support large spans, being quite common as roof or walls support elements.

Cold-formed profiles are more susceptible to the occurrence of local buckling. Additionally, in these members the global buckling (flexural buckling in columns or lateral-torsional buckling in beams) and distortional buckling are also common failure modes. These instability phenomena are intensified at high temperatures.

The manufacturing process of thin cold-formed steel members introduces residual stresses and increases the yield strength in the folding regions (corners).

This work has the main objective of presenting a numerical study on the fire behaviour of cold-formed beam-columns with thin walled sections when subjected to high temperatures. The different instability modes will be analysed with different software CUFSM (developed at Johns Hopkins University in the United States) [1] and RUBY (developed at the University of Aveiro in Portugal) [2]. These obtained instability modes will be used to define the initial geometrical imperfections (Figure 1).

Thus, the influence of the different geometrical imperfections and their combinations added to the consideration of residual stresses on the ultimate load is going to be evaluated. Moreover, comparisons between the finite element numerical results, obtained with geometric and material non-linear analyses, which are performed with SAFIR (developed at the University of Liege in Belgium) [3], and the Eurocode 3 Parts 1-2 and 1-3 [4,5] design rules are also going to be presented (Figure 2).



a) Local b) Distortional c)Global d) Imperfections combination

Figure 1 – Initial geometrical imperfections (C-section beam) and graphical representation from SAFIR software with local, distortional and global imperfections combination (amplified 50 times) of a beam with 2 m length.

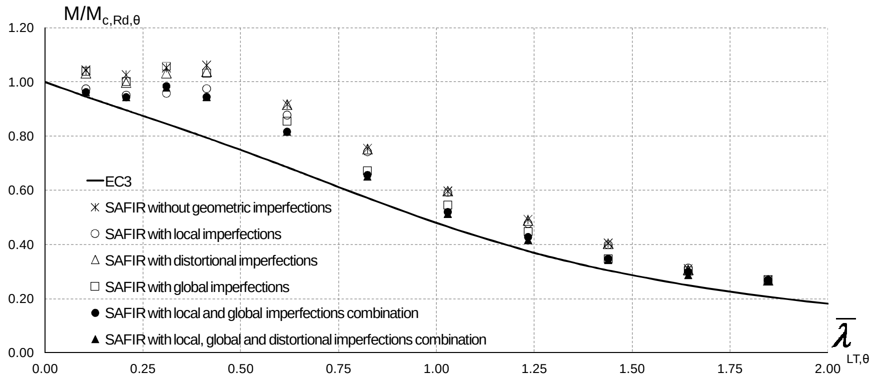


Figure 2 – Results of initial imperfections influence and comparison with the EC3 at 500 °C.

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BUCKLING RESISTANCE OF A REINFORCED CONCRETE FRAMES IN FIRE CONDITIONS

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The subject of my PhD thesis is buckling resistance of a reinforced concrete (RC) frames in fire conditions. The columns are, besides the beams, the basic structural elements of the each frame. Therefore, the behavior of the columns has the significant impact on the behavior of the frames as a whole. The failure of the columns may occur due to material failure (stocky columns) or due to buckling (slender columns), which is mainly the geometric properties of the column. The deformability of the structure increases during the fire, adding to the exposure of RC frames to the buckling and stability phenomena. Because the concrete and steel are the plastic materials, the buckling resistance of the RC frames depends on plastic buckling of columns characterized by additional post-critical buckling resistance.

In the analysis of the buckling load frames, in addition to the aforementioned local plastic buckling of the column, the robustness of frame is also important. This is the ability of the frame that the local column failure does not result into the global collapse of the construction. The property is particularly important for fire safety of the frame, protecting human life and to reduce costs. To sum up, modern fire-safety design of the multi-storey RC frames requires a holistic approach, where the local and global stability of the frame have essential account.

The proposed model is a new numerical model for the non-linear geometric and material analysis of a reinforced concrete frames exposed to the mechanical and fire load. The model will define the buckling resistance and the behaviour of columns by post-critical buckling analysis. Additionally, the model will provide fair evaluation of prevalent parameters, which are applied for defining the criteria for explosive spalling of the concrete. Accordantly with the results, we will be able to predict the behaviour of RC frames at elevated temperatures.

Due to the complexity of the present phenomena, the model can be divided into three phases. In the first phase of the model, the time dependent change of temperatures in the fire compartment surrounding the RC frame will be determined. The heat transfer affecting the surface of the RC frame will be accounted for in boundary conditions of the next steep of fire analysis. The temperature distribution of the fire can be calculated by using the complex CFD methods or defined by standard ISO 834 fire curve, which is simpler way of determining the surrounding temperature.

In second phase, the coupled heat and mass transfer in the concrete exposed to fire will be observed due to heterogeneous structure of concrete, which consist of solid matrix, water and gaseous mixture of water vapour and dry air. Accordingly, the model include the determination of heat and moisture transfer in concrete during fire and the estimation of the special processes within the material exposed to the elevated temperatures, e.g. concrete spalling.

The third phase of the fire analysis will consists of the mechanical response of RC frames. Once the temperature and pore pressure variation in time and space has been obtained, the stress-strain state evolution in the RC frame during fire can be pursued. The contact between the concrete and reinforcement will be defined by a non-linear constitutive law. The material properties of the concrete and the steel will be temperature dependent. Further, the Reissner's kinematically exact planar beam theory will be used in the mechanical model. The governing equations consist of kinematic, constitutive, equilibrium and constraining equations will be written separately for the concrete and the reinforcement. Furthermore, we will assume the additive decomposition of geometric deformation into elastic, plastic, temperature and creep deformation of concrete and steel and transient deformation of concrete. We will look for the numerical solution of basic equations employing the strain-based finite element method. The numerical model will also consider the longitudinal delamination of the concrete-steel contact, weakening of the cross-section of the columns due to explosive spalling of the concrete and associated local buckling of the reinforcement.

Given the generality of the presented numerical model, the results of PhD thesis will enable a better understanding of holistic stability behaviour of the reinforced concrete frames in fire conditions. Finally, the findings of the research work will also bring technical benefits. With the presented numerical model, we will more accurately assess the fire safety reinforced concrete frames and after that, new requirements for the design of the RC structures will be set.

