WG2

Structural Safety in Fire

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GLOBAL MODELLING OF FIRE-AFFECTED STRUCTURES

Understanding the global behaviour of all but simplest of structures in fire has only been possible since the development of suitable numerical tools and modelling techniques. Considerable research effort has been dedicated in recent years to providing the knowledge needed for this and much progress has been made. It turns out that structural behaviour in fire in all but the simplest cases is much more complex than analyses based solely on loss of material strength due to heating, such as those based on the Standard Fire Test, can predict. A key aspect of the findings of recent research is that analyzing structural elements, such as beams and columns, in isolation and with idealized supports (as is common at ambient temperature) in a fire analysis is insufficient if an understanding of the fire resistance of entire structures is desired. For accurate results to be produced, either the behaviour of whole structures or the behaviour of large parts of structures with appropriate boundary conditions must be considered. As a result in all but the most straightforward cases numerical analyses are required to accurately predict the strength and behaviour of structures in fire.

Modelling the Cardington Tests

Much of the early development of numerical modelling of heated structures was validated against the fire tests undertaken on the Cardington Frame, a full-scale steel-concrete composite structure on which fire tests were undertaken. The Cardington frame is one of the very few full-scale structures that have ever been tested in fire while heavily instrumented. Consequently, it allowed real and numerically predicted responses to be readily compared. Full data including deflections, strains, rotations and temperatures during a sequence of four fire tests is freely available and numerous numerical models have been developed to represent these tests. The Cardington tests have been widely used as a benchmark when developing numerical models for both stress and heat transfer analyses.

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Modelling the Collapse of Fire-affected Structures

The collapse behaviour of fire-affected structures has recieved close attention since the World Trade Center attacks. Modelling approaches have been developed and various collapse mechanisms identified for the high-rise structures subject multi-floor fires. Research has examined both how a structure responds to such fires and also how the fires themselves may develop. Optimal numerical schemes for modelling structural collaspe have also been identified.

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Development of Material Models

Numerically representations of material behaviour, particularly concrete, at high temperature have developed rapidly recently. It has become possible to include and increasingly comprehensive range of material phenomena in numerical models such as plasticity, transient thermal strains, strain softening, cracking and crushing.

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FULLY COUPLED TEMPERATURE-DISPLACEMENT ANALYSES OF STEEL STRUCTURES UNDER FIRE

Motivation

The behaviour of steel structures under fire needs particular attention since the structural steel undergoes considerable deterioration in presence of high temperatures, such as the reduction of both resistance and stiffness of steel. This can cause the collapse of structures that are safely designed for ordinary load combinations, in which the fire scenario is disregarded. Consequently, the behaviour in fire of steel structures requires deep investigations from both experimental and numerical points of view.

Methodology

On the basis of such considerations, many efforts have been made in recent years in order to evaluate the performances of steel structures under fire. Recently a numerical study aimed at investigating the behaviour of steel structures under fire based on the use of fully coupled temperature-displacement finite element analyses, carried out by means of the advanced computer program ABAQUS has been presented. The used method allows to consider at the same time the mechanical and thermal aspects of the problem. The mechanical and thermal problems are faced up in a unique model, in which the actual phases of the modeled phenomenon, say the sequential application to the structure of the design loads and, then, of the fire scenario, are reproduced in a step-by-step analysis. Such approach differs from the usually adopted one, which consists, for the sake of simplicity, in performing the heat transfer analysis and the mechanical one separately (uncoupled analyses): the first one allows to evaluate the temperature-time law within the structural elements exposed to fire, completely neglecting the stress-displacement aspect; the second one consists in the usual structural analysis, in which the structure is subjected to the external loads; at the end of the structural analysis, the temperature-time variation, obtained from the preliminary heat transfer analysis, is imposed to the structural members, so allowing the calculation of the fire resistance of the structure. On the contrary, in the case of fully coupled temperature-displacement analyses, the used finite elements are endowed with both displacement and temperature degrees of freedom, so that the mechanical and thermal equations are written simultaneously and the mutual interactions between the two aspects of the problem can be easily caught.

Application

Applications have been carried out to simple steel portal frames, focusing on the main geometrical and mechanical parameters that influence the fire resistance of the considered structures, such as the span over height ratio, the massivity ratio of the structural members, the steel grade and the exploitation degree of the material. However such a methodology was already applied for the investigation of the behaviour of steel structures exposed to fire after being damaged by an earthquake.

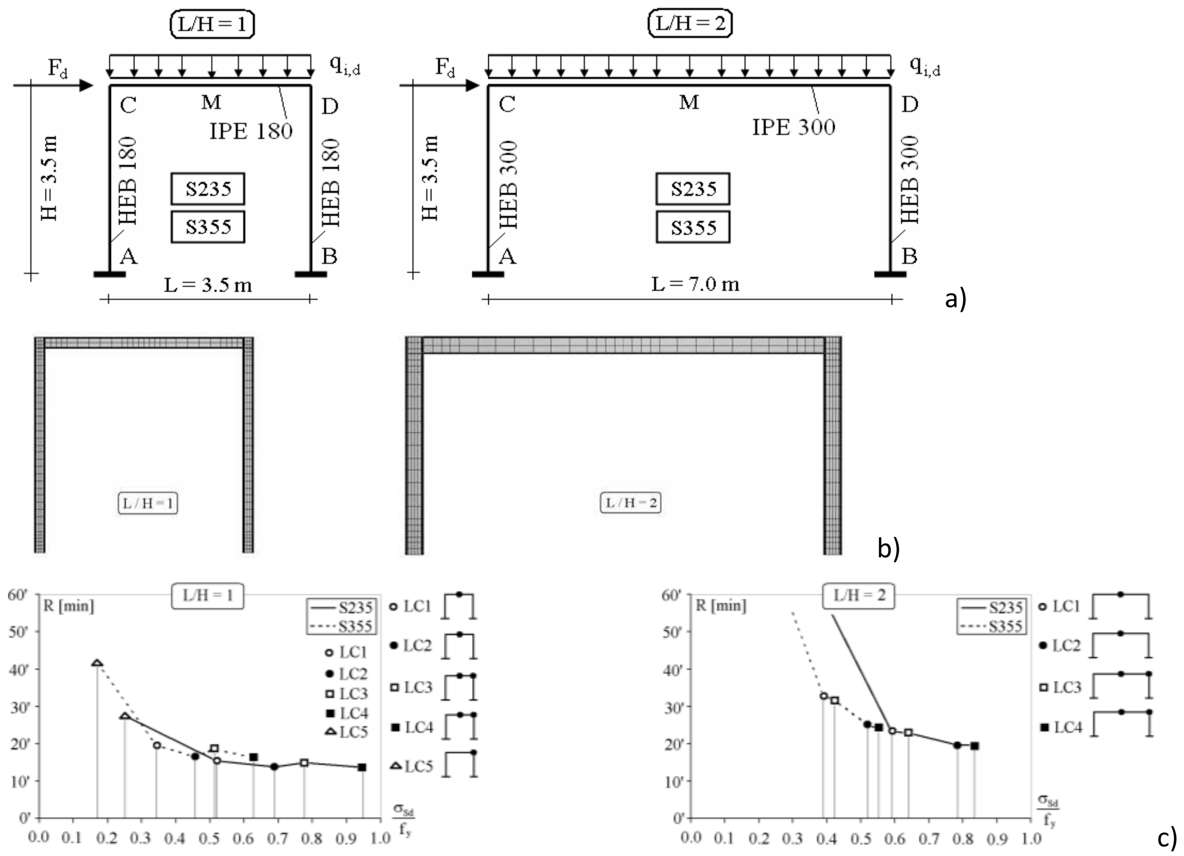

Figure 1. a) case studies; b) finite element meshes of the models; c) results.

Further developments

Further studies are needed and will be carried out, in order to enlarge the comprehension of the study phenomenon and to establish the efficiency of the refined model. Additional analyses, based on the same adopted methodology, will increase the number of the considered mechanical and geometrical parameters. Moreover, the analyses will be extended to multi-span multi-storey frames, with the possibility of studying the effects of the fire position in the frames.

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METHODOLOGY FOR THE ROBUSTNESS ASSESSMENT OF STRUCTURES SUBJECTED TO FIRE FOLLOWING EARTHQUAKE THROUGH A PERFORMANCE-BASED APPROACH.

Motivation

In order to preliminary take into account in the design phases the effect of the combination of the seism and fire accidental loads, a methodology aimed at the robustness assessment under fire of structures already damaged to different extent by the earthquake, through a performance- based approach, is envisaged. The procedure should be valuable as a design tool in all seismic prone area, as it is suitable for buildings of high strategic importance.

Methodology

A methodology for the assessment of the robustness of structures subjected to fire following earthquake should apply a performance-based approach inspired from the FEMA 356 Guidelines and the philosophy of the Fire Safety Engineering, it considering each behavioural condition to be undergone by the construction, from the application of vertical service loads, through the earthquake-induced damage, up to the exposure of the structure to fire (Faggiano et al. 2010).

The methodology consists of two main subsequent phases:

1) the identification of the seismic damage state, according to the pre-fixed seismic performance levels, in relation to the intensity of the seismic event;

2) the determination of the residual bearing capabilities of the seismic damaged structures subjected to fire, according to pre-fixed fire performance levels, in relation to the fire event.

The preliminary task to be accomplished is the definition of the fire performance levels. They could be easily borrowed in the general terms from the seismic ones (FEMA 356), as it follows:

Operational fire (Of): Very Light overall damage; it shall be defined as the fire damage state in which the structural and non-structural components are able to support the pre-event functions present in the building.

Immediate Occupancy fire (IOf): Light overall damage; it shall be defined as the fire damage state that preserves equipments and contents and guarantees the structure to remain safe to be occupied.

Life Safety fire (LSf): Moderate overall damage; it shall be defined as the fire damage state that guarantees the structure to retain a safety margin against onset of partial or total collapse, while architectural, mechanical and electrical systems are damaged.

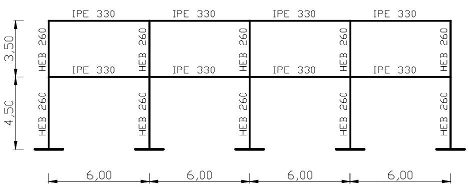
Collapse Prevention fire (CPf): Severe overall damage; it shall be defined as the fire damage state that allows the structure to support gravity loads, without retaining a safety margin against collapse; while extensive damage to the non structural components are present.

Application

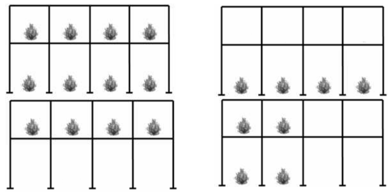
The procedure is illustrated with reference to a simple steel framed structure made of S275 steel, whose geometrical features are shown in Figure 2. Equivalent static incremental seismic analyses and fire analyses have been carried out by means of the ABAQUS Ver.6.5 software (2004).

The seismic performance levels for a steel structure can be characterized by the extent of the inter-storey drift δ/h (where δ is the lateral displacement and *h* is the storey height) and the plastic hinge rotation θ according to the FEMA 356 Guidelines. The reference values indicated in Figure 2c have been assumed. For the sake of brevity and simplicity, as a first rough attempt of application, the performance levels in fire have been identified with reference only to structural damage, according to definitions that are strictly pertinent to steel structures (Figure 2c).

The results, in terms of the time (s) necessary to reach the different performance fire levels, starting from the predetermined seismic performance levels IO, LS, CP1 and CP2 are indicated in Figure 2d, with reference to the condition of fire on half structure only.



a)

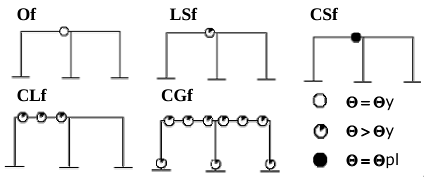


b)

Seismic performance level

PERFORMANCE LEVEL		δ/h [%]	Θ [rad]
Immediate Occupancy	(IO)	0.7	-
Life Safety	(LS)	2.5	-
Collapse Prevention 1	(CP1)	5.0	-
Collapse Prevention 2	(CP2)	-	0.05

Fire performance level



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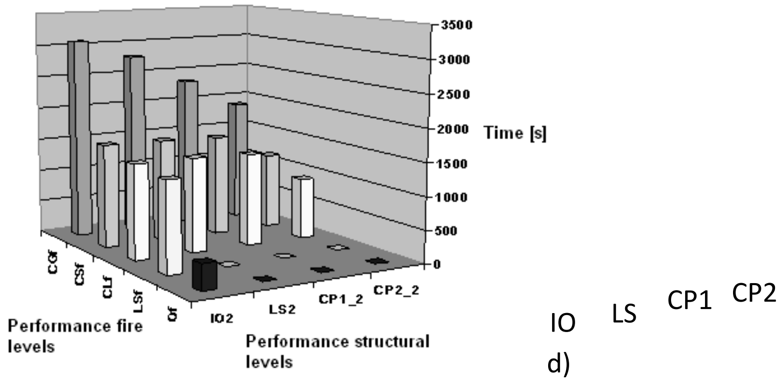

d)

Figure 2: a) Case study; b) Fire location; c) Performance levels; d) Results (Faggiano et al. 2010).

Further developments

The fire after earthquake performance chart seems to be a very useful and powerful tool both for fire after earthquake capability analysis and for fire after earthquake design. In fact for a given structural type, given a fire scenario, once fixed the seismic damage extent corresponding to the design seismic performance level, it is possible either to carry out a fire performance capability analysis according to the prefixed fire performance level, or to design the structure in fire in order that it could reach the fire performance level required at the given acceptable time.

This methodology is particularly appropriate for the analyses of constructions of particular strategic or historic- monumental importance. In the first case (hospitals, police station, government buildings), it is necessary to guarantee performance levels able to assure the usability of all functions of the buildings also under effect of a fire after seism. In the second case (churches, museum, villas, palace, theatres), the safety measures must be balanced with conservation requirements of the historic-artistic heritage. So for both cases, the standard seismic or fire regulations cannot be applied.

In this perspective, for the future, the development of this study must be directed to individuate and quantify the fire performance levels peculiar of the particular classes of buildings.

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FIRE SAFETY ENGINEERING FOR BUILDINGS AND OPEN CAR PARKS.

Research significance

According to ISO/TR 13387-1, the Fire Safety Engineering (FSE) is the application of engineering principles, rules and expert judgement based on a scientific appreciation of the fire phenomena, the effects of fire and the reaction and behaviour of people, in order to: save life, protect property and preserve the environment and heritage; quantify the hazards and risk of fire and its effects; evaluate analytically the optimum protective and prevention measures necessary to limit, within prescribed levels, the consequences of fire.