FIRE RESISTANCE OF CONCRETE SLABS REINFORCED WITH FRP BARS

Experimental investigations and numerical simulation on the thermal field and the mechanical behaviour

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Use of fiber reinforced polymer (FRP) bars or grids instead of traditional steel reinforcements is an interesting application, especially to improve structural durability and extend the actual service life. Several building codes are now available for the design of concrete structures reinforced with FRP even if no calculation model taking account of fire conditions has been suggested. Intuitively, the fire endurance of concrete members reinforced with fiber reinforced polymer (FRP) bars is related to the decrease in the mechanical properties of the materials concerned, especially resin. Large-scale fire tests recently performed on nine concrete slabs reinforced with glass FRP bars, characterized by different values of concrete cover and anchorage length, demonstrated the importance of bond between FRP and concrete for performance under fire situations. The experimental results showed that (1) the length of the FRP bars in the zone of slabs not directly exposed to fire (namely, anchoring length in fire situations) can be much more relevant to fire endurance than the concrete cover in the zone directly exposed to fire; and (2) the shape of the bar, for instance bent at the end, allows a reduction in anchoring length. From a design point of view, evaluating the necessary anchoring length through a bond model seems to be a key aspect.

The experimental programme is extensively reported, giving detailed information on tests to highlight the practical significance of the experimental research. The results of investigations are discussed with particular reference to the structural behavior. A detailed discussion of the experimental thermal readings is reported to give as a support to the remarks on mechanical response. In particular the influence of concrete cover on temperature in exposed area and the temperatures in the area not exposed are examined to investigate the effectiveness of the anchor. The influence on the temperature in the bars of different concrete thermal properties is investigated. Furthermore, the influence of the thermal properties of the bars on the temperature field is evaluated.

Test results, were used to investigate the bond behavior of FRP bars embedded in concrete at high temperature and to assess a procedure to predict bond stress, slip, and load transfer at elevated temperature, based on both the results of numerical thermal analysis and the predictions of a bond theoretical model adjusted for fire situations. The design procedure outlined for calculating the minimal required anchoring length proves a valuable approach for the practicing engineer and stands together with the experimental results presented earlier. Finally strains and displacements recorded during the tests by means of strain gauges and displacement transducers applied on concrete and FRP bars are compared with the results of numerical simulations.

Results are shown with the aim of providing ideas for experimental tests, benchmark for numerical simulation, suggestions for updating design codes, proposals for further development.

NUMERICAL ANALYSIS OF A COMPOSITE STEEL-CONCRETE COLUMN SUBJECTED TO FIRE USING ABAQUS

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The presentation is focused on the numerical model for a composite column using solid elements. The input data for the model are taken from the German National Annex DIN EN 1991-1-2 which provides several results for thermal and structural analysis of the column.
The analysis was performed using the computer program Abaqus, during the STSM at Warsaw University of Technology, Poland, under the supervision of prof. Leslaw Kwasniewski. The issues of the analysis relate to the boundary conditions applied, mesh dimensions, material properties and interactions. The 3D analysis will highlight considerations that are not present in a 2D analysis using the beam element.

The parameters for the behavior of the materials, the numerical procedures, the boundary conditions, etc. considered in the numerical model, as well as the results, are discussed in comparison tothe work performed by Prof. Leslaw Kwasniewski and Katarzyna Ostapska, using the computer program Ansys.

TIMBER-FIBRE CONCRETE STRUCTURES IN FIRE

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The use of timber-concrete structures has considerably increased especially in case of reconstructions and constructions of residential houses. The benefits are an obvious increase of the load bearing capacity, a reduction of the deflection, better vibration behaviour of the ceiling and an improvement of building physical properties like sound insulation and fire resistance. The reinforcement of the concrete slab is necessary, but leads to a large slab thickness in connection with the necessity of a sufficient concrete cover and to disadvantages during the execution of construction work. Therefore it is reasonable to replace the conventional reinforcement by steel fibres. Experimental and theoretical studies shows that the compressive strength at elevated temperatures of fibre-reinforced concrete is higher than that of plain concrete. The presence of steel fibres increases the ultimate strain and improves the ductility of fibre-reinforced concrete elements.

The design of timber-concrete floor slabs for fire resistance is usually based on prescriptive generic ratings that specify the minimum slab thicknesses. These generic ratings have generally been based on standard fire resistance tests using furnaces which are not representative of real construction because they do not account for two-way action or the effects of axial restraint at the slab supports. Once large deflections occur, tensile membrane action can significantly increase the fire resistance of reinforced concrete slabs, especially two-way slabs. For ambient conditions developed a theory to determine the load carrying capacity of reinforced concrete slabs at large deflections by considering the tensile membrane action. Both theoretical and experimental research into membrane action of concrete slabs at large displacements has previously been limited due to the difficulty in identifying any practical application. During a fire, large displacements of the structure are acceptable provided overall structural collapse is prevented. With the identification of the practical use of membrane action at large displacements previous work, findings on slabs tested at ambient temperature, has been re-visited and the need to understand the mechanics of membrane action in slabs when subjected to a fire has been stimulated amongst researchers and practitioners. Significant analytical work on the steel to concrete composite slab has been conducted, based on the fire test results from the Cardington building. The modellers, however, have found difficulties in modelling the cracking behaviour of the concrete slab together with an accurate prediction of the fracture of the reinforcement, with the conclusion that more fundamental research is required.

The fire resistance of timber-fibre concrete floors is important especially when used in multi-storey building. The fire safety of a building with these wooden elements can match or even succeed that of other structural materials. For this reason it is necessary to gain a deeper knowledge of the behaviour of timber-fibre concrete structures in fire, to remove all unknown and to ensure safe use for the intended purpose. The fire resistance of timber-fibre concrete composite construction was studied at few laboratories only. The study of the fire resistance of the timber-fibre concrete structure was not published yet.

The main objective of the proposed project is the preparation of the analytical prediction model for the fire resistance of the fibre concrete and timber concrete slab with dispersed reinforcement. The model will utilize the current knowledge of the design of the timber concrete and steel concrete composite slabs at ambient and elevated temperatures. Based on the prepared bibliographic search the experiments at ambient and elevated temperatures will be prepared. After its evaluation and FE sensitivity study the analytical model will be prepared. The model will describe the initial behaviour, the ultimate resistance as well as ductility demands. The current generation of the materials will be taken into account: the fibre concrete and the glue laminated beams. The proposed model will describe the development of membrane behaviour, its progress and the achievement of the ultimate limit state including the boundary conditions. The model will facilitate the increase of the fire resistance of the multi-storey building by the optimal structural solution of its floor slabs for reconstructions and new structures.

Furnace test of timber-fibre concrete structure was performed on one full-size floor specimen at the Fire testing laboratory PAVUS. Floor specimen was 4,5 m long and 3 m wide, consisting of 60 mm fibre concrete topping on plywood formwork, connected to GL floor joists. It was subjected the standard fire for over 150 min. The membrane effect of the floor was progressively activated due to burning of the timber internal beams. The full collapse of the test was reached at 154 mins due to damage of the fire protection of edge beams.

APPLICATION OF FIRE SAFETY ENGINEERING IN A TALL BUILDING

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This presentation is devoted to the application of Structural Fire Engineering to a tower, with office use, according to Italian and European Codes. The tower is 101.00m high and has 29-storeys above the ground; the structure has steel beams and columns and a reinforced concrete core.

The aim of fire safety assessment concerns the mechanical resistance and stability in fire situation of the tower. In agreement with Fire Brigades, the performance level assumed for fire safety check of the structure is: “maintaining of the fire resistance requirements, which ensure the lack of partial and/or complete structural collapse, for the entire duration of the fire”. In addition, with reference to the most probable fire scenarios, which involve the effectiveness of active protection systems, a limited structural damage after the fire exposure is also required.

The design fire scenarios are identified applying the concepts of the Fire Risk Assessment, through the event tree approach according to ISO-16732 Guidelines. A fire scenario in an event tree is given by a time-sequence path from the starter condition through a succession of intervening events till to an end-event. Each fire scenario corresponds to a different branch of the event tree, therefore the branches represent all fire scenarios. The main events, which may affect the development of the fire, are taken into account in the risk assessment. In particular, first aid suppression, alarm activation (smoke detectors), sprinklers activation, sprinklers suppression and barrier effectiveness are considered. Moreover, secondary events, such as doors and windows state as well as the location of fire ignition, are implicitly taken into account in the fire model.

The post-flashover fire is modelled by one-zone model and CFD model, applying Ozone (provided by University of Liegi), C-Fast and FDS (provided by NIST) softwares.

In order to evaluate the structural fire safety, Italian and European Codes allow the global structural analysis, the analysis of part of the structure (substructure analysis) and the analysis of a member (single member analysis). In the case study, due to the building’s large size, in order to reduce the computational time, the substructure analysis is adopted. The static scheme of the building allows to define simple substructures, which are able to represent the global structural behaviour. Note that the structural static scheme does not produce significant indirect actions.

The results of the structural analyses under the highest risk fire scenario show that no relevant plastic strains occur in the structure, thanks to passive protection systems, avoiding structural collapse. Moreover, in the most probable fire scenario, characterized by sprinkler activation, the temperatures in the structural members are very low, so that no significant structural damages are achieved.

THE BEHAVIOUR OF PROTECTED AND UNPROTECTED WOODEN MEMBERS UNDER FIRE

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This presentation is focused on the timber structures exposed to fire, especially on the contribution to the fire resistance of timber structures boards. The calculation of this contribution according to Eurocode 5 is simple but applicable to only limited amount of materials. The correct modelling of the fire and sufficient knowledge of wood behaviour at elevated temperatures leads to improvement and specification of the results of the fire resistance times. The focal point of this study is the research of the contribution to the fire resistance of timber beam using boards. On the basis of the test results when the timber beam was covered by calcium silicate fire protective boards, evaluation and numerical model in ANSYS was carried out.

For the elements which are protected by the fire shell, the beginning of charring moved till the time tch. The charring of the timber element can occur before the deformation of the fire protection but with lower speed than specified in Eurocode 5.

Using the new testing standards which are not much used in the Czech Republic yet, the fire test was performed to determine the contribution to the fire resistance. This test standard specifies a test method for determining the contribution of the fire protection systems to the fire resistance of structural timber members Based on this standard is determined the ability of the fire protection system to delay the temperature rise throughout the timber member, to maintain coherence and link to the timber member and to provide data of the thermal characteristics of the fire protection system, when exposition to the load according to the standard temperature/time curve. This test procedure is also applicable to timber structural members incorporating insulating materials between the timber members.

The Annex B describes the relationship of this test method and the assessment of the results obtained therefore to EN 1995-1-2 and guidelines for the use of this test method. Based on this test is determined the time when the temperature of the timber member reaches 300 ° C, the temperature when we assume that the timber element will burn. By this tests is also determined the coefficient k_β, which reduces the rate of charring β_0 (β_n).

RESTRAINED BEAM BEHAVIOUR IN FIRE
Comparison of FEM to Hand Calculation Model

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The current design procedures prescribed by the codes for design of steel beams at elevated temperatures require that the ultimate flexural resistance of the beam should be checked against the applied loading. This approach does not take into account the redistribution of bending moment due to fire exposure that takes place in a redundant frame. The axial and rotational restraints at the beam to column connections in such a frame play an important role as to how the beam behaves in restrained conditions when exposed to fire. This is particularly important at relatively high temperatures when the beam has undergone significant deflections and as the catenary action in the beam gradually takes over as the resisting mechanism beyond the limiting temperature prescribed by the codes.

Simplified design procedures that satisfactorily describe the restrained beam behaviour should be used to avoid the high cost and complexity of finite element analysis and fire tests. A proposed simplified design procedure has been used to analyse axially and rotationally restrained beams in sub-frames in this study and the results are compared to the results from their finite element models. The finite element models of the sub-frames were validated against fire tests conducted on sub-frames.

COLD-FORMED STEEL PORTAL FRAME STRUCTURES IN FIRE

Preliminary full scale testing and numerical modelling

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Project goal and Objectives

The primary aim of this project is to provide design recommendations for the design of cold-formed steel portal frame structures at elevated temperatures. This is to ensure acceptable failure modes of such structures within fire boundary conditions (prevent outwards sway failure). Specific objectives of the research are as follows:

- To conduct a full scale fire test of typical portal frame arrangement.
- Test joint components at ambient and elevated temperature.
- Validate non-linear FEA shell models which incorporate semi-rigid joints.
- Investigate the effect of joint stiffness, initial imperfections and stressed skin action.