The performance-based approach, as opposed to prescriptive one, is based on a detailed analysis of the structural behaviour using advanced analytical models. Therefore, through the engineering method, following the steps in the layout of Figure 1, it is possible to evaluate the structural fire safety level.

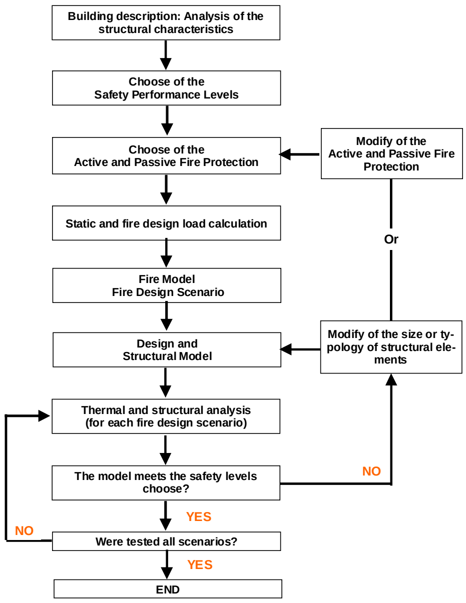

Figure 1: Fire Safety Engineering: Layout.

Case study: Office Building

The case study treats with the steel-concrete composite structure for a public office building, already described above (see Figure 2). Each floor can be considered as a compartment. The compartment is open space (576 m2), with 12 windows 5.0 m width and 1.50 m height. The enclosure material has a density of 2000 kg/m3, a specific heat of 1113 J/kgK and a thermal conductivity of 1.04 W/mK. The possible types of fire action are both localized fires and generalized fire. The first type can be dangerous for some structural members, the second one can be dangerous for all the structural elements in the compartment (see Figura 1).

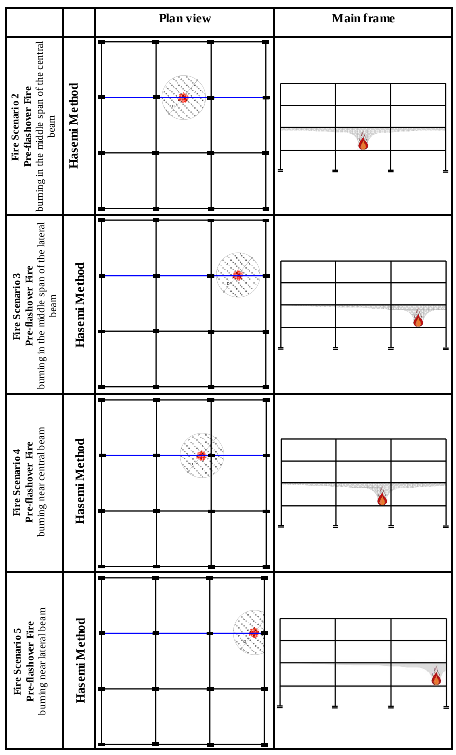

Figure 2: Office Building: Design Localized Fire Scenario.

Results

The analyses developed confirm that the Fire Safety Engineering allows the structural fire behaviour through advanced computational models applied to both fire and structure to be evaluated. A natural fire is characterized by a heating phase and by a cooling phase. The thermal gradient in structural elements produced by the cooling phase is opposite to that produced by the heating phase. During the heating fire exposure the structural behaviour is non-linear and the plastic strains can be achieved in the structural elements; for this reason, the structure during the cooling phase is different from the original structure. Therefore, after the cooling phase the stresses and the forces in the structural element can be different from the ones before the fire exposure. The stresses and the forces induced by constrained thermal deformations may cause structural collapse; however, they can not fully controlled by the prescriptive approach, as this approach is based on the assumption of a standard fire curve which increases unrealistically. Note that the generalized fire scenario, represented by parametric fire curve (scenario 1), is in this case the most dangerous in terms of maximum temperatures achieved in the structural elements exposed to fire action, as expected.

The analyses confirm that the study of further scenarios is however necessary to take into account the effects of localized fires, which may led to partial collapses or damages with consequent risks for the intervention of Fire Brigades.

Case study: Open Car Park

For car parks structures, Italian prescriptive code requires that the load bearing function is maintained during 90 minutes of fire exposure (R90). This resistance time can be very onerous for the steel structures. The car parks are often characterized by extensive natural ventilation in each floor, and for this reason they are called open parking. This feature provides positive effects on the structural behaviour under fire situation, encouraging the use of steel structures. Recently in Europe several experimental fire tests for assessing the structural behaviour of steel structures and steel-concrete open car parks were performed. The research project ended with the publication of a guideline for the definition of fire scenarios for open car parks (INERIS, 2001).

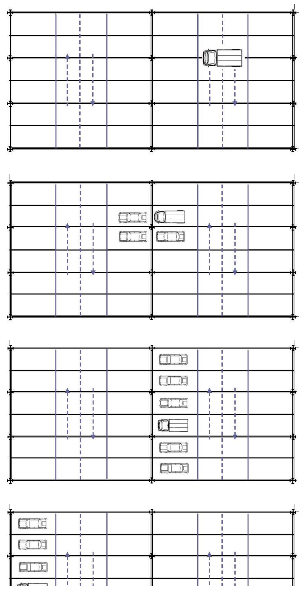

Figure 3: Open car parks: Design Fire Scenarios.

A design fire scenario is the description of the course of a particular fire with respect to time and space. It would typically define the ignition source and process, the growth of fire on the first item ignited the spread of fire, the interaction of the fire with its environment and its decay and extinction. The scenario of fire is strongly affected by the geometry of compartment and its opening conditions. Nevertheless, for the open car-park, the number of the most onerous fire scenarios is limited. In Guideline INERIS (2001) three most dangerous fire scenarios are defined, thus the fire scenarios of Figure 3 was used to asses the structural behaviour of the prototype built with steel and composite steel-concrete members. The analyses were performed with:

- Fire Scenario 1: characterized by the fire of a vehicle class 3 or, if necessary, a commercial vehicle at the centreline of the beam.
- Fire Scenario 2: characterized by the fire of four vehicles of class 3 (if necessary commercial vehicles) placed around a column with a initiation time delay for each vehicle of 12 min.
- Fire Scenario 3 and 4: characterized by a symmetrical spreading of the fire from the central car with a initiation time delay for each vehicle of 12 min.

Application to a real case

In this section an application of the "Fire Safety Engineering" for the assessment of structural resistance in case of fire is briefly showed with reference to the garages located on the ground floor of buildings in the CASE Project in L'Aquila. These garages are made with steel columns supporting the seismically isolated superstructure. In particular the car parks (Figure 4) examined have the following properties: 50 cm thick concrete slab on 260 cm height steel columns; the circular hollow steel sections have a device at the top allowing

Figure 4: Open car park in L'Aquila.

the isolator replacement. The thermo-mechanical analysis, performed by using the fire scenarios showed in Figure 4, allowed to affirm that the structures, and in particular the unprotected steel columns, attained the chosen performance level, thanks to the column over-strength in normal temperature condition.

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EXPERIMENTAL FIRE TESTS ON CONCRETE SLABS REINFORCED WITH FRP BARS

Research significance

Fiber-reinforced polymers (FRP) materials have several meaningful characteristics, such as high strength-to-weight ratios and resistance to corrosion, which are advantageous in the construction field. Recent progresses in research and technology of FRPs have led to reduced material costs and increased confidence in the use of polymers for a variety of civil engineering applications, as a lot of examples around the world can show. Nowadays several building codes (CAN/CSA 806-02, 2002; ACI 440.1R-04, 2003; CNR-DT203, 2006) are available for the design of concrete structures reinforced with Fiber Reinforced Polymers bars in place of traditional steel reinforcement, even if few provisions and no calculation model taking account of fire condition are suggested. Consequently FRP-RC employment is limited mainly to applications, where fire resistance aspects are not particularly meaningful. Thus, in order to improve the confidence in the use of FRP-RC members in multi-story buildings, parking garages, and industrial structures, the performances of these materials in fire situations must be evaluated. Therefore, to improve the knowledge of the structural response of FRP reinforced concrete members in fire conditions, experimental tests on nine concrete slabs reinforced with glass fiber reinforced polymer (GFRP) bars have been planned and partially performed.

Experimental program

The experimental tests were planned to evaluate resistance and deformability of the nine slabs in fire situations by varying (a) external loads in the range of the service loads, (b) concrete cover in the range of usual values (30-50mm), (c) bar anchorage shape (straight or bent) and length at the end of the concrete members, namely in the zone not directly exposed to fire (250-500mm). Note that zones not directly exposed to fire are often represented by mutual connections between members in concrete structures. The experimental program involved the design and fabrication of nine full-scale concrete slabs reinforced with GFRP bars (see Figure 8).

Figure 8: Slabs reinforcement grids before casting.

Three slabs S1, S2 and S3 were 3500mm long, 1250mm wide and 180mm thick. The concrete cover was 32mm, as estimated by reference to the centroid of the GFRP bars. The slabs S4, S5 and S6 were 4000mm long, 1250mm wide and 180mm thick; the concrete cover values were 51mm. The slabs S7, S8 and S9 were identical to slabs S1, S2 and S3, respectively, except for the shape of the longitudinal bottom bars at the end.

The concrete was identical for all slabs and characterized by calcareous aggregate (C35/45 according to EC2). E glass fibers and orthophthalic polyester resin were used by the manufacturer providing the FRPs. The experimental program, the main geometrical characteristics and the spacing of the reinforcement of specimens is summarized in Table 1.

Set	Slab	Length [mm]	Width [mm]	Thickness [mm]	Cover [mm]	Bottom bars (diameter/spacing) [mm]		Anchoring length [mm]	Bar shape
						longitudinal	transversal		
I	S1	3500	1250	180	32	Φ12/150	Φ12/200	250	Straight
	S2								
	S3					Φ12/225			
II	S4	4000	1250	180	51	Φ12/125	Φ12/200	500	Straight
	S5								
	S6					Φ12/200			
III	S7	3500	1250	180	32	Φ12/150	Φ12/200	250	Bent
	S8								
	S9					Φ12/225			

Table 1: Fire test main parameters for FRP reinforced concrete slabs.

Experimental results

The slabs S1-S6 (Sets I and II) have been recently tested in a four-point bending scheme in fire conditions by exposing them to heat in a furnace (see Figure 9) according to the time-temperature curve of ISO834 provided in EN 1363-1 (2001). The results of these tests, widely reported and discussed in Nigro et al. (2009a,b and 2010a,b), are briefly described in the following. Three slabs of set II, characterized by concrete cover values of 51mm and anchorage length values in the slab unexposed zone of about 500mm, showed better structural behaviour in fire than three slabs of the set I, characterized by concrete cover values of 32mm and anchorage length values of about 250mm. Hence the importance of concrete cover in the zone directly exposed to fire for the protection provided to FRP bars, due to concrete low thermal conductivity was confirmed.

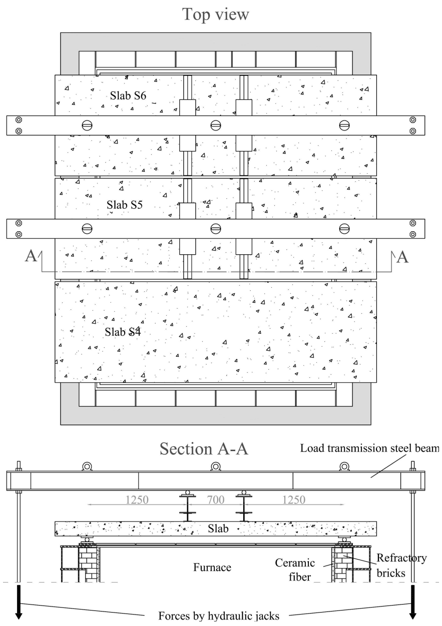

Figure 9: Test set-up – Slabs on furnace (dimensions in mm)

Moreover the anchoring length of the FRP bars in the zone of slab not directly exposed to fire at the end of the members was crucial to ensure slab resistance once in the fire exposed zone of slab the glass transition temperature was achieved and the resin softening reduced the adhesion at the FRP-concrete interface.

In particular, the experimental outcomes highlighted that the failure of the concrete slabs can be attained due to the rupture of the fibres in the middle of the member (see Figure 10a) if a continuous reinforcement from side to side of the concrete element is used and zones not directly exposed to fire are guaranteed (i.e. 500mm, see Figure 10b). These zones, near the supports, are necessary to ensure adequate anchorage of bars at the ends once in the fire exposed zone of slab the glass transition temperature is achieved and the resin softening reduces the adhesion at the FRP-concrete interface. By contrast, the fire strength strongly decreases due the to pull out of the bars (see Figure 10c), if lower anchorage lengths of zones not directly exposed to fire (i.e. 250mm) are adopted.

Figure 10: Slab S5 viewed from furnace after test. slab anchorage (a) 500mm; (b) 250mm.

Further developments

In a short time, the tests on the last set of three slabs (Set III), reinforced with bars bent at the end of the member in order to make better the anchorage of the bars within a short zone not directly exposed to fire (i.e. 250mm) will be performed. Based on the previous results, very good performances are expected for these slabs. Furthermore, a simplified method to evaluate fire resistance of concrete slabs will developed. A detailed modelling of RC slabs will leave out of consideration whereas the most meaningful constructive details necessary to attain good structural performances, will provided. In particular the design method will be mainly based on a simple calculating procedure taking into account the definition of the mechanical properties of bars at different temperatures, with particular attention to high values of temperature for which sudden decrease of strength with high uncertainty are expected for bars.

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FIRE ANALYSES OF COMPOSITE STEEL-CONCRETE FRAMES

Research significance

The advanced calculation models allow to evaluate the structural fire behaviour of single members, substructures and entire structures. The topic of the activities research is the application of advanced calculation models for fire structural analysis of composite steel and concrete frames.

The influence of some aspects of structural response developing during the fire exposure, generally neglected in the member analysis, on the assessment of the fire structural safety is pointed out, such as: indirect fire actions, large displacements, geometrical and mechanical non-linearities. Composite steel-concrete frames are designed with this purpose and are subjected to different fire scenarios.

Parametric Analysis

The considered frame presents a 24 meters overall length consisting of three equal spans and a 14 meters height consisting of four levels. The frame belongs to a three-dimensional structure with a square plan braced along the direction perpendicular to the studied frame. The columns are arranged with the axis of maximum inertia within to the plane of the frame. Beam-to-column connections ensure the rigidity of the nodes and they are assumed to be able to withstand the forces for a time at least equal to the time of fire resistance of elements transmitting the forces. The building was designed and checked under normal conditions for all load combinations required by the Italian Technical Standards for Construction. The seismic design of the frame was done in low ductility class and by respecting the capacity design criteria according to the Italian Code. The design of structures for earthquake resistance was conducted with reference to two different seismic zones (see Figure 1a), according to the Italian Code: (a) seismic zone 2 (ag = 0.25·g); (b) seismic zone 4 (ag = 0.05·g). The mechanical actions considered for fire design situation were defined by the exceptional load combination. The characteristic value of variable load was assessed according to the specific use of the office areas.