Background

Research on the behaviour of cold-formed steel portal frames [1] at elevated temperatures is limited [2] and has yet to include the effect of joint flexibility (Fig. 1) and imperfections. These are vital to the overall behaviour as cold-formed steel members are susceptible to complex coupled instability modes (Fig. 2). This susceptibility is heightened at elevated temperatures due to the thin-walled nature and high conductivity of the section (Fig. 3).

The current SCI design guide [3] outlines the fire boundary condition for hot-rolled steel portal frames only. There is no definitive guidance available for cold-formed steel portal frames. For this reason, a comprehensive experimental and numerical research programme is being carried out.

Method and Results

Experimental testing

A full scale fire test is planned and will comprise a full burn out test (Fig. 4) with appropriate instrumentation to measure temperature and displacement. Most vital is to determine the overall collapse mechanism. Laboratory testing on joint components is also being carried out. Experimental testing will provide input data and validation for numerical simulations.

FE Models

The commercial package ABAQUS is being used to develop non-linear FE models for the following at ambient and elevated temperatures.

- Individual joint components (Solid and Shell models of lap joints and B2B beam tests)
- Single bay portal spans (Shell model incorporating semi-rigidity of joints)
- Multi bay portal frame arrangements (As above including purlins/side-rails/cladding).
- Study into effect of initial imperfections and residual stresses.
- Parametric study investigating effect of fire location, knee braces, span, pitch, un-symmetric frame arrangements and diaphragm action.

Potential for application of results

The results of the research will lead to improved understanding of the behaviour of cold-formed steel portal frame at ambient and elevated temperatures. It will provide guidance for design engineers and act as a base for further research into the behaviour of such structures at elevated temperatures.

Images

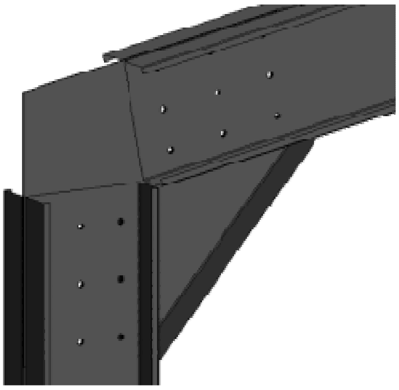

Fig. 1 - Eaves connection detail

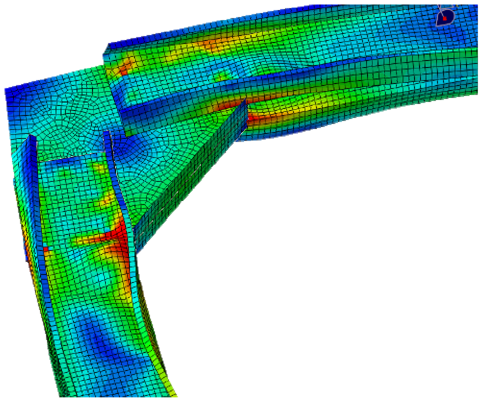

Fig. 2 - FEM of eaves connection

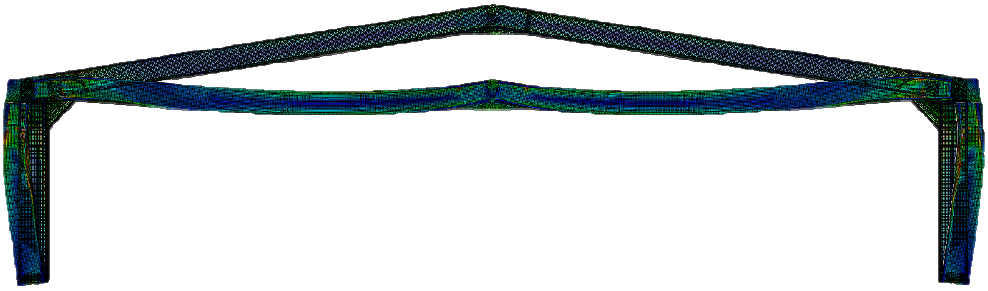

Fig. 3 - FEM of single portal at elevated temperature

Fig. 4 - Full scale site fire test frame

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EMBEDDED COMPOSITE COLUMNS IN FIRE

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The properties of concrete filled steel tube (CFT) columns in fire are well known. However, most of the research papers and design manuals only consider columns in uniform fire, where the fire is acting at all sides of the column. In reality, many of the columns in buildings are located next to walls or in corners and are exposed to fire non-uniformly, which affects their heating rate and induces thermal bowing.

Numerical analysis of embedded CFT columns in fire was conducted in a master's thesis completed in 2013. Thermal and mechanical analysis were done using a commercial finite element software ABAQUS. Reinforced concrete filled square steel tubes were considered with three different sizes and two different buckling lengths. The ISO fire was acting at three, two adjacent or one side of the column staying constant along the column. The remaining sides were protected with concrete or sandwich panel walls. The columns were compressed with constant loads to failure and the resulting fire resistance periods were compared to similar cases in uniform fire. There were several difficult problems during FEM-modelling of which the working concrete material model was the hardest one to solve.

The results show that the average fire resistance times increase with the ratios 1.3 (3 sides), 2.1 (2 sides) and 3.5 (1 side) with respect to the cases where fire is acting at all four sides. It was also found that concrete wall can act as effective heat sink for embedded composite columns and slow down the heating rate even more.

Tests are badly needed to verify the calculations, but they present a whole new set of problems. How many CFT columns should be tested? The furnace floor in TUT cannot resist loading, so the columns would have to be pulled against the top of the furnace. Is this even feasible, how it could be done or are there better alternatives? How the columns should be partly shielded from fire (concrete or mineral wool) and how these protections should be attached to the columns?