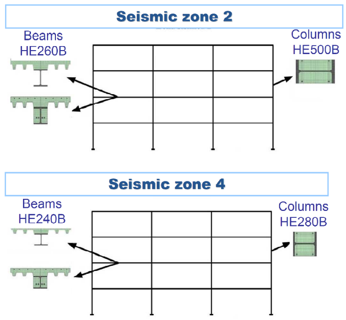

Figure 1: Steel-concrete composite structure.

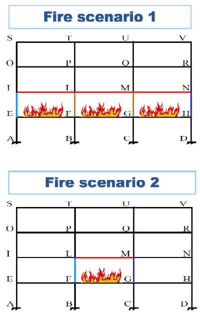

Figure 2: Fire scenarios.

The fire action is taken into account considering two different fire scenarios (see Figure 2):

a)Scenario 1 - assuming each floor as a single fire compartment, the fire involves only the first floor;

b)Scenario 2 - assuming the compartmentation of both each span and floor, the fire involves only the central span of the first floor. For both fire scenarios the thermal action is taken in accordance with standard fire exposure.

Results Discussion

The analyses are conducted by using the non linear software SAFIR2007, developed at the University of Liege (Belgium) and in Figure 2 are reported the main results. By the comparison between steel-concrete composite frames designed in two different seismic zones it is clear that, despite the different column overstrength resulting from the design criteria in normal conditions (capacity design and damage limit state), the two structures show similar collapse time in fire situation. It’s due to the level of indirect actions caused by constrained thermal expansions which result, indeed, higher in the case of frames having more stiff columns. With regard to the substructure analysis, the main processes for defining the size and boundary conditions of the substructures have been highlighted. From the analysis it is clear that, in general, the reliability of the analysis depends on the substructure itself. Particularly significant is the case of substructures b2 and c2 for fire scenario 2, where the presence of horizontal translational restraint in nodes I and N allows to develop the catenary’s action on the heated beam overstating the structural fire resistance.

Moreover, the comparison between single-member analysis and global analysis implies that single member analysis can lead to conservative results when the failure occurs on the beams, because the stresses on the beams are less affected by the effect of constrained thermal expansion. Instead, the single member analysis is not conservative when the failure is in the columns because the columns are important for both the second order effects and the effects associated with constrained thermal expansion.

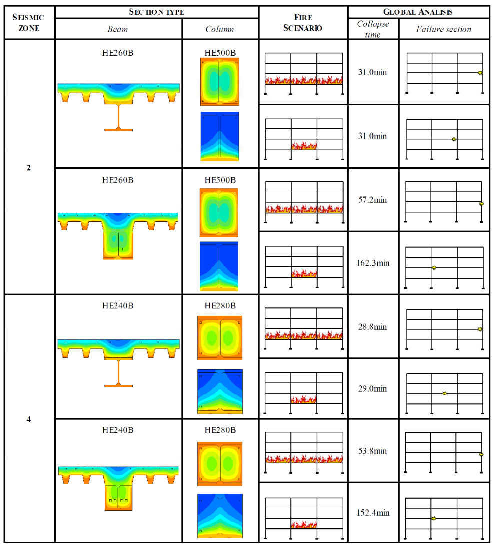

Figure 3: Global Analyses Results

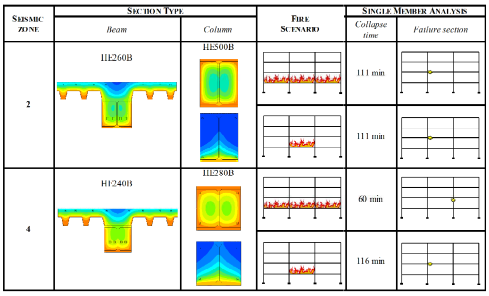

Figure 5: Member Analyses Results

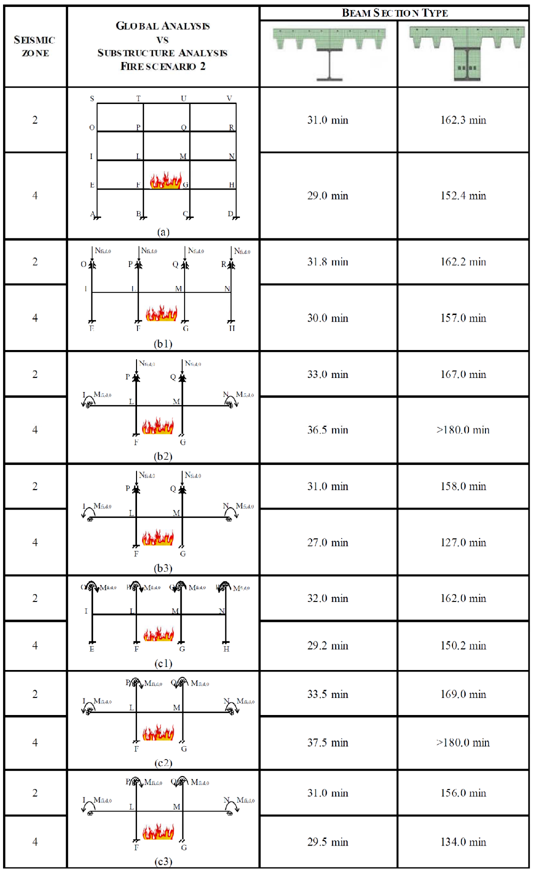

Figure 4: Substructures Analyses Results

Future developments

These results are basically valid for the analysed cases. In order to extend these results to a significant class of framed structures a full parametric analysis need to be carried out. Moreover, to establish simple criteria for verification of composite structures taking into account the different described phenomena, a wide number of cases of analysis will be considered, by varying the main parameters of influence; appropriate consideration of the actual temperature trend during a real fire will be also performed.

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FIRE TESTS AND INVESTIGATION ON BUILDING MATERIALS AND STRUCTURES

Investigation of material properties at elevated temperature - Heat effect by natural building materials as stones and adobe

Numerous historical monuments or also modern buildings contain stone parts or often the whole structure is built of stone. Although natural stones are non-combustible building materials it doesn't mean that they don't suffer damages by heat effect. Fire and high temperature cause changes in the petrological and petrophysical properties of the building stones that often lead to stability problems. The knowledge of mechanical properties of natural stones is fundamental for conservation and restoration of the building stones of the monuments.

Natural stones are considered as less sensitive materials to fire. According to testing of different natural stone types (limestones, sandstones, tuff) at various temperatures, it has been proved that fire can cause rapid and irreversible physical changes (Hajpál & Török 2004, Hajpál 2008). These alterations negatively influence the strength and static behaviour of the whole monument (Hajpál 2008). Test results have shown that the compressive strength of various lithologies depends on the heating temperature. It can be observed, that the heating does not cause a decrease in the strength for all rock types.

Some sandstone and also the rhyolite tuff have higher strength after the heating at 900°C than at room temperature. The limestone types lost their strength only at elevated temperatures.Strength parameters and axial deformation of limestones do not change uniformly. The tests have demonstrated the differences of compressive stress and axial deformation with increasing temperature.Indirect tensile strength of limestones shows slight increase up to 150°C, which is followed by a decrease, while the tensile strength of sandstones and rhyolite tuff do not reflect a clear trend with increasing temperature.

Adobe and rammed earth are natural materials made of a mixture of fines (usually clay), sand, small stone fragments, organic material as fibre. In some adobe lime was also used. Significant number of adobe buildings have been damaged or lost in fire. To understand the behaviour of adobe under fire laboratory experiments were preformed (Alvarez de Buego et al. 2006). For the tests adobe cubes were prepared and heated at temperatures of 22, 150, 300, 450, 600, 900°C in an electric oven for a six-hour period. The test results were evaluated and compared to field and laboratory studies of burnt adobe structures. Colour changes, bulk densities and ultrasonic pulse velocities were analyzed as well as changes in mineralogy and micro-fabric. For most of the samples a decrease in density were documented after the heat shock. The strength parameters did not show uniform decrease, instead cubes that experienced 600°C show increased strength compared to specimens tested at 150, 300, 450°C.

The heating causes a colour change of stones and adobe. Not only colour but also other external signs of heat are observed. Limestone samples are cracked at lower temperatures while at higher temperature the samples collapsed or exploded. According to the thermal decomposition of carbonates this processes is dedicated to the formation of new mineral phases (portlandite).

The most important kind of decay of stones due to fire are scaling off, spalling, cracking, rounding off the edges. Fire can completely destroy ornaments and can damage carved forms. Fire damaged stones are often replaced by new ones (Hajpál 2000).

The firing model for earthen materials is different from that for stone materials, the effect of fire is more ubiquitous than for stones. The damaged zones are more severe in the interior part of the adobe than at stones. The heterogeneity and the characteristic manufacturing of earthen materials characterize their response to fire, mainly due to the addition of confined vegetable matter (straw), which creates an anoxic combustion. Firing can cause a positive change in adobe in terms of strength, since to a given temperature an increase in strength was observed under laboratory conditions (Alvarez de Buego et al. 2006).

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Fire resistance tests of building structures in accordance with the EN Standards

ÉMI Nonprofit Ltd. has a Laboratory for Fire Safety in Szentendre, Hungary, where we can make big fire resistance tests on horizontal and vertical non-load-bearing and load bearing building structures (walls, ceiling, pillars, etc.).

The appropriate temperature of the furnace chamber in the test furnace is provided by automatically controlled oil burners. The temperature in the furnace chamber is measured at more points by Ni-CrNi thermocouples. In accordance with the regulations of EN Standards on both sides of the model Ni-CrNi thermocouples can be installed during the test.

Measured temperatures and other data (pressure, distortion, etc.) can be also recorded.

The test results and observations are registered and after the test a test report will made. The fire safety grade classification and fire proofness of the investigated structure can be given.

References:

Part 5, Section I/4 of OTSZ (National Fire Safety Code)

The Decree 9/2008 (II. 22) ÖTM

MSZ EN 1364 and MSZ EN 1365 Standards

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BEHAVIOUR OF R/C SECTIONS, ELEMENTS AND STRUCTURES EXPOSED TO FIRE

Determining the fire response of structural elements and their assemblies is a complex problem of nonlinear analysis in which the strength and the stiffness of the elements as well as the inner forces are continuously modified. To solve this problem the computer program FIRE was developed. The program was verified on the bases of the experimental investigation results available in literature. This first [1] paper describes the analytically achieved results for the fire resistance of centrically loaded RC columns. The influence of: element geometry, concrete cover thickness, steel ratio and intensity of axial force are analyzed. Four RC beams, exposed to different fire models are analyzed too, and the predicted results are compared with those experimentally achieved by other researchers. Today, as a result of many years of investigations, there are three basic methods for determination of fire resistance of structural elements and their assemblies. The oldest method is the performance of a fire test of loaded elements, in compliance with the national regulations and standards, or comparison of the elements with the results from already performed tests on similar or identical elements. The second method implies the use of empirical formulae that are based on the results from performed fire tests and holds for a certain combination of: structure, material and protective coating. The third method represents an analytically elaborated approach to design elements with a predefined fire resistance and it is based on the principles of structural mechanics and theory of heat transfer. The solution technique used in FIRE is a finite element method coupled with time step integration. The used analysis procedure does not account for the effects of large displacements on equilibrium equations. To define the fire response of reinforced concrete structure is thus a complex nonlinear analysis problem in which the strength and stiffness of a structure as well as internal forces continually change due to restraints imposed by the structural system on free thermal expansion, shrinkage, or creep. Because linear elements and frames are modeled as an assemblage of members connected to joints, the basic analytical problem is to find the deformation history of the joints when external loading at the joints and temperature history within the members are specified. Since only linear elements and two dimensional frames are considered, each joint has three degrees of freedom, two translations and one rotation. Likewise, there are two forces and a moment at each joint.

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FIRE AFTER EARTHQUAKE

Structures exposed to fire after earthquake is relatively new research area especially when reinforced concrete structures are considered. In the scope of the COST Action TU0904 we find an excellent opportunity to extend our research in analysing structural behaviour in very severe conditions of fire environment after survived earthquake. Plastic stress-strain earthquake response histories of: mildly, moderately or severely damaged RC structures will be preserved so that in the continuation of the analysis the damaged structures will be exposed to different fire scenarios.

Calculating structural response to fire after earthquake is a few step process: modeling the structure including nonlinear analysis options, choice for earthquake analysis scenario, seismic nonlinear analysis (pushover or dynamic time history), fire hazards analysis to identify all possible fire scenarios, thermal analysis to calculate temperature history in each member, structural analysis to determine forces, stresses and deformations to estimate whether local or global collapse would occur during any of the fire hazard scenarios. The seismic excitation induces damage and lateral deformation provoking additional stresses in the frame due to the moment caused by the P-□ effect. Structural members and joints are also weakened by the cyclic inelastic deformation, causing stiffness and strength degradation. Once the earthquake-induced damage in the structure is determined, the damaged structure is subjected to a fire scenario, which involves fire hazard analysis to determine the time history of fire growth and spread and stress and collapse analysis of the structure but also to analyse no-collapse conditions and cooling after fire.

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FINITE ELEMENT MODELLING OF LAP SHEAR RIVETED CONNECTIONS IN FIRE

Ancient metal structures represent an important architectural and historical heritage in Italy. These structures are generally affected by a spread damage state mainly due to corrosion and structural inadequacy. In particular, recent research carried out by the authors showed that riveted connections represent the weaker elements of these structures. To characterize their mechanical behaviour under actual service loads and under exceptional actions, like fire, a wide experimental-theoretical study is still ongoing, in collaboration with Italian railway society (RFI). Indeed, the basic modelling issues are presented and discussed and the preliminary fire modelling issues are introduced. With this regard, a highly detailed three-dimensional (3-D) finite element (FE) model has been created using the ABAQUS software. To characterize the mechanical behaviour of riveted connections under actual service load, the 8-node brick continuum element C3D8R was adopted for modelling both rivet and plates. The material stress-strain relationships for the rivets and plates have been obtained starting from the relevant experimental test on materials. The plasticity behaviour was based on the Von Mises yield surface criterion. Large deformation effects have been considered. The rivet clamping was also taken into account. Finally, the load pattern has been simulated by applying a relative displacement between the two opposite terminal ends of each connected plates. The response of the finite element model was compared with the experimental results. The load-displacement curve obtained from numerical simulation is in a good agreement with experimental results in terms of stiffness and strength.

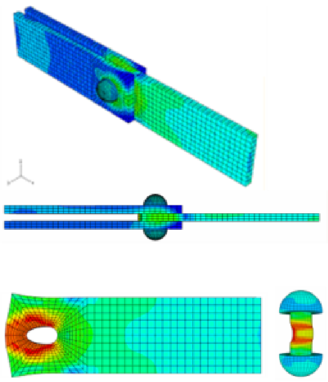

Figure 1: Predicted collapse mechanism of S16-10-1

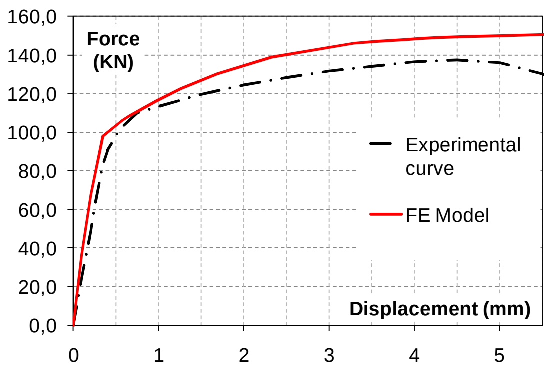

Figure 2: Numerical vs. Experimental response curve

This calibrated model has been updated to simulate the fire condition. This implied the modification of the material, mesh and contact properties. Indeed, the material properties at the elevate temperature were determined from the engineering stress-strain relationship using nonlinear material curves recommended in Eurocode 3, Part 1.2. The expansion coefficient, specific heat, and conductivity were also defined, and reduced according to EC3 when temperature increases. The Stefan-Boltzmann constant and the absolute zero temperature were also defined in Abaqus. Both the rivet and the plates were re-meshed using a 3D 8-node, thermally coupled brick element (C3D8RT). Once more large deformation, and geometric and material non-linearity have been taken into account. A thermal load was also added to apply the fire condition. The amplitude was set equal to the temperature-time curve given by the Eurocode 1 Part 1.2. The heat transmission due to radiation from the ambient where the fire develops to the external surfaces of the connection was also modelled.

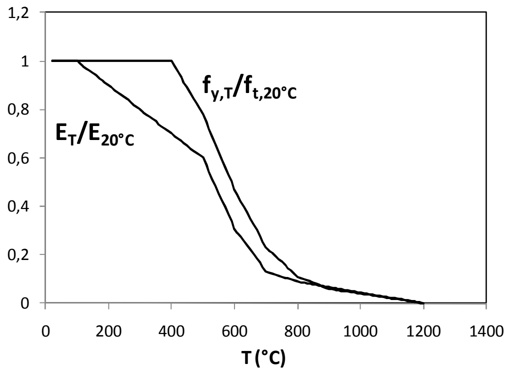

Figure 3: Mechanical properties of steel in function of temperature.

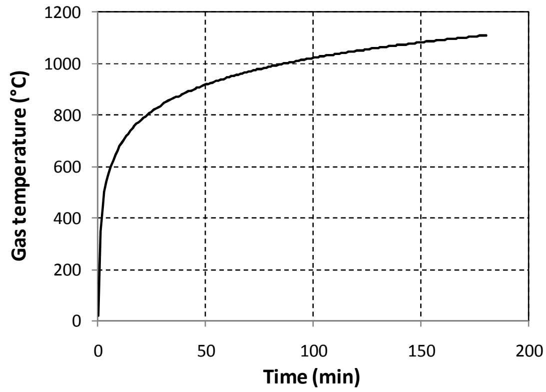

Figure 4: The applied fire (time-temp. curve given by the EN 1991 Part 1.2)

The temperature versus time behaviour of lap joints shows that until 500°C the strength and the deformability of the material is almost the same of the one at the ambient temperature. After about 5 minutes, the temperature overcome 500°C, and a great reduction of the connection response is noted. This behaviour advised that the lap shear joint worked until 500°C, that correspond to an increment of the displacement of 5%. After this time (about 5 minutes), the connection failed due to the reduction of its mechanical characteristics. However, further effort are necessary to improve the fire model especially for what concerns the interaction definition such as the Coulomb friction in contacts.

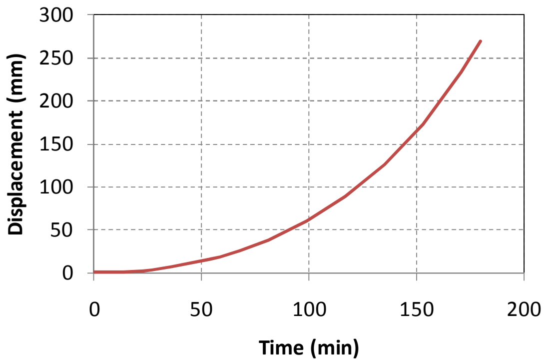

Figure 5: Time-Displacement curve of lap shear joint to fire

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COMPUTER SIMULATIONS OF STRUCTURES IN FIRE - VERIFICATION AND VALIDATION

Widely spreading implementation of computational methods in many fields of research and technology including studies on structures subjected to elevated temperatures, raises questions about the predictive capabilities of computer simulations. There are many contradictory opinions about the reliability of computer predictions [1]. Consider G. Box's well-known statement: "Essentially, all models are wrong, but some are useful" [2]. Nowadays verification and validation (V&V) is recognized as the primary method for evaluating the confidence of nonlinear computer simulations and of the mathematical model underlying them [3]. Recently, there has been a lot of attention dedicated to V&V methodology, with much research (see [4] for a review of this literature), workshops [5], and the first guides and standards published as the result (see [6-9]). There are two perspectives for V&V: that of code developers and that of analysts (users of the codes). In the software V&V, a code is a customer whereas in the model V&V the whole modelling process for a specific physical problem is considered. The code developers are more involved in code verification, while the analyst's responsibility is more oriented towards (experimental) validation.

Verification

Verification is supposed to deliver evidence that mathematical models are properly implemented and that the numerical solution is correct with respect to the mathematical model. Due to the high complexity of mostly nonlinear problems that are practically important for fire engineering, such verification can be conducted only empirically using "a posteriori" approach where the reasoning is based on the experience coming from repeated calculations. A standard example is the posteriori error estimation based on numerical results for different mesh resolutions. In the literature, verification is subdivided into two parts: code verification that primarily belongs to software developers and computational verification addressed to analysts (code users) [9]. According to AIAA [7], code verification can be conducted through tests of agreement between a computational solution and four types of benchmark solutions: analytical, highly accurate numerical solutions of an ODE or PDE problem, and manufactured solutions [10]. In contrast to numerical solutions used in the validation stage, the numerical solutions applied for verification can represent mathematical models with little physical importance.

Validation

Experimental validation is the final check to reveal possible errors and to estimate the accuracy of the simulation. [9]. Possible disagreement can be caused by the differences between mathematical and physical systems, the differences between computerized and mathematical models, and the distinction between a physical system (our concept of it) and the subject of an experiment used for validation [4]. The soundness of an experiment as a source of data for validation depends also on the relationship between the application and the validation domains [11]. The application domain defines the intended boundaries for the predictive capability of the computational model. The validation domain characterizes the representation capabilities of the experiment. When a complex system is modelled, there is a need for many validation experiments capturing different physical aspects of the system (e.g., different loading scenarios, mechanical and thermal boundary and initial conditions). The ideal situation, possible only for simple systems, is when the validation domain completely overlaps the application domain. This means that the available set of the validation experiments covers all possible parameters defining the computational model within its intended application. When complex systems are analyzed, it is sometimes infeasible or even impossible to conduct all necessary experiments to verify all features of the computational model. An example of such a situation is the global analysis of structures in the fire [12].

There have been only a few full-scale experimental fire tests (i.e., the Cardington [12] or Mokrsko [13] tests) conducted so far, but there are numerical capabilities for such complex analysis. The extreme, theoretical situation is when all possible or available experiments are too far from the application of interest and there is no overlap between the validation domain and the application domain [11]. The credibility of such a computational model, validated only through extrapolation, is obviously much smaller. To improve the predictive capability of computation in such cases, hierarchical validation is introduced where closer correlation of the domains is possible for lower-level experiments and then the gained confidence is extrapolated to the global model.

As stated before, the experiments may have many limitations, and practically the number of validation experiments is always limited. The tests conducted on large-scale and complex systems, on the one hand, are expensive or even infeasible and, on the other hand, are less useful for validation due to their complexity and too many uncertainties encountered at the same time (e.g. space and time distribution of temperatures). Even in supposedly simple experiments, there is usually a range of uncertainties for the input such as, for example, thermal and mechanical boundary conditions. To optimize the validation activities, application of the validation hierarchy is recommended [14]. In this approach, the experiments for the considered system are usually divided into three or four levels (tiers) representing different degrees of complexity. Such division can be done conceptually in different ways depending on the type of problem [10]. The tests classified to different levels can represent different portions of the physical system but, more importantly, capture different portions of the physics.

Validation and calibration

During the model development, the problem of modelling uncertainties is commonly treated using calibration. The idea of the calibration procedure is to establish the quantities of modelling parameters that give the model's response closest to the actual experimental data. The calibration is performed through comparison between an experiment and repeated calculations with modified input parameters. It is often pointed out that the calibration procedure should not replace validation but be a part of it and that the calibration should be minimized to only unmeasured input quantities [11]. It can happen that due to superimposing of errors we can get good correlation between experimental and numerical results for a wrong model defined by incorrect input parameters. Often, such a situation can be detected when the model is used for a different case with changed input conditions. Also, a complex model with only some of the input parameters "correctly" calibrated should give a response different from the experimental data due to the indetermination of other parameters. This is why validation based on more than one experiment is more reliable.

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BEHAVIOR OF RC ELEMENTS IN CASE OF FIRE

Determining the fire response of structural elements and their assemblies is a complex problem of nonlinear analysis in which the strength and the stiffness of the elements as well as the inner forces are continuously modified. Mainly, three groups of nonlinearity source can be identified: nonlinear distribution of temperature thru the element thickness, nonlinear temperature-dependent material properties (thermal and mechanical) and nonlinearity due to reaching of strength capacity.

Behaviour of RC beams under different fire scenarios

Performance assessment of concrete elements in case of fire is carried out with respect to a standard heating curve developed in a fire resistance test furnace. This heating regime is defined purely in terms of a temperature-time curve, originally conceived as being representative of the development of a fire in a standard living room, and expressed in essentially identical form in a number of standards, both internationally, i.e. the ISO-834 fire curve, and nationally, i.e. the BS-476 curve in the UK, ASTM E-119 in the US. Other fire curves, (short duration-high intensity or fire curves with decay phase) exist which is intended to replicate the temperature developments in other assumed scenarios, and in some cases they can be more realistic compared with the standard fire curves. Temperature distribution per height and over time for one reinforced concrete beam element is analyzed for two different fire scenarios, ISO-834 fire curve without and with two hours decay phase which starting 60 minutes from the fire beginning. Results from analysis show the big difference in temperature distribution along the section height, especially in the time of cooling phase.

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Coupled Thermal - Stress Analysis

The program FIRE (Cvetkovska 2002) carries out the nonlinear transient heat flow analysis (modulus FIRE-T) and nonlinear stress-strain response associated with fire (modulus FIRE-S). The solution technique used in FIRE is a finite element method coupled with time step integration. The modulus FIRE-S takes in to accounts the dimensional changes caused by temperature differences, changes in mechanical properties of materials with changes in temperature, degradation of sections by cracking and/or crushing and acceleration of shrinkage and creep with an increase of temperature. Four RC beams, exposed to different fire models were analyzed, and the predicted results are compared with those experimentally achieved by other researchers. Two beams were tested using the ASTM E119 fire exposure and another two were exposed to a short duration, high intensity (SDHI) expose.

The approach used in FIRE provides better agreement between the calculated and experimentally achieved deflections in case when ASTM fire model is used, but that is not a case during the cooling phase, when beams are subjected to SDHI fire model. The effect of creep at elevated temperatures in the program FIRE is involved by the temperature dependent stress-strain relationships for concrete and steel, recommended in EC2. They are defined while specimens are subjected to ASTM E119 (or ISO 834) fire model, so they are not adequate for SDHI fire model.

The model proposed is capable of predicting the fire resistance of reinforced concrete structural elements with a satisfactory accuracy.

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Axial Restraint Effects on Fire Resistance of RC Beams

The various support conditions can have a big influence on fire resistance of reinforced concrete elements. Increasing of temperature, initiate elongation of structural elements, this can lead to the initiation of internal forces if they are restricted.
Two different support conditions (pin-pin and fully fixed) were used to model structural elements with various level of axial restraint. These beams were exposed to the ISO-fire curve without decay phase. From the obtained results can be concluded that increasing of axial spring stiffness increases the induced axial forces and fire resistance of the element and decreases the maximal vertical deflection.

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FIRE FOLLOWING EARTHQUAKE

Fire following earthquake is probably one of the most concerning hazards in both urban and industrialized areas. It can be looked at as a relatively low probability event characterized by extremely high consequences. Records from historical earthquakes show that sometimes the damage caused by the subsequent fire can be much more severe than the damage caused by the seismic action itself, this being true for both single buildings and whole regions (Scawthorn et al., 2005). Therefore, the behaviour in fire of structures, which have been damaged by earthquakes, represents an important investigation field, since the earthquake-induced damage may lead to a structure which is more vulnerable to fire effects than the undamaged one. In the perspective of resistance to the fire following earthquake, the relevant effects of the earthquake may be both non-structural and structural, the former ones being related to the damage to protection systems and facilities and the latter being related to the intrinsic resistance of the structure.

Post-earthquake fire resistance of steel and composite steel-concrete frames

Studies on the fire resistance of steel structures damaged by earthquakes have been carried out (Della Corte and Landolfo, 2001; Della Corte et al., 2003a, b). In those studies, both steel portal frames and multi-span multi-storey moment resistant frames were considered, with the aim of determining the fire resistance rating reduction of frames as a function of the maximum residual inter-storey drift angle and the seismic intensity. The work was developed in two main phases: 1) Dynamic time history seismic analyses, aiming to identify the type and intensity of earthquake-induced damage; 2) Fire analysis on the structural configurations distorted due to the seismic damage, carried out by means of an ad-hoc software. With regard to the simple portal frames, abaci were developed for computing the fire resistance rating reduction at increasing levels of residual storey drifts. With regard to the multi-storey frames, the effects of the seismic design and of the structural system layout were assessed, and the identification of the type of collapse mechanism in fire, exhibited by both the undamaged and the earthquake-damaged structures, was obtained.