INFLUENCE OF CROSS-SECTION SHAPE ON FIRE RESISTANCE OF COMPOSITE CONCRETE-STEEL COLUMNS

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The purpose of this study is to investigate the fire response of centrally loaded composite columns subjected to Standard fire curve according to ISO 834. The variables considered in the study include shape of the cross-section, cross-sectional size and axial load ratio. The analysis have been carried out by nonlinear finite element program for predicting the structural behavior of frame structures exposed to fire, developed by Professor M. Cvetkovska.

The columns are exposed to fire on all four sides and the end conditions of the columns are: fixed at the bottom and freely supported at the end. Four different types of cross-sections are investigated: composite-concrete filled section in which the concrete is hidden, totally encased section, partly encased section and reinforced concrete section. All cross-sections are symmetrical about both axes and reinforced. Dimensions are varied from 30x30, 30x50 to 40x40, and axial load ratio from 0,1 to 0,3.

At the end comparation of results conducted with this computer program with results calculated with other commercial software package is discussed.

A NOVEL SYSTEM FOR THE STUDY OF STRUCTURES IN FIRE

Moving Away from the Status Quo

Cristián Maluk

BRE Centre for Fire Safety Engineering, The University of Edinburgh, Scotland, UK

Rapid growth in the use of new construction techniques and innovative materials in building construction is being driven by the need for optimization, energy efficiency, sustainability, and architectural creativity. Advances in fire protection engineering of buildings, from both practitioners and researchers, have thus far allowed the industry to keep up with the evolving modern building construction environment. In contrast to this progress, the structural fire testing community has mainly relied in the use of the standard fire resistance test (i.e. furnace test) for assuring regulatory compliance testing but also for scientific understanding of material and structures response to fire. Developed in the early 1900s and fundamentally unchanged since then, the pass/fail standard testing procedure is characterized by its high cost, low repeatability, and unrealistic thermal and mechanical conditions. More than half a century of enhancements, essentially in line with additional standardisation mechanisms, have been unsuccessful in addressing the inherent problems with the standard fire resistance test.

Developed at The University of Edinburgh and named the H-TRIS (Heat-Transfer Rate Inducing System), the novel testing methodology uses a mobile array of propane-fired high performance radiant panels, along with a mechanical linear motion system. Whilst this is not the first time that mobile radiant panels have been used for thermal testing of construction materials, H-TRIS is the result of a mental shift associated with controlling the thermal exposure not by gas temperature but rather by the time-history of thermal energy absorbed, never before done, at this scale, for the study of structures in fire. The thermal loading imposed by the H-TRIS is defined by a numerical inverse heat transfer model which uses through-thickness temperature measurements (thermal gradients) taken from control specimens exposed to the actual fire conditions intended to be replicated (e.g. a standard furnace exposure in a specific fire testing furnace). Alternatively, a time-history of thermal energy absorbed can be specified using outputs from a fire dynamics model.

Thermal loading of test specimens, is controlled using incident heat flux (i.e. flow of thermal energy) measurements, rather than temperatures, taken during a pre-programmed calibration procedure. Recalibration can thus be performed before each new test, relevant to the specific conditions of the material or structure being tested, as well as to the ambient laboratory conditions on any given day. This allows a previously unachievable level of repeatability between tests. During a test, the computer-controlled linear motion system adjusts the radiant panels' location (i.e. distance from the specimen) so as to follow any pre-defined time-history of thermal energy absorbed. H-TRIS thus allows accurate quantification of the thermal energy flow absorbed by a tested element with good repeatability; all at negligible economic and temporal costs in comparison to furnace tests. Potentially, it also allows rational simulation of any real fire or furnace exposure condition.

The first research project based on application of the H-TRIS methodology has evaluated the occurrence of heat induced concrete spalling in high performance structural concrete under standard heating regimes. Since then, due to the multiple benefits of the H-TRIS, a number of diverse projects have been executed or are scheduled, including studies on the performance of intumescent coatings under non-standard heating regimes, the thermo-mechanical incompatibility between concrete and polymer based reinforcements, through-thickness temperature predictions relevant to the fire performance of post-tensioned concrete slabs, and the performance in fire of phase change materials used to insulate energy efficient buildings.

NUMERICAL APPROACH TO THE EFFECT OF FIRE EXTINCTION PROCESSES ON THE SPALLING RISK AND RESIDUAL PROPERTIES OF HIGH STRENGTH CONRETES

Tai Ikumi Montserrat, Angel Guerrero

Polithecnic Universtiy of Catalonia, Materials Resistance and Structures in Engineering Department, Spain

The major aim of the presentation is settled in the domain of the analysis of the effect of a spectrum of cooling processes on the hygro-thermo-chemo-mechanical state of a structural element, manufactured with High-Strength concrete, during the development of a natural fire –more precisely, in its computational approach with the aid of HITECOSP software– with the particular objective of:

- Analyzing both phenomenologically and from a mechanistic point of view the effect of a spectrum of cooling processes on the hygro-thermo-chemo-mechanical state of a structural element, manufactured with High-Strength concrete, during the development of a natural fire.

To do so, although there are developed more than forty five hygro-thermo-chemo-mechanical analyses resulting from combinations of the parameters' values initially considered, two reference cases are selected where the extinguishing actions conditions are varied in order to cover the widest possible range of situations found by Fire-Fighting Services during a natural fire extinguishment: the type of cooling – either cooling the gases in the enclosure or the structural element's surface – and the cooling start instant and its rate.

This settling of objectives also includes the development of more than twenty Computational Fluid Dynamics simulations by means of Fire Dynamics Simulator software (FDS) in order to work out the evolution of temperature at surfaces during several extinguishing actions.

To conclude, the development of a heuristic analysis of the effect of cooling processes on the hygro-thermo-chemo-mechanical state of a square column, manufactured with High-Strength concrete, during the development of a natural fire in a High-Rise Building, is also included, being understood as an introductory extension of the abovementioned analyses to cases with bi-dimensional fluxes such as square columns, where Corner Thermal Spalling is often the most dangerous type.

FIRE SAFETY TOOLS
MAC IOS APPS development

Francisco Javier Nieto Uriz

Building Services and Energy Section, School of Architecture, University of Navarra, Spain

The aim of this presentation is to show the processes followed for the creation of a fire safety application for iPhone/iPad devices. In order to be able to understand the importance of this first app we are going to fill you in on the background of the project.