The fire following earthquake topic was faced up also within the COST C12 European Cooperation Programme titled “Improving buildings’ structural quality by new technologies”. In particular, the Working Group 2 (Chairman: F.M. Mazzolani) was devoted to the study of the “Structural integrity under exceptional loads”. The output of this work was summarized in a paper on the structural effects of fire following earthquake presented by Della Corte et al. (2005) at the COST C12 Final Conference, held in Innsbruck, Austria, on 20-22 January 2005. The interest in the topic was later confirmed by the COST C26 European Cooperation Programme titled “Urban Habitat Constructions under Catastrophic Events” (Chairman: F.M. Mazzolani), where a full Working Group (No. 1) is devoted to the “Fire design”. During the COST C26 Workshop held in Prague on 30-31 March 2007, a paper was presented by Faggiano et al. (2007). The work aimed at carrying out the structural analysis under fire of earthquake-damaged structures through the following steps: 1) Seismic pushover analyses under horizontal loads of structures subjected to constant vertical loads, aiming at the damage identification; 2) Definition of the performance levels, correlating seismic intensity and damage extent; 3) Fire analysis on the damaged structures. In this study, portal frames made of steel were considered and the attention was focused on: 1) the evaluation of the fire resistance of the portal frames with relation to the geometrical span-over-height and overstrength ratios of a structural member; 2) the evaluation of the effect of the seismic-induced damage on the fire resistance and the collapse mode of the study structures. During the COST C26 Workshop held in Malta, on 23-25 October 2008, studies on the fire following earthquake risk management and structural analysis and design were presented (Faggiano et al., 2008a, b).

More recently, within the first Italian research project ReLUIS, research line no. 5 “Steel and composite structures”, both analytical and experimental studies on the fire resistance of beam-to-column joints pre-damaged by earthquake actions have been carried out (Alderighi et al., 2008; Ferrario et al., 2007a, b; Pucinotti et al., 2008). A multi-step approach was followed, consisting in: 1) application of a cyclic inelastic loading history to the specimens; 2) fire tests on the damaged specimens; 3) numerical simulations of these tests by means of 3D finite element models; 4) numerical analysis of moment resisting frames.

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BEHAVIOUR OF ALUMINIUM ALLOY STRUCTURES UNDER FIRE

Research significance

The prediction of the mechanical response of aluminium alloy structures exposed to fire is complicated for two principal reasons: on one hand, the intrinsic difficulty of developing accurate structural analyses in post-elastic field, taking correctly into account the mechanical features of the basic material, such as the strain-hardening and the limited deformation capacity; on the other hand, the inadequate knowledge of the material behaviour under high temperatures. The methods of structural analysis in fire conditions should take into account the influence of the material constitutive law and thus of the kinematic strain hardening on the global behaviour of the structure.

Mechanical features of aluminium alloys at high temperatures

Common aluminium alloys melt at about 600°C and loose the 50% of their original strength at about 200°C. The alloys in the work hardening state (H) and the ones being in the hardening state by means of heat treatment (T) exhibit a relevant loss of strength with temperature, which is of about 70-80% at 250°C. Besides, the alloys in the annealed state (O) show a less significant decay of strength, which is of about 30-50% at 250°C. Heat treated and work hardened alloys (types T and H) are characterized by ultimate strength remarkably larger than the alloys in the annealed state (type O), only up to temperatures of about 100-150°C. At ambient temperature annealed state alloys (type O) present strain hardening ratio ($f_t/f_{0.2}$) about twice larger with respect to the heat treated and work hardened alloys (types T and H), such difference strongly reduces as far as the temperature increases, starting from temperatures of about 100-150°C. In addition, tempering and plastic working processes improve the material strength, but in the meantime they reduce both the effect of the strain hardening and the extent of the ultimate elongation (ε_u), which experiences a revival with the increase of the temperature.

From further data available in literature, it comes out that the resistance of the aluminium alloys, given in terms of both conventional yielding stress and ultimate strength, decreases as far as the exposure time to an assigned temperature increases. On the contrary, the ultimate elongation, and therefore the material ductility, increases with the prolonged exposure to high temperatures.

Proposal of stress-strain relationships for aluminium alloys at high temperatures

In order to interpret correctly the evolution of the mechanical characteristics of the material with the temperature, it would be possible to apply the Ramberg and Osgood model, whose *n* exponent measures the strain hardening of the alloy, ruling the shape of the curve in the post-elastic field. The extension of the Ramberg - Osgood relationship to high temperature is based on the introduction of the variation law with the temperature of all the relevant mechanical parameters, such as $f_{0.2,T}$, $\varepsilon_{u,T}$ and $f_{t,T}$.

For every alloy the values of the strain hardening factor *n* obtained at different levels of temperature, included the ambient temperature, have been provided (Figure 1). In order to evidence the influence of the mechanical properties on the strain hardening factor *n*, the value obtained considering the actual variation of the single mechanical parameters with temperature (n-analytical), is compared with the n values obtained taking the ultimate elongation as a constant and equal to the value at ambient temperature (n-ε_u=cost) and the constant value of n at ambient temperature.

It should be observed that for all the alloys the n value for high temperatures is remarkably different with respect to that one obtained at ambient temperature. Furthermore the *n*(T) relationship does not present a single trend for the different examined materials. In particular, for not treated materials (type O) it can be noted that at increasing temperatures the strain hardening factor exhibits an increment higher than 50% with respect to the value at room temperature. On the contrary, for treated materials (H and T types) the *n* value is higher than the corresponding value at ambient temperature, only up to a temperature of about 200°C, beyond which there is a reversal trend, with values of the n factor lower than the ones at ambient temperature. Moreover it can be observed that the variation of the elongation at collapse ε_u with the temperature has not a significant influence on the strain hardening factor *n*. As a consequence, in order to simplify the mathematical expression of the strain hardening factor, the ultimate elongation of the material could be actually taken constant and equal to the one at ambient temperature. Some numerical cases have been developed by the authors showing the effect of the material strain hardening at high temperatures, which should be actually taken into account for a correct interpretation of the resistance of aluminium structures.

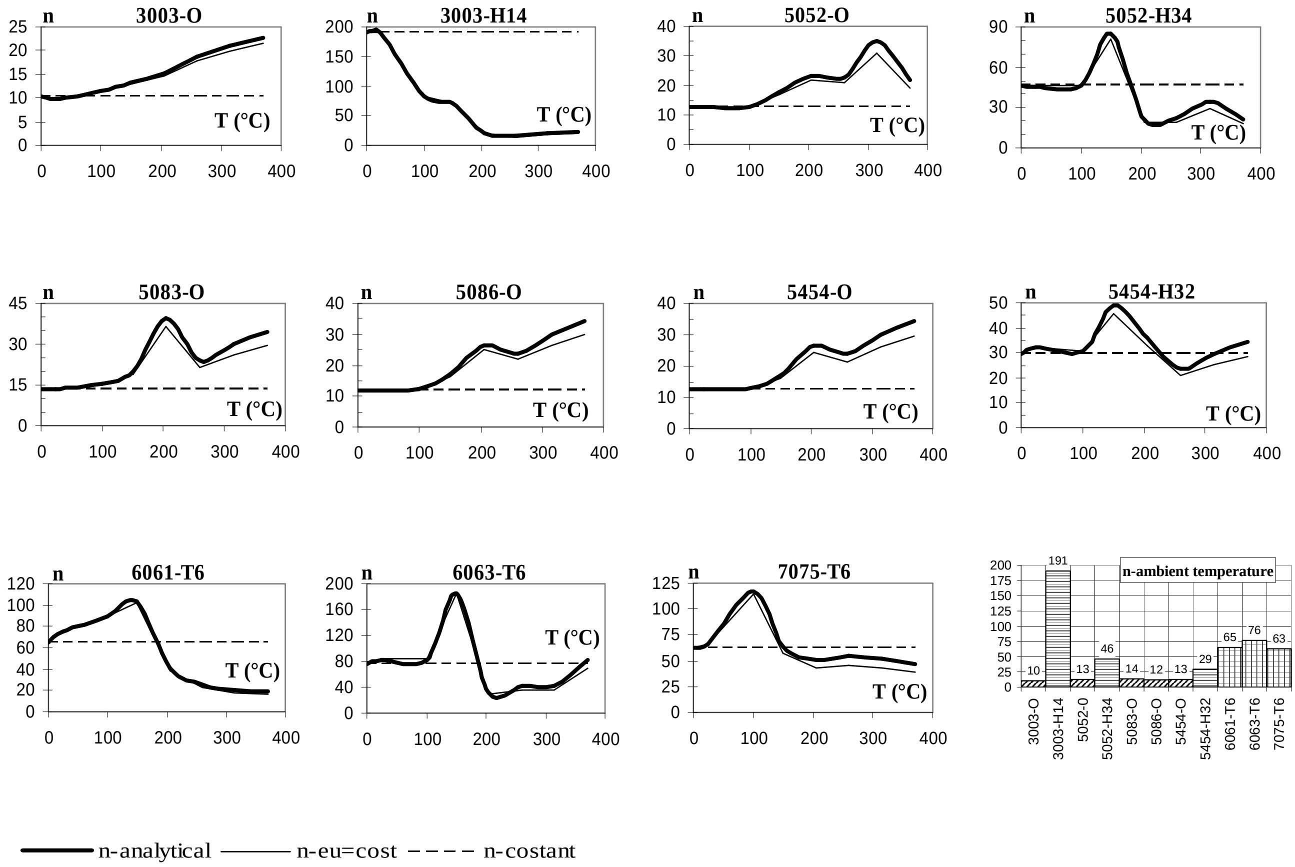

Figure 1: The strain hardening factor n as a function of temperature.

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STEEL COLUMNS IN FIRE

Behaviour of structures in case of fire is usually strongly affected by primary and secondary thermal effects which can substantially reduce the structural robustness. The structural analysis can be conducted on global level or limited to selected important structural components such as columns or connections. The analysis of isolated structural members is practiced very often in experimental studies which are usually based on the standard furnace tests on structural elements, often represented with reduced scale specimens. The same tendency dominates for numerical investigations and especially for the analytical simplified procedures which are developed for the design practice.

On one hand buckling of columns subjected to fires can be the primary cause of failure in framed structures. On the other hand, the structural performance of columns in fire depends on many conditions and can experience different scenarios. Some of these aspects are discussed briefly below with the references to the published research.

Behaviour of steel columns in fire

For steel columns and beam-columns in fires thermal effects can lead to premature buckling which can be local, distortional, flexural or lateral-torsional. The first thermal effect which needs to be considered is the reduction of mechanical properties of steel at elevated temperatures. At high temperatures, especially reaching above 350 C, the structural steel experience substantial degradation of material properties including elastic modulus and yield stress. These phenomenon is well described through usage of reduction coefficients which can be found at.

In case of confined fires, adjacent structural elements having much lower temperatures, can impose both axial and rotational restrains. In such cases the thermal expansion can generate additional loading in axially and rotationally restrained columns. Test results from a compartment fire in the eight-story steel-framed building at Cardington, have shown that the columns, which were heavily fire protected, were subjected to significant induced moments. The prediction of this additional loading is difficult as it depends on temperature distribution in both the column and the restraints (connections).

The effect of imperfections on buckling is magnified in fire conditions especially when a column is subjected to non-uniform temperature distribution caused by a local fire, partial insulation or due to partially damaged fire protection.

Unprotected steel columns have low fire-resistance due to the high thermal conductivity of steel. To protect steel structures against fire, the heat transfer between the structure and surroundings is reduced usually using spray-on fire protection. The behaviour of columns in fires with partially damaged fire protection has been investigated by many researchers mostly analytically and numerically. Much less experimental research is documented on these topic.

Some of the researchers point out that the creep governs the behaviour of steel columns above 400 C under general fire conditions. For some extreme cases, the temperature threshold can be as low as 350 C. For such cases it is suggested to conduct transient analysis in which creep is explicitly considered.

Simplified analytical procedures

The Eurocode 3 part 1-2 provides simple rules for determination of compressive resistance at elevated temperature. These rules are based on the concepts of standard design for members at normal temperature. The same cross-section classification can be applied without considering any change due to increased temperature. For members with cross-section classes 1, 2, and 3 the thermal effects are taken into account through reduction factors encountering the reduction of yield stress and modulus of elasticity at elevated temperature. For compressive members with class 4 cross-sections it may be assumed that its compressive resistance is satisfactory if at time t the steel temperature θa at all cross-sections is not more than 350° C. Compression members with a non-uniform temperature distribution may be treated in the same way as members with a uniform steel temperature θa equal to the maximum steel temperature reached at time considered . Also according to the buckling length lfi of a column can be generally determined in the same way as for normal temperature design with the exception for the braced frames where under some conditions the buckling length may be taken as for a fixed column in an intermediate storey and as for a hinge –fixed column in the top storey.

Some of the researchers point out that the rules given by Eurocode 3 do not sufficiently take into account many important thermal effects and may be inaccurate in many practical situations leading to both too conservative uneconomical and unsafe values.

Using analytical models and based on the eigenvalue analysis for several selected cases Gomes et. al. developed alternative formulas to determine the buckling length at elevated temperatures for braced frames. They also showed that the buckling length of a steel column in a braced frame, indicated by the Eurocode 3 part 1-2 may be unsafe particularly in the case of fire in an intermediate storey.

Based on the results of a series of tests and calculations, Cabrita Neves et. al. proposed a simple method correcting the value of the critical temperature of steel columns free to elongate. The recommended formula takes into account the interaction with the adjacent structure, represented by elastic restraint to the thermal elongation.

Using an extensive set of calibrated finite element models and regression analyses, Wang et. al. developed simple equations for calculating critical temperatures corresponding to the column's buckling and failure. They considered uniformly heated, axially restrained steel columns with geometrical imperfections, subjected to axial compression load eventually combined with bending moments.

A practical design method for calculating the buckling and failure temperatures of restrained steel column under axial load or combined axial load and bending moment is presented in. Based on the results of extensive numerical parametric studies new design equations are adopted for calculation of the buckling temperature of a restrained column including the effect of additional compression force generated due to restraint thermal elongation.

Paper presents research work conducted on bi-axially loaded steel columns under fire conditions. The authors extended Rankine method governing the load-bearing capacity to predict the fire resistance of steel columns subjected to bi-axial loading under standard fire curve. Predictions from the proposed approach were compared with the computational results obtained using finite element program SAFIR.

Zeng et. al. proposed an analytical method to predict the fire resistance of a pinned-pinned steel column, taking into account the complicated creep strain, as well as the degradation of steel mechanical properties. The predictions are verified experimentally and numerically.

Experimental studies

Experimental tests are conducted usually following three scenarios. In the first scenario a specimen is kept under constant mechanical loading while the furnace temperature is increased. The objective of this test is to determine the failure mechanisms and critical temperatures, corresponding to buckling or column's failure. In the second scenario a specimen is firs heated and then loaded. Such tests could be used to find the ultimate mechanical loading for a specific temperature. In the third scenario both mechanical and thermal conditions are time dependent. This case take place for example If the column is axially restrained and additional loading is generated due to thermal elongation.

Tan et. al. conducted a research program on an experimental investigation to determine the failure time of unprotected steel columns subjected to various axial restraint ratios. The test results showed that axial restraints, as well as initial imperfections, significantly reduce the failure times of axially-loaded steel columns. By contrast, bearing friction substantially retards column failure times.

An experimental study on axially loaded steel columns with partial loss of fire protection was performed by Wang and Li. Furnace tests were carried out under the ISO834 standard temperature variation for two steel columns protected with 20mmthickness of fire protection and with the damaged length equal to 7% or 14% of the total length. The experimental results are compared with calculations obtained using an analytical continuum model and finite element analysis.

Three companion papers present experimental tests and numerical parametric study on the restrained steel columns in fire. The first paper reports the results of two fire tests on steel columns axially and rotationally restrained by a connected beam. The columns are loaded with constant axial external load and by additional increasing and decreasing axial force generated in the restraining beam.

The extensive experimental programme for parametric investigation on the performance of rotationally restrained steel columns in fire is presented in papers and. As a part of steel frames, half scale steel columns were tested in fire under different values of axial and rotational restraints. Ali et. al represented also a method of estimating the effective length of fixed end (partial fixity) columns tested under fire.

The paper describes fire tests performed to investigate the mechanics and capacity of steel beam-columns subjected to non uniform heating with temperatures varying through the cross-section. Partially insulated wide-flanged specimens, loaded axially were tested vertically in a furnace following a realistic three-sided heating scenario adequate to a column on the perimeter of a building frame.

A series of fire-resistant steel columns were experimentally tested at specified temperature and under increasing loading reaching ultimate states. The effects of width–thickness ratios, slenderness ratios and residual stress on the performance of fire-resistant steel H-columns were examined. An analytical model and design guidelines were proposed for fire-resistant steel H-columns under elevated temperature.

Wang and Davies tested non-sway loaded steel columns, exposed to fire and rotationally restrained by two loaded steel beams. The mechanical loading was kept unchanged throughout the fire test in order to simulate a column with free thermal expansion. The objectives of these tests were to evaluate the effect on the failure temperatures of bending moments generated in the restrained columns.

Numerical analyses

A review of recently published numerical studies on the behavior of steel columns in fire shows some clear tendencies. In most of the work, commercial nonlinear FE programs are implemented, such as: ABAQUS, ANSYS, LS-DYNA. The most commonly applied is a geometrical and material non-linear finite element program SAFIR, developed in Liege especially for the analysis of structures submitted to fires. Less frequently self-developed FE programs such as FEMFAN2D or FINEFIRE are used. Beam element models dominate, and most of the considerations are confined to 2D subsystems. Numerous simplifications applied in the models are justified by the required limitation of the computational time and recourses. The numerical models are used as a tool for extensive parametric study, for verification of analytical models, as an addendum of experiments, and just for illustration of experiments.

Depending on the simulated test scenario, three types of analysis can be considered: structural, thermal or coupled structural-thermal. Structural stress analysis should be able to take into account strains due to elastic and plastic deformation and due to thermal elongation if coupled structural-thermal analysis is performed. Creep strains can usually be captured using transient analysis. Incremental, transient structural analysis should be based on explicit or implicit methods for time integration. Application of explicit methods in coupled structural-thermal fire analysis can be performed through controlling the time step, in order to produce quasi-static responses.

Coupling thermal and structural calculations in one numerical analysis is rare for structural fire engineering investigations. Usually thermal conditions are defined through constant or time dependent prescribed temperatures applied to selected nodes.

Huang et. al. presented a numerical study conducted on thermally restrained steel columns subjected to predominantly axial loads. The investigated parameters included the column slenderness ratio, axial restraint ratio, rotational restraint ratio, and axial load utilisation factor. Extensive investigation was conducted to study the creep effect on the development of stress and strain, internal forces and critical temperature of a column.

A numerical study of the behaviour of steel I-beams subjected to fire and a combination of axial force and bending moments is presented in. Program SAFIR was used to determine the resistance of a beam-column at elevated temperatures. The numerical results have been compared with those obtained with the Eurocode 3, part 1–2 (1995) and the new version of the same Eurocode (2002).

Computer simulations of 10 fire tests on restrained steel beam-column assemblies using five different types of joints are presented in a paper which depicts development and validation of detailed finite element model built of three-dimensional solid elements and dedicated for ABAQUS/Standard solver. The FE models are dedicated for numerical parametric studies on steel framed structures in fire.

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LARGE SCALE FIRE TESTS

Many aspects of behaviour occur due to the interaction between structural members in a structure exposed to fire and cannot be predicted or observed from isolated tests. Standard tests cannot predict global or local failure mechanisms that are a function of deformations and stresses caused by restraint to thermal expansion provided by the unheated portion of the building. Similarly standard tests cannot demonstrate alternative load paths mobilised through a redistribution of forces from heated to unheated parts of the structure. The large scale tests are performed on the real building or on the large parts of the structure. The fire load is often created by wooden cribs 50 × 50 mm of length 1 m from softwood or by gas burners. The variable mechanical load during the fire experiment is mostly simulated by bags filled by sand. Over the years many isolated member tests have been carried out. However, investigations involving the well documented full-scale tests under natural fire, which is summarised below, are limited.

Sprinklers and unprotected steel test

Sprinklers and unprotected steel test was examined by a series of four fire tests was carried out to obtain data for the second risk assessment. The tests were to study matters such as the probable nature of the fire, the performance of the existing sprinkler system, the behaviour of the unprotected composite slab and castellated beams subjected to real fires, and the probable generation of smoke and toxic products. This simulated a typical storey height 12 m x 12 m corner bay of the building. The test building was furnished to resemble an office environment with a small, 4 m x 4 m, office constructed adjacent to the perimeter of the building. This office was enclosed by plasterboard, windows, a door, and the facade of the test building. Imposed loading was applied by water tanks.

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Office compartment demonstration test

Office compartment demonstration test was constructed to simulate a section of a proposed steel-framed multi-storey building in Collins Street, Melbourne. The purpose of the test was to record temperature data in fire resulting from combustion of furniture in a typical office compartment. The compartment was 8.4 m x 3.6 m and filled with typical office furniture, which gave a fire load between 44 and 49 kg/m2.

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Open car parks test

Between 1998 and 2001, as part of an ECSC funded project, fire tests were performed on an open car park with a composite steel and concrete structure. A single storey composite steel-framed open car park was constructed specifically for full scale fire tests. The floor of the car park occupied an area of 32 × 16 m^2, which is equivalent to a 48 space car park and the storey height was 3 m. The structure was composed of: unprotected steel edge columns HEA180, central columns HEB200, composite beams: unprotected steel beams IPE 550, IPE 400 and IPE 500, connected to the composite slab, composite slab with a total thickness of 120 mm.

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Cardington laboratory

The Cardington Laboratory was a unique worldwide facility for the advancement of the understanding of whole-building performance. Most aspects of a building's lifecycle, from fabrication to fire resistance and explosions through to demolition, can be investigated on real buildings. This facility was located at Cardington, Bedfordshire, UK and consists of a former airship hangar 48 m x 65 m x 250 m.

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Cardington steel framed building

The steel test structure was built in 1993. It is a steel framed construction using concrete slabs supported by a steel decking in composite action with the steel beams. It has eight storeys (33 m) and is five bays (5 x 9 m = 45 m) by three bays (6 + 9 + 6 = 21 m) in plan. The structure was built as non-sway with a central lift shaft and two end staircases providing the necessary resistance to lateral wind loads. The main steel frame was designed for gravity loads and the connections, which consist of flexible end plates for beam-column connections and fin plates for beam-beam connections were designed to transmit vertical shear loads. The building simulates a real commercial office in the Bedford area and all the elements were verified according to British Standards and checked for compliance with the provisions of the Eurocodes. Seven large-scale fire tests at various positions within the experimental building were conducted; see Tab. 1. The main aim of the compartment fire tests was to assess the behaviour of structural elements with real restraint under a natural fire. The principal parameters of these tests are summarized in Tab. 2.

No.	Test	Fire compartment		Load	
		Size, m x m	Area, m^2	Fire	Mechanical
1	Restained beam	8 x 3	24	Gas	30%
2	Restrained frame	21 x 2,5	53	Gas	30%
3	Corner compartment	10 x 7	70	45 kg/m^2	30%
4	Corner compartment	9x 6	54	45 kg/m^2	30%
5	Large compartment	21 x 18	342	40 kg/m^2	30%
6	Office demonstrational	18 x 9	136	46 kg/m^2	30%
7	Internal compartment	11 x 7	77	40 kg/m^2	56%

Table 1: Fire tests on steel structure in Cardington laboratory

No.	Org.	Level	Time to max. temp.	Reached temperature °C		Measured deformations	
				Gas	Steel	Maximal	Residual
1	BS	7	170	913	875	232	113
2	BS	4	125	820	800	445	265
3	BS	2	75	1020	950	325	425
4	BRE+SCI	3	114	1000	903	269	160
5	BRE	3	70	-	691	557	481
6	BS	2	40	1150	1060	610	-
7	CTU	4	55	1108	1088	> 1000	925

BRE – Building Research Establishment; BS- British Steel (now Tata); BRE+SCI with Steel Construction Institute; CTU – collaborative research proposed by Czech Technical University in Prague.

Table 2: Summary of results from fire tests on steel structure in Cardington laboratory

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Cardington concrete framed building

The seven storey concrete framed structure in Cardington laboratory was designed on plane 30 x 22,5 m with height 25,2 m. The building represents a commercial office in the Bedford area. The fire experiment was focused to slim framed structures loaded by well defined mechanical load. The slab was mechanically loaded by 3.25 kN/m2 using sandbags. The timber cribs create a fire load 40 kg/m2, e.g. 720 MJ/m2.

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Cardington timber framed building

The fire tests on timber framed building were conducted under the project Timber Frame 2000. The structure was designed as light skeleton for the multi-storey residential buildings according to Platform frame system. Except of the large scale fire tests, which allowed the precision of the standard for fire resistance of timber structures EN 1995-1-2, there was an integrity test of building exposed to impact and explosion and smaller fire tests. At each floor were designed four apartments, the timber stairs and the lift well. The external load bearing walls were created by cladding of two pasteboards of thickness 12.5 mm and a OSB plate 9 mm. The internal frame with columns 38/89 mm in distance 600 mm were designed from timber of class C16. The space between the columns was filled by thermal insulation. In distance 60 mm in front of external walls was built a brick wall. The internal load bearing walls were designed a similar way as the external ones. The cladding of internal wall created one pasteboard 12.5 mm only. Floor beams 38/225 mm each 600 mm were designed of timber class C16.

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Steel frame connections temperatures and forces

Unprotected steel floor 3.80 × 5.95 m fire test was carried out on a three-storey administrative building which was attached to a single-storey framed building of the Ammoniac Separator II in the Mittal Steel Plant in Ostrava, Czech Republic in 2003. The fire compartment was 3,80 × 5,95 m with a height of 2,78 m and was built on the second floor. The mechanical load was applied on the third floor. The total load, including self weight of the structure, was 5,7 kN/m2. Wooden cribs were used as the fire load, which created the fire load density of 1039 MJ/m2. Two fire tests were carried out on the building. The first, a localised fire test, was performed on 15 June 2006, and was set up to measure the temperature of the steel column and beams close to the centre of the fire. The second was a compartment test and was performed on 16 June 2006, and was designed to obtain the gas temperature in the fire compartment, the temperatures of the beams.

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Composite floor 12 x 18 m to collapse

The main objective of the fire test in Mokrsko were the temperatures of partially encased header plate connections, behaviour of castellated composite beams with the sinusoid openings Angelina, and beams with corrugated web of thickness 2.5 mm. The experimental structure represents one floor of the administrative building of size 12 x 18 m, with the high 4 m. The fire load was created by unwrought wooden cribs 35.5 kg/m2 of timber and it simulated the fire load 620 MJ/m2. The applied load by plastic bags filled by road-metal represents the characteristic value of the variable action at elevated temperature 3.0 kN/m2 and the characteristic value of flooring and partitions 1.0 kN/m2. The predicted resistance of the slab 60 min was reached in 62 min.

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Composite unprotected floor 8.735 x 6.6 m

Composite unprotected floor 8.735 x 6.6 m was tested under the FRACOF project the composite steel and concrete floor composed of four secondary beams, two primary beams, four short columns and a 155 mm thick floor slab. The test was evaluated to the application of the catenary action and simple design procedure in European design.

References:

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Composite unprotected floor 6.6 x 8.4 m

In the scope of COSSFIRE project specific composite floor 6.6 x 8.4 m was fire tested. For this floor, the cross sections of steel beams and steel columns were IPE270 and HEB200 of steel grade S235.The design of floor system was undertaken in accordance with the requirements of EN1994-1-1 for room temperature design of composite structures with a permanent load of 1.25 kN/m² in addition to self weight of the structure and a live load of 5.0 kN/m². The fire test was conducted with a load of 3.93 kN/m² which corresponds approximately to 100% of various permanent actions and 50% of live actions according to Eurocode load combination in fire situation for office buildings.

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Composite floor with cellular beams 15 x 9 m

Composite floor with cellular beams 15 x 9 m was tested acting in membrane action with large deflections. The slab was made of 51 mm deep profile of the Kingspan Multideck 50 type with a concrete cover of 69 mm on the profile, which makes a total depth of 120 mm. A steel mesh of 10 mm with a spacing of 200 mm in each direction made of S500 steel was used as reinforcement. It was located at a vertical distance of 40 mm above the steel sheets. The slab was fixed on all steel beams by means of steel studs on the upper flanges for full connexion. All connections from secondary beams to main beams and from beams to columns arc simple connections. Horizontal bracing was provided in 4 positions leaving the slab completely free of external horizontal restraint. The natural tire was created by a wood crib fire load of 700 MJ/m2 and the 9 x 15 m 110m survived the fire that peaked at 1000°C and lasted for 90 min.