From the Section of Building Services of our school, there's always been an aim based on two apparently unconnected points: 1. University teaching, research and the professional practice of architecture should not be unconnected activities, but the complex reality of the world of construction means that they are seen as separate. / 2. It is obvious that many technological tools such as PC tablets, smartphones… are being used by the general public in their everyday lives.

Taking advantage of the recent years widespread of technological devices, which have become part of our everyday life, we decided to develop a collection of Apps that may assist to both, students and professionals with the Building Services design requirements.

Nowadays, you can download UNAV-FIRE from AppStore just using your device.
UNAV-FIRE was thought to help architects in the complex task of developing an architectural project, which means making calculations that lead to a final result. Based on our experience in the Fifth Year subject Building Services Design, where the architectural students must, in a very short time, find the main values for everything to do with fire safety elements in the projects they design.

All of this makes up the objective of the app, which assists with the design requirements for fire safety in a residential building. Although the Spanish regulations in Basic Document CTE-DB-SI are used as its basis, the essence of the app is not to fulfill any particular regulations, but to provide a rule of thumb which, for the first sketches of the building design, would allow one to see how close the creation of a safe building was from this perspective; a tool that brings teaching and professional practice together in such a way as to be within the reach of anyone anywhere.

With this tool we can determine the occupation density, the number of exits per floor, the maximum evacuation distance and the sizing of the main evacuations means (doors, corridors, landings and staircases).

In the presentation by will also explain the main problems related with the help text according to legal considerations.

FEM SIMULATION OF COMPOSITE COLUMN DURING FIRE EXPOSURE BASED ON DIN EN 1991-1-2/NA:2010-03

Katarzyna Ostapska

Faculty of Civil Engineering, Warsaw University of Technology, Warsaw, Poland

The aim of this presentation is to provide step by step implementation of a numerical model for the benchmark problem provided by the DIN EN 1991-1-2/NA:2010-03 (CC.4.11 Beispiel 11 - Verbundstütze mit Kammerbeton). A composite column is considered with initial geometric imperfection during fire exposure. Initial deformation is parabolic with the peak value in mid-span. The column's section is bisymmetrical reinforced concrete with partially encased steel profile and four reinforcing bars placed symmetrically. The analysis is performed using FE programs Abaqus and Ansys in cooperation with dr. Ioan Both and prof. Raul Zaharia. Obtained results are compared with DIN data as well as with other numerical results. The main parameters taken into account for comparison are: fire resistance and mid-span displacement at selected time points after subjecting column to uniform heating on four sides. Performed numerical simulation helped to estimate initial parameters, materials types, and thermal analysis options and to verify assumed mesh for this DIN benchmark.

FIRE ENGINEERING LEARNING AT THE SCHOOL OF ARCHITECTURE

Maria Perez Echeverria

University of Navarra, Spain

In our presentation for the Action Training School "Fire Engineering Research- Key Issues for the Future II", we will explain how future architects learn from Fire Design Safety in the Universidad de Navarra, Spain.

The presentation will be focused on three main points: 1. the fire engineering learning, 2. the fire design safety course, with the theoretical and practical implementation, 3. an example of a real project carried out by a fifth year student

Fire engineering learning is considered an important topic in architecture studies in the Universidad de Navarra. Other Schools of Architecture do not consider this course as important and thus there are no mandatory courses related to this topic. A diagram will be shown in the presentation to explain different profiles of study plans of architecture in Spain.

In order to design an efficient learning system, the School organizes the Fire Engineering Education in three academic years of the degree in architecture; as we will explain in the Action Training School.

During the first year, the third of the degree, the course is focused on understanding theory essentials and developing a wide understanding of theory principles of fire design safety.

Since Architecture is a practical discipline, the goal of the fifth year is to relate theory and practice. For this reason, classroom learning, exercises and research become as important as laboratory instruction. For the first time in the degree, students have to design and implement the acquired abilities in real projects.

In the last year of the degree in Architecture, students do their final project, where they have to design and implement correctly the Fire Design Safety.

As we will explain in the Action Training School, the Architecture School of the Universidad de Navarra tries to encourage students to continue in the study of Fire Design Safety with Research Training Programs.

Extra academic activities such as international seminars, technical cabinets in the laboratory or collaboration with Navarra's Emergency Agency, are also an essential part of Fire Engineering learning in the school.

To conclude, we will present a practical implementation of Fire Design Safety in a real project carried out by a fifth year student. This example summarizes the main points of Fire Engineering education taught in the School of Architecture of the Universidad de Navarra.

SHEAR PANEL COMPONENTS IN THE VICINITY OF BEAM-COLUMN CONNECTIONS IN FIRE

Guan Quan

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As the final goal of performance-based structural fire engineering design is to develop the robustness of buildings to prevent any possibility of progressive collapse, columns and joints become the key elements of a building in fire scenarios. On the one hand, the investigation of "7 World Trade" in New York City indicated that the building was unaffected by the aeroplane impacts but collapsed totally due to the effect of fire. This was triggered by the failure of beam-to-column joints as a result of large thermal expansions of beams. Joint failure may initiate fire spread or may lead to progressive collapse of the whole building. On the other hand, once a column buckles the redistribution of column loading may overload the adjacent columns. This phenomenon may cause severe local collapse, or even progressive collapse of the whole building.

This project has so far mainly been concerned with developing component models for the shear panel zones close to the ends of beams. Several of the full-scale Cardington Fire Tests indicated that shear buckling at the ends of the steel sections of composite beams is very prevalent under fire conditions. Beams can hardly break in fire scenarios, but shear panel behaviour in the vicinity of the steel beam-column connections can have two significant effects on the adjacent joint. Firstly, shear buckling can cause redistribution of the forces in the column-face bolts. In the post-buckling stage, most of the vertical beam reaction is resisted by the tensile stress across the diagonal of the shear panel. Together with the effect of lower-flange buckling, which is essentially a rotational effect, the forces generated may differ from the traditional design forces for the connections. Secondly, transverse drift of the shear panel, and rotation of the lower-flange, can contribute to the deflection of the beam. This effect will help with catenary action under large beam deflections. Catenary action may in turn change the redistributed stresses in the shear panel zone.

In the first year of this study, three steps have been carried out:

1. A logical component-based mechanical theory has been proposed, based on tension field theory, particularly to predict the geometry and stress redistribution within the shear panel zone during the plastic buckling period. This theory is firstly applied at ambient temperature, and then extended to elevated temperatures.

2. A range of ABAQUS models have been created to investigate the behaviour in the vicinity of the connection and to validate the component model over a range of geometries. The model can be used to produce force-transverse deflection relationships which are necessary for a component-based beam-end finite element.

3. By validating the mechanical theory with ABAQUS models, reasonably consistent results have shown that the proposed method provides a good approximation to the more complicated numerical analysis.

The next objective, after sufficient validation has been carried out, is to implement the component-based shear panel element in the software *Vulcan*, which will then be tested against existing experimental data. The software will subsequently be used to conduct a series of parametric studies to investigate the effects of shear panels in beams and columns on performance of steel frames in fire.

FIRE PERFORMANCE OF SECONDARY TUNNELS LINING WITH DIFFERENT FIBER COMBINATIONS

Josip Radeljic

University of Zagreb, Faculty of Civil Engineering, Zagreb, Croatia

This research plan has been designed in order to increase security in the tunnels in case of fire and to find effective and optimal solutions for fire protection of tunnel lining. The focus of this research plan is to find solutions for reducing the explosive spalling of concrete which in case of fire directly endangers human lives, interferes with firefighters while rescuing people and causing significant material damage. Previous studies that have been conducted mainly on reinforced concrete with polypropylene fibers have produced good results in terms of resistance of such concrete to fire action. The plan is to explore that area in more detail in terms of fire resistance regarding the secondary tunnel lining made of reinforced concrete with different combinations of microfibers with an emphasis on the use of recycled microfibers. In addition to fire resistance research in this study we will be exploring the economic component of each of the tested combination and the possibility of simple preparation and installation of such concrete.

As a basic reference sample type we will examine concrete reinforced with polypropylene (PP) fiber (22mm long with 32µm diameter). Second type of sample will be reinforced with recycled polyethylene terephthalate (RPET) microfibers. The other five types of samples will be reinforced with a combination of two or three types of fibers - hybrid fibers (H). Hybrid fiber combination H1 is a combination of PP and steel microfiber. H2 is a combination of RPET and steel fibers. H3 is a combination of three fibers from recycled car tires, first one is composed of polymeric tire cords (RTF), second one is composed from recycled tire – rubber strips (RTR), which were the main component of tires, and the third is composed from recycled tire steel fibers which where the radial steel reinforcement of tires. Fiber combination H4 contains combination of nylon and steel fibers (NF), and finally H5 combination contains glass (GF) and steel fibers. Before samples fire testing standard mechanical tests on standard samples will be performed to get information about compression strength, tension strength and elasticity module of each concrete type.The fire tests will be conducted with Rijkswaterstatt (RWS) fire curve of 2 hours with a peak temperature of 1,350 ° C using large panels measuring 1,200 mm x 1,700 mm x 300mm. In addition to testing the samples to fire action there will be measures and test to mechanical action with the aim of optimizing the required amount of reinforcement.

SHEAR BUCKLING IN STEEL MEMBERS SUBJECTED TO FIRE

Andre Reis

LABEST - Civil Engineering Department, University of Aveiro, Portugal

The ultimate resistance capacity of steel structural members may be influenced by shear buckling, an important and common phenomenon for the analysis of beams with slender cross-sections [1,2]. In fire situation, the buckling phenomena in these steel members are amplified by the reduction of the mechanical properties caused by the high temperatures [3, 4].

Recently, there has been an increase of the use of plate girders with slender webs, arising from the search of more economically competitive solutions. These slender webs are largely affected by shear buckling.

Thus, it is intended in this PhD to develop a numerical and experimental study about the shear buckling phenomenon in steel beams subjected to fire. The main goal is to validate the existing analytical models adapted to elevated temperatures, or to develop new design approaches, if needed, to be applied by structural engineers.

The presentation will focus on already performed numerical analysis and on the PhD main goals and tasks. It will be presented some numerical models to be used on this study, which are defined by comparisons with experimental results at normal temperature that can be found on the literature [5]. After the normal temperature preliminary study, elevated temperatures (500 ºC) were applied to the same numerical models. The influences of different geometrical imperfections and residual stresses on the ultimate load are analyzed at both normal and fire conditions.

Additionally, comparisons between the finite element numerical results and the simplified rules within Eurocode 3 Parts 1-2 and 1-5 [6, 7] will also be made.
The program SAFIR (developed at the University of Liege in Belgium) [8] was used to obtain the numerical results with geometric and material non-linear analysis.

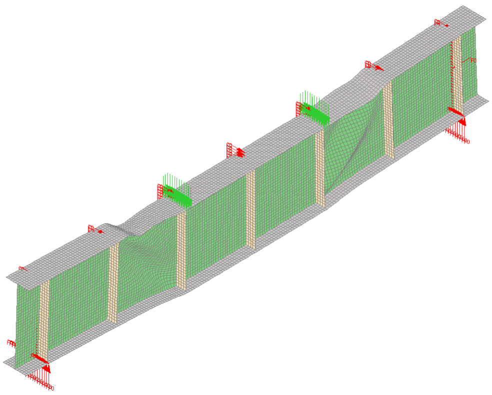

Figure 1 – Numerical model

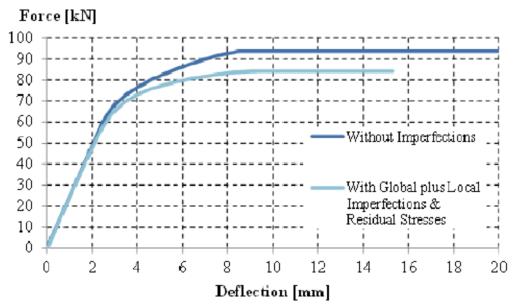

Figure 2 – Relation between imposed force and displacement

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FIRE ANALYSIS OF PARTLY DELAMINATED CURVED REINFORCED CONCRETE BEAM STRUCTURES

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Abstract

The topic of my research work and my PhD thesis is fire analysis of partly delaminated curved reinforced concrete beam structures. Extreme fire in tunnel can result in human casualties, material damage, pollution of environment and economic loss. To prevent such incidents fire safety engineering has become a significant part in the process of tunnel design and construction. The idea/goal of our research work is to use the knowledge obtained from the fire analysis of partly delaminated curved reinforced concrete beam structures to evaluate the behaviour of tunnels in fire conditions.