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STEEL BEAM-COLUMN UNDER THERMAL GRADIENT

Beam-column is a term which is used to describe a structural member which is simultaneously subjected to an axial compressive force and a bending moment. This type of element is commonly met in steel frame buildings. A beam in such buildings tries to expand due to thermal loading that is induced to it, but the restraints prevent this expansion and as a result, a compressive force develops on the member, in addition to the bending moment in place due to the gravity load. Similarly, a possible expansion of a beam can cause additional moments to the column of the structure, apart from the axial force already imposed to it. Contemporary provisions of the Eurocodes assume a uniformly distributed temperature over the steel members for the estimation of their capacity. Such a hypothesis, for the members that are located on the borders of the fire room, may lead to disproportional results in relation to the true situation.

Combined axial-bending capacity of steel double-T cross-sections subjected to non-uniform temperature distribution

Eurocode produces higher values for the modulus of elasticity for the elastic region than the Ramberg-Osgood equation. This fact changes as the cross-section enters the plastic region where the R-O modulus of elasticity shows a more prominent hardening, a fact that makes the R-O seem more optimistic, especially, when the temperatures are not the highest that may develop during a fire. Using the EC relationship for the estimation of the axial load-bending moment capacity, it was found that the capacity envelope that EC 3 (Part 1.1 – cl.(6.36)) proposes may be conservative or non-conservative in relation to the real situation. Thermal gradient alters the capacity of the crosssection. The normalization of N-M values was made for the (constant) mean value of the temperature field. EC envelopes illustrate the capacities of the beam-column elements, assuming uniformly distributed temperatures. On the one hand, in the region where the accumulation of the points falls outside the safety envelopes, EC appears conservative, whilst in the opposite situation, the EC approach appears to be optimistic. Therefore, as the slope of the thermal gradient increases, so does the discrepancy between the EC capacity envelopes and the true ones.

As a conclusion, it can be said that:

- the region of safe operation of the cross section presents under that presence of thermal gradient shows a differentiation in shape that is not accounted for by the present regulatory framework;
- extensive parametric research is needed in order to obtain N-M interaction safety regions for the commonly used structural steel cross sections;
- the absence of a distinct hardening form of the stress-strain curve at elevated temperatures requires, to the authors opinion, a reconsideration of the concept of allowable stress so as to obtain the same safety margin with the low temperatures range.

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Determination of the K1 increasing factors of the stress-strain relationship for steel double-T cross sections subjected to non-uniform temperature distribution

EC3 proposes reduction factors Kθ for the determination of the stress-strain relationship of steel at elevated constant temperatures . These factors give the effective yield strength, the proportional limit and the slope of linear elastic range according to the imposed temperature. In case of non-uniform temperature distribution, the use of the stress-strain relationship with the Kθ factors derived from the maximum temperature seems to be conservative, whereas with those derived from the average temperature seems to be optimistic. Assuming the Kθ factor of the maximum temperature on the cross-section and dividing it by a new K1 factor will increase the capacity of the steel member and be more realistically. The aim is to determine the increasing K1y factor of the effective yield strength and the increasing K1E factor of the slope of the elastic range for various types of steel double-T cross sections. To conclude; a) Extensive parametric research is needed in order to obtain the K1 safety regions for the commonly used structural steel cross sections; b) The use of the K1y factor of the effective yield strength can increase the capacity of the steel double-T cross sections at least 15% for $\Delta\theta > 100\ ^{o}C$; c) The present regulatory framework proposes the K1y factor = 0,7 for unprotected beams exposed on three sides, which seems to be very optimistic; d) The use of the K1E factor can increase the slope of the elastic range of the steel double-T cross sections at least 10% for $\Delta\theta > 100\ ^{o}C$.

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A SCIENTIFIC APPROACH TO BEHAVIOUR OF INTUMESCENT PAINTS

Intumescent paints or coatings are one of the products usually used in passive fire protection for structural uses; there are a lot of paint manufacters in the market working with different kind of paints or coatings for specific applications on steel, concrete, aluminium, wood or other structural materials. In the case of steel structures the main advantage relies on the capability to protect the steel from the high temperatures in a fire scenario without breaking the aesthetics of the steel and without increasing the self weigh of the frame.

The basic principle of the intumescent paint is that it reacts and it swells when the fire heats it, producing a layer of insulating material that can be between 50 or 100 times bigger than the initial dry thickness. This allows the steel remain at secure temperatures and avoid the collapse in fire scenario during some time. Typical values for fire ISO834 resistance are R15 to R60.

To evaluate the contribution to the fire resistance of structural members by intumescent paints, several tests are made with different specimens in official fire laboratories, in order to analyze the thermal and thermo-mechanic behaviour of the steel and the intumescent paints. From the test results, semi-empirical mathematics models are used to reproduce the same insulation that the intumescent paint produces, this allows relating the variables like time, temperature, section factor of the profile and the initial thick of paint, enabling to deliver technical characteristics of the product.

The procedure to make this fire test and the mathematic treatments done later is regulated in Europe for Euro norms as the ENV 13381-4 [1] [11] or its more up to date version and more specific for intumescent paints, the EN 13381-8 [2]. These standards define how the fire test must be performed, how the loss of the insulation effectiveness must be taken into account due to the stickability (ability of the intumescent layer to remain coherent and in position along the defined range of deformations), and furthermore several mathematical models are proposed by regression to assess the performance of the intumescent coating to calculate the necessary thickness to be applied in the structures [4] [5] [6] [7] [8] [9] [10].

Nowadays, the official fire laboratories that certify and accredit the paint from different manufactures, are using one of the methods defined in the standard ENV 13381-4 [1] or prEN 13381-8 [2] named "Numerical Regression Analysis". This method is very effective on reproducing the results from test specimens without the need to know about the thermal properties of the coating, and leaves on easy way to calculate the necessary thickness for a required fire resistance, but presents several inconveniences that make intumescent paints expensive:

Normally the numerical regression analysis is done taking 500°C as a maximum temperature for steel. This means that we are introducing too much paint in frames not very strongly loaded where the aspect ratio can be low.

Numerical regressions done for higher temperatures don't give accurate results for temperatures ranges below the maximum temperature considered.

Usually the official European fire laboratories don't want to deliver several linear regressions for different maximum temperatures from the same test. To do this, they want repeat the test and this is more expensive for the manufactures.

The numerical regression method only allows calculating the necessary thickness in cases where the fire curve considered is the normalized ISO 834 (the same one used in test).

In the standards there are other alternative methods that take less to obtain effective thermal properties of the paints from the dates of the test specimens. This makes possible to reproduce, in a more transparent way and for all range of temperatures from 350°C to 750°C, the heating up of the profiles. One of these scientific methods is presented in the standard prEN 13381-8 [2] as “Differential Equation Analysis” (or Variable λp Approach).

This method uses the known differential equation for simple calculations models defined in the standard EN 1993-1-2 [3] to evaluate the temperature progress for internal steelwork insulated by fire protection material, and it uses the effective thermal conductivity (□p) as major parameter that includes the most of thermo-mechanical effects during the process of intumescence.

Although this method requires a bit more accurate tests in fire laboratories, it has the big advantage of making possible to calculate the necessary thickness of paint for all ranges of temperatures of steel. Furthermore, this method gives to engineers the thermal property (□p) that reproduces the temperature progress of the steel cross-sections by analytical approach in EN 1993-1-2 [3] or by finite elements analysis (FEA) in a profile with complex geometry.

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FIRE BEHAVIOUR OF BOLTED CONNECTIONS

The conventional approach of fire safety engineering uses prescriptive regulations to calculate fire resistance of single members according to ISO-fire curve. At present this approach is changing into a more performance based calculation. It becomes usual to calculate temperatures by realistic fire scenarios based on fire loads and ventilation conditions. Consequently it is necessary to calculate the structural behaviour on realistic scenarios as well. This must also take into account the interaction between members inside the structure instead of excluding one member and testing it in a controlled environment in a laboratory. When calculating a structure of more than one member, it is obvious to consider the connection behaviour.

It becomes important to gather more information about connection behaviour in fire situations. For this reason different research projects have been carried out in the recent years in Germany, which are fully or partially investigating connections in steel and composite constructions in fire. In the following, parts of different research projects are described, which are aimed at the connection behaviour.

Behaviour of high strength bolts in fire

While material behaviour of structural members like beams and columns is well known even for high temperatures, there is still a lack of knowledge in high strength bolt materials. Especially the fire behaviour of high strength bolts can be worse than behaviour of normal strength bolts or steel members because of the strengthening process. For this reason it is necessary to develop methods to simulate the behaviour of high strength bolts in fire conditions.

An actual research programme deals with the fire behaviour of grade 10.9 bolts, which are the most common high strength bolts in Germany. Test series at different temperatures have been arranged for real bolts and test specimen consisting of bolt material. The load direction is varied to cover tensional and shear failure of the bolts. In addition the failure of bolts after cooling is tested to predict their behaviour after a fire.

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Behaviour of slim-floor-beams in fire

Slim floor beams consist of different shaped cross sections, which are fully or partially integrated into a concrete slab. This kind of beam provides a longer fire resistance time compared to bare steel beams. This is because high temperatures in fire situation are kept away from the steel parts by the surrounding concrete for a certain period of time. In many cases it is possible to leave the fire exposed steel parts of the slim floor beams unprotected, if only a short fire resistance time (e.g. 30 min) is needed.

To increase the fire resistance time of different slim floor beams, a research project has been conducted recently. Aim was to increase the fire resistance by activating reserves of the static system instead of protecting the fire exposed steel parts. This was done by calculating the moment capacity of internal column connections, which are calculated as pinned at the ultimate limit state calculation. For the reason of the partial concrete encasement of the connections, their temperatures and hence their static behaviour had to be calculated using finite element simulation. It was found that even the very small moment capacity of the tested internal connections can significantly increase the fire resistance time.

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No references at the moment; will be added

Fire behaviour of connections consisting of high strength bolts

The fire behaviour of connections in steel and composite structures depends on the bolt behaviour but also on many further parts of which the connection consists. For example the thickness of a fin plate or the flange of a connected column can have large influence on the moment-rotation-relationship. At ambient temperatures it is possible to use the component method to predict the connection behaviour. In case of fire, there is no validated method at the moment. For this reason it is necessary to use finite element modelling to investigate the connections more in detail.

An actual research project aims at the development of validated finite element models for two different types of connections containing high strength (10.9) bolts. The models will be validated by two large scale tests at internal beam to column connections. Using the validated numerical models, parametric studies will be conducted to predict the effects of different modifications to the connection geometry.

References:

No references at the moment; will be added

Fire performance of external semi rigid composite joints

In a recently finished research project, the fire behaviour of unbraced frames has been investigated. The main aim was to design composite frames that do not need to be braced by walls or another kind of wind bracings.

One main task was the calculation of the behaviour of the external joints between the columns and the beam. To investigate the fire performance four fire tests were carried out. In addition a three dimensional numerical model was established with the finite element code Abaqus to study local phenomena. The data from the fire tests were used to validate the model. Using the validated model, the investigated parameter set was extended. After finishing the calculations, recommendations for the design of the developed joints have been worked out.

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PREDICTION OF TEMPERATURES IN STEEL CONNECTIONS

Structural fire design is mostly based on single member tests. Due to the nature of these tests, the behaviour of the connections is neglected suggesting that they do not play a critical role in fire. In support of this theory, connections generally have a lower temperature than the surrounding structure during fires and are usually protected. This assumption of cooler connections is valid but this does not justify ignoring them in fire design. During both heating and cooling, connections will be subject to conditions, for example large moments and shear forces, which they will not typically have been designed for. The response of connections to these conditions is complex and is largely based on the material strength degradation and the interactions between the various components of the connection. To evaluate the material strength degradation over time and to predict how the behaviour of connections affects global performance in fire, temperature profiles must initially be established [1]. With the aim to quantify the temperatures within a joint, some studies with various temperature distributions have been done in several joints typologies [2].

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Methods for predicting connection temperatures

The Eurocode 3 suggests connection temperatures can be calculated as percentages of the mid-span beam flange temperature. However, results show this method to be unreliable and should therefore be used with caution.

The lumped capacitance method, based on the heated surface area of the connection and its volume –the local massivity value (A/V), showed good correlation with average connection temperatures. More work should be done to look at predicting temperatures of individual connection elements and to define what volume of the connection beams and columns should be included in calculations. The 3D finite element model, using the commercial software package Abaqus, showed good correlation with experimental results. This method uses heat transfer theory to predict connection temperatures over time and can be recommended if a detailed temperature profile is needed for mechanical analysis. A detailed yet simple method for predicting connection temperatures is still unavailable, and more work is required in this field.

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Temperatures of header plate connections during fire test on steel framed building at Mittal Steel Ostrava

To study the global structural and thermal behaviour of buildings in fire, a research project was conducted including a fullscale test on a three storey steel frame building at Mittal Steel Ostrava before demolition. The main goal of the experiment was to verify the method for predicting joint temperatures and to improve it for the cooling phase. Comparisons are made between the test results and the temperatures predicted by the structural Eurocodes.

Calculating the temperature of the beam-to-column/beam-to-beam connection from the measured gas temperature in the fire compartment based on the mass of the connection parts is overconservative/ conservative during the heating phase. A calculation based on the bottom flange temperature of the supported beam is less conservative/may be improved by using a factor of 1.0 instead of 0.88.

The sensitivity of the resistance of the bolts to the in predicted temperature was shown for different temperature predictions, and compared to the measured values. The next generation of analytical and numerical models for connection temperatures may lead to more economical design of connections exposed to elevated temperature and improved predictions during the cooling phase of the fire.

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Temperatures of connections partially encased in the concrete slab during the Mokrsko fire test

The Mokrsko fire test focused on the overall behaviour of the structure, which cannot be observed on the separate elements, and also on the temperature of connections with improved fire resistance. Measured values from the test show the differences between the behaviour of the element and the behaviour of the structure exposed to high temperatures during a fire.

The SAFIR program was selected to predict the temperatures in the connection, which was partially encased in the concrete slab. The fire was modelled using the Ozone 2.2 program. The results of the numerical simulations compared well with the measured temperature values in the connections. The maximum temperature of the lower bolt in the beam-to-column/beam-to-beam connection reached 56 %/46 % of the temperature in the lower flange in the beam midspan, and the upper encased bolt reached 17 %/22 % of the midspan maximum in the flange.

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Temperatures in unprotected joints between steel beams and CFT columns

The study presents experimental, numerical and analytical results of temperatures in different components of unprotected joints between steel beams and concrete-filled tubular columns in fire. The joint types include fin plate, endplate, reverse channel and T-stub. The results of the experiments indicate that the different components that are in the same region of a joint may be considered to have the same temperature. Steel to CFT column joint may be divided into two regions and an appropriate section factor may be calculated for each region to be used in lumped mass temperature calculation equation from EN 1993-1-2 for unprotected steelwork. Therefore, the main objective of this study is to derive suitable expressions to calculate the section factors for the different components of the joints tested in this study.

The experimental results have also been used to assess the simple temperature calculation method in Annex D of EN 1993-1-2, which relates the joint temperatures to the temperature of the connected beam. It has been found that this method generates grossly inaccurate results.

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NONLINEAR FINITE ELEMENT ANALYSIS OF RC STRUCTURES SUBJECTED TO FIRE

To define the fire resistance of structures as assemblies of structural elements, experimental investigations of models are almost impossible. The time dimension of spreading of the temperature field is practically impossible to be simulated on a model of small proportions. Hence, model investigations can hardly be accepted due to the high cost. For the last twenty years, particular importance has therefore been given to analytical definition of the problem.

The computer program FIRE have been developed as analytical tool to study the fire response of reinforced concrete frame structures. Histories of: displacements, internal forces and moments, stresses and strains in concrete and steel reinforcement, as well as current states of concrete (cracking and crashing) and steel reinforcement (yielding) are calculated subject to temperature field development in the thermal time history of the structure. Since a physical testing program for investigating the response of a large variety of structural elements under differing restraint, loading, and fire conditions is impractical and expensive, analytical studies supported by the results of physical experiments could efficiently provide the data needed to resolve questions related to the design of structures for fire safety. Parametric studies, helping to identify important design considerations, could be easily achieved throughout implementation of this program. The time response capability of FIRE can also be used to assess potential modes of failure more realistically and to define the residual capacity of structure after attack of fire.

The columns as structural elements have an important role in preventing loss of global stability of structures under fire. If these elements do not suffer failure, damages shall be of a local character, which shall enable evacuation and efficient extinguishing of the fire. For that reason the influence of different parameters as: element geometry; concrete cover thickness; type of aggregate; compression strength of concrete; steel ratio and intensity of the axial force and bending moment were analyzed and important conclusions for the fire resistance of centrically and eccentrically loaded RC columns exposed to fire from all sides, or incorporated in a wall for separating the fire compartment, were made. The results were presented by curves which enable determination of the fire resistance of these columns without use of numeric procedure. Four RC beams, exposed to different fire models were analyzed, and the predicted results were compared with those experimentally achieved by other researchers. As a next step the axial restrain effect on fire resistance of RC beams was analyzed.

Three-bay, two-storey reinforced concrete frame was analyzed too. For a given specific loading and element geometry and different fire scenarios, the fire resistance was defined.

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Residual concrete strength after fire action

Temperature over 400oC causes reduction of the compressive strength and other mechanical properties of concrete and this process is irreversible (the strength of concrete does not recover in the cooling phase). The mechanical properties of hot welded steel (reinforcing bars) decrease as well, but in the cooling phase they increase again. According to these statements and for realization of the repair projects of the fired RC structures, experimental and numerical determination of the residual concrete strength was done. Numerically achieved results with program FIRE correspond well with experimental results obtained by laboratory testing of specimens taken from the fired elements.

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Fire after earthquake

Calculating structural response to fire after earthquake is a few step process: modeling the structure including nonlinear analysis options; choice for earthquake analysis scenario; seismic nonlinear analysis: pushover or dynamic time history; fire hazards analysis to identify all possible fire scenarios; thermal analysis to calculate temperature history in each member; structural analysis to determine forces, stresses and deformations to estimate whether local or global collapse would occur during any of the fire hazard scenarios.

Using program FIRE, a two storey three bay RC frame was monotonically loaded with triangular distribution of storey horizontal forces (pushover from right to left) and then unloaded. After unloading the corresponding residual plastic displacement was defined. After unloading the structure was exposed to two different fire scenarios (in the first and the second story left bay) and the fire resistance of the frame was obtained.

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GLOBAL MODELLING OF THE BEHAVIOUR OF FRAMED BUILDINGS IN FIRE

Vulcan software

Experience increasingly shows that the interactions between components of large continuous framed buildings in fire are so complex that simplified analysis considering isolated elements is inadequate for reliable performance-based fire resistance design. On the other hand the use of general-purpose finite element software can lead to a very lengthy stage of model creation and development. The University of Sheffield has undergone a long-term process of development of the non-linear global modelling software ***Vulcan***, with the objective of allowing researchers and designers to create and analyse thermo-structural models of buildings or three-dimensional subframes in different fire scenarios. A version of the program which includes a Windows interface has been used extensively in structural fire engineering design, mainly of steel/composite buildings. The software won two of the 2005 national software awards by the British Computer Society. Current development of the program is focused on enabling the analysis to continue up to ultimate collapse, so that the issue of robustness and progressive collapse in fire can be addressed properly.

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Static/Dynamic analysis for structural robustness modelling in fire

The loss of stability of structural elements in a fire can cause dynamic effects, including successive impacts or progressive collapse. Alternatively, unstable behaviour may be capable of regaining stability after either small or large deformations have occurred. A prime objective has been to provide Vulcan with the capability to perform dynamic analysis as well as quasi-static high-deflection, high-temperature modelling. This has already been applied to steel portal frames in fire, for which a UK design process based on rather arbitrary assumptions has been in existence for nearly 30 years; the new procedure has been used to develop a new simplified design approach to calculate final collapse temperatures. The development is intended to follow the structural behaviour from static response through local failure of components, and to model the subsequent dynamic behaviour using an explicit scheme. This kind of model is necessary in order to follow the sequence of behaviour leading to progressive collapse. It is currently being used to study the conditions under which an initial column failure may lead to a cascade of such failures or to re-stabilization. It will later be used to investigate building robustness when connections progressively fracture.

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Modelling localisation of tensile cracking of concrete slabs in fire

All of the software currently used to analyse the behaviour of large-scale floor systems in fire treats concrete as a homogeneous material, and treats cracking when the tensile peak strain is exceeded as being “smeared”, both horizontally and through the layer system used in the slab model. This is practical but fallacious; concrete does not smear cracks in zones of high and largely uni-directional principal tensile strain in lightly reinforced slabs – it relieves the stresses which would be created by forming large localised cracks. High membrane tension above the protected beams, and at the interface between a slab and a core-wall, is caused by the combination of high angles of rotation with restraint to the differential edge movements which would be created in an isolated slab by high deflection in its central zone and low deflection at its protected edges. An advanced prototype XFEM slab element has been developed in which the occurrence and development of localised tensile cracking was modelled directly. This is now being followed-up with an attempt to develop a more generally applicable element to predict accurately the occurrence of this type of compartment integrity failure in global modelling.

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Component-based modelling for connection robustness in fire

The most promising way to enable the interaction of connections with beams, columns and slabs in fire is to use a component-based approach. This is especially important because of the high compressions and tensions, and the associated deformations, which coincide with moment, shear and rotation at different stages of a fire. This was recognised in about 2000, and a series of experimental and analytical projects since that time have been used to characterize components of common bolted connections under conditions of high temperature and high deformation. At present the objective is to create a general-purpose finite element to represent the column-face "connection" zone, later proceeding to the representation of the finite-length parts such as the column and beam-end shear panels which are included in the wider "joint" zone. The principles developed should be applicable to implementation in different software packages, but the element is being developed particularly for Vulcan.

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EXPERIMENTAL STUDIES OF STEEL CONNECTIONS IN FIRE

Since 1993 experimental studies have been conducted on common bolted steel and composite connections in fire. The early studies concerned rotational behaviour at elevated temperatures. More recent work has concerned the robustness of connections, especially their fracture when subjected to combinations of high rotation and high normal forces which usually change their direction as temperatures rise.

Moment-rotation-temperature characteristics of endplate connections

In two successive projects cruciform M-⍰ tests were performed at constant moment and increasing furnace temperature on flush and extended endplate connections, of which the first series were purely steel-to-steel. The later series included composite beams, and particularly connection details taken from the Cardington composite building frame.

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Testing of connections under combined moment, shear and tying forces

A large number of cantilevered connection tests to destruction on connections under inclined forces were performed at temperatures up to 650°C, on four typical steel beam-column connection types. Modelling using Finite Element analysis rationalised the results, which were subsequently used to help with the development of simplified component characteristics, to be used in constructing component-based joint elements for global modelling. The project's photos and test data can be downloaded from the website fire-research.group.shef.ac.uk/downloads.html. In a follow-on project similar tests are being performed on connections to concrete-filled and partially-encased composite columns in fire.

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Robustness in fire of connections to composite columns

The current project COMPFIRE, funded by RFCS, involves collaboration with groups at Coimbra, Luleå, Prague and Manchester, together with Tata Steel. It concerns the behaviour and robustness in fire of practical connections between steel or composite beams and two types of composite column - concrete-filled hollow sections and partially-encased H-sections. Among the institutions involved tests are being carried out at various scales, accompanied by detailed FE modelling, leading to the development of a component-based approach for these connections at elevated temperatures. During the first year of the project the Sheffield group is conducting a total of 20 tests under combined forces, in a setup similar to that used for steel-to-steel connections in the previous project, at both ambient and elevated temperatures. The types particularly addressed are end-plate connections to partially encased H-columns and reverse-channel connections to both square and circular concrete-filled hollow-section columns. These tests are to be used mainly to develop and validate connection component models which will enable connection interaction to be modelled in whole-structure modelling software. The objective is to create a general element to represent the column-face "connection" zone, possibly later proceeding to the representation of the finite-length zones such as the column and beam-end shear panels which are included in the wider "joint" zone. The principles developed should be applicable to implementation in different software packages.

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Test data is available from www.fire-research.group.shef.ac.uk/downloads.html. At present, access to the data sheets is restricted to authorised users, and is password-protected. If you wish to view or download them please contact Ian Burgess, ian.burgess@sheffield.ac.uk.

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THERMAL AND STRUCTURAL BEHAVIOUR OF CONCRETE SLABS AT HIGH TEMPERATURES

A new simplified fire-resistance design method for composite slabs, embodied in a recent design document, is based on a simplified model of the enhancement to yield-line slab capacity which is caused by tensile membrane action at high deflections. In fire such deflections are acceptable provided that no structural collapse or loss of fire compartmentation occurs. The method was investigated with respect to its own formulation, in comparison with numerical modelling, and using a large number of small-scale loaded ambient- and high-temperature tests. At model scale it was possible to perform large numbers of tests, and these were used to test both the simplified method and advanced modelling approaches. In particular, the membrane stresses and cracking mechanisms caused by thermal gradients through the slab thickness, acting alone, were studied. A detailed comparative study was made between the simplified method for tensile membrane action and modelling of a number of composite slabs using Vulcan. This highlighted particularly the structural failure case in which protected edge beams eventually fold, limiting the range within which tensile membrane action acts as the main load-bearing mechanism. A simple additional calculation which covers this structural resistance failure mode has been proposed.

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PERFORMANCE OF CELLULAR COMPOSITE FLOOR BEAMS UNDER FIRE CONDITIONS

Despite the current popularity of long-span composite flooring systems, the current structural fire engineering design codes EC3/4 Part 1.2 and BS5950 Part 8 do not contain rules or guidance on the fire resistance of composite floors employing cellular steel beams. The purpose of this project is to investigate the performance and failure mechanisms of composite cellular floor beams at elevated temperatures, including the influences of both flexure and shear. The research at the University of Sheffield is coordinated with a programme of physical model fire testing at Ulster University, which is providing carefully monitored data. A configurable finite element model has been developed to demonstrate the 3-dimensional behaviour of composite cellular beams, and this has been successfully validated against the tests, ensuring that all types of failure modes are predicted. Some progress has been made in developing a simplified global modelling technique for composite CBs, with the ultimate aim of permitting efficient whole-structure modelling. The project has also developed a design methodology for such members in fire.

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FIRE RESISTANCE OF COMPOSITE PARTIALLY FIRE PROTECTED FLOOR

The design of the floor steel to concrete composite slabs for fire resistance is traditionally based on prescriptive generic ratings that specify the minimum slab thicknesses and the required concrete cover to the reinforcing steel. 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. Park and Gamble and others, describe how significant tensile membrane action in slabs at ambient temperatures can occur if the movement of the edges of slabs is restrained. Both theoretical and experimental research into membrane action of concrete slabs at large displacements has been limited due to the difficulty in identifying any practical application. However, in an accidental design state, such as during a fire, large displacements of the structure are acceptable provided overall structural collapse is prevented. During 1995 and 2003, a total of seven fire tests were conducted on a full-scale, eight storey, steel framed building at Building Research Establishment Laboratory at Cardington. The test results show that the fire performance of steel-concrete composite floor is better than that obtained from traditional design method, and the load capacity of composite floor slab in fire condition is usually higher than the predicted capacity without considering membrane action.

Analytical unrestrained slab panel model

Following full-scale fire tests on a steel-framed building, together with observations from real fires, it has been shown that membrane action, at large displacements, of composite floors comprising steel deck, concrete, and anti-crack mesh, is extremely beneficial to the survival of the building. It was therefore decided to review previous research conducted on unrestrained concrete slabs, under large displacements, at normal temperatures. It was found that the assumptions used to develop previous theoretical predictions for the load-carrying capacity, for a given vertical displacement, are only valid for square slabs and do not conform to test observations for rectangular slabs. A theoretical approach is presented which is valid for both square and rectangular slabs and conforms to the mode of behaviour observed in tests. The design method is shown to give excellent correlation with published test data. A prediction for ultimate collapse of the slab due to fracture of the reinforcement is also presented, which limits the allowable mechanical strain in the reinforcement. Comparison with available test data shows that this prediction is always conservative. The design method has been validated, against the Cardington laboratory fire tests and a number of cold slab tests at large displacements. The method is, however, limited in that it forces the designer to use isotropic reinforcement which is acceptable for square concrete slabs but is uneconomical for rectangular slabs.

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Analytical zone model

An alternative method to calculate the load capacity of simply supported composite floor slabs with considering the membrane action is presented. The slab is divided into five parts at the limit state of load capacity, including a centre-elliptic part and four rigid parts around. The deflection of the slab, the force of rebars in high temperature, and the force distribution between four rigid parts are reasonably assumed. According to force and moment equilibrium requirements on the slab, a series of equations are obtained to calculate the ultimate load capacity of floor slabs in fire condition. The effectiveness of this new method is validated through comparison with results from experiments and different theoretical simulations. The comparis on shows that this new method is more reasonable in predicting the deflection and ultimate load capacity of floor slabs in fire condition than previous methods.

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Advanced modelling of membrane action

Several studies have been published to the advanced modelling of the partially protected floor in Cardington frame as well as other tests. The results show that this type of modelling predicts the deflection behaviour with considerable accuracy, especially considering the uncertainties embodied in representing the biaxial properties of concrete at high temperatures, and using analysis which does not consider the formation of discrete cracks. All the cases modelled follow very much similar deflection patterns; even with boundary assumptions which neglect all edge support provided by the vertical wind-posts