The proposed model is a new numerical model for nonlinear geometric and material analysis of partly delaminated curved reinforced concrete beam structures exposed to simultaneous mechanical and fire load. Firstly, the model will define stiffness, ductility and load bearing capability of partly delaminated curved reinforced concrete beam structures. Furthermore, the model will provide fair evaluation of significant parameters, which are used for defining criteria for concrete spalling. Based on the obtained results from the model we will be able to predict the behaviour of tunnels during fire.

The model can be divided into three basic steps. In the first step of the fire analysis the time dependant change of temperatures of the fire compartment surrounding the beam structure will be determined. Heat flux affecting the surface of the beam structure due to convective and radiative heat flows from the surrounding fire compartment will be accounted for in boundary conditions of the next step of the fire analysis (hygro-thermal calculation). The temperature of the fire compartment, i.e. in tunnel, can be calculated by using parametric temperature-time curves (hydro-carbon fire curve) or CFD methods. Parametric fire curves present simpler way of determining the temperatures in fire compartment, while CFD methods are more complex and require appropriate fire scenario. As tunnel is a vast fire compartment, where temperatures during fire are distributed unevenly, we assume CFD methods, i.e. FDS, will be nearly inevitable in the fire analysis.

In the second step of the fire analysis heat and mass transport model will be implemented due to heterogeneous structure of concrete. RC is heterogeneous material consisting of solid matrix, water and gaseous mixture of water vapour and dry air. The model allows us to determine heat and moisture transfer in concrete during fire and detect special processes within the material due to high temperatures, e.g. concrete spalling. The governing equations of the heat and mass transport model will be solved numerically using finite element method. FEM software will be developed in Matlab environment.

The third step of the fire analysis will evaluate the mechanical response (stress-strain state) of the partly delaminated curved reinforced concrete beam structures. The beam structure will be presented as two connected curved RC beams, where the contact between the beams will be defined by a nonlinear constitutive law with respect to longitudinal and transversal slip. Reissner's kinematically exact planar beam theory will be implemented in the mechanical

model. Governing equations are equilibrium, kinematic and constitutive equations. The principle of additivity will be considered in the mechanical model as well, meaning that the increment of total strain is the sum of strain increments due to temperature, stress and creep in concrete and steel plus transient strains in concrete. The basic equations of the mechanical model will be solved with finite element method involving a strain-based planar curved beam finite-element.

The main goal of our research is to connect the second and the third step of the fire analysis. Transfer of heat and moisture in RC due to high temperatures is significantly affected by the stress-strain state of two connected beams. On the other hand, longitudinal and transversal slips have a great impact on the stress-strain state of two connected beams. For better understanding and more accurate results of the fire analysis of partly delaminated curved reinforced concrete beam structures, interaction between hygro-thermal and mechanical model must be considered. We assume that the mathematically coupled model (hygro-thermal + mechanical) can be used for the evaluation of the behaviour of tunnels in fire and detecting special fire events such as concrete spalling.

FINITE ELEMENT MODELLING OF BEAMS IN ELEVATED TEMPERATURE
Benchmark problems

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During the presentation idea of benchmark problems and their importance will be shown. A proper FE benchmark should be verified by means of cross-checking of results obtained from different FE codes and, if possible, of analytical solutions. This problem was partially presented during ASFE 2013 conference in Prague, Czech Republic (Benchmark example problems for beams at elevated temperature; Sawicki B., Pełczyński J., Kwaśniewski L.). Current results, shown in feasible template proposed by prof. Ian Burgess will be presented, including considerations on different cross-sections (H-beam) and structural materials. Problems of FE modeling in LS-Dyna® commercial code will be emphasised. Plans for future works will be also presented, including examples with other cross sections, Eurocode stress-strain curves for structural steel and RC beams.

FIRE RESISTANCE OF REINFORCED CONCRETE CONTINUOUS BEAMS

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In this work we will define the fire resistance of reinforced concrete continuous beams that are exposed to a standard fire ISO 834, and depending on the support conditions (structurally undefined), the dimensions of the cross section, the intensity of the initial fire load, percent of reinforcement, thickness of the protection layer and the fire scenario – the position of the elements in terms of the fire scenario. Also, the redistribution of the stress and deformation in the cross section of the constructive elements, as well as along their length will be defined, and in relation to the time progression of the temperature field.

For the above mentioned purpose, the computer program FIRE [Cvetkovska,2002] written in the program language FORTRAN 90, will be used. The computer program FIRE is comprised of two modules out of which one is in relation for non-linear structural analysis FIRE-S (Fire Response Structural analysis), while for the calculation of the problem of the non-linear and non-stationary transfer of the heat, based on the approximation of the minimized integral of the finite element method, the computer module FIRE-T (Fire Response thermal analysis) is used.

The problem will be analysed as a two dimensional heat transfer. In this case – two scenarios are analysed. In the first case, for the entire duration of the fire, the bottom side of the beam is exposed to the fire, and in the latter case, the top side of the beam is exposed to fire. This is done in order to see the influence of the fire scenario on the fire resistance of reinforced concrete beams.

THE FIRE-AFTER-EARTHQUAKE EVENT IN A LIBRARY BUILDING
Simulation of natural fire

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Post-earthquake non-structural damage can alter significantly the fire behaviour of a building which, if not taken under consideration, could downgrade the structural safety and pose a threat for the fire fighting and rescue crews. The target of this study is to examine the impact of the damage of the non-structural members on the development of natural fire in a four storey library building. Several fire scenarios that correspond to different levels of damage are simulated and the gas temperatures arising in the vicinity of the steel structural members are discussed. The simulation is performed on a 3-D model, using the Fire Dynamics Simulator (FDS), a Computational Fluid Dynamics code for the simulation of thermally driven flows with an emphasis on smoke and heat transport from fires. The fire spread within the compartment is simulated using a temperature controlled activation of heat release devices representing the combustible materials. The intensity of the fire scenarios is discussed in correlation to the existing damage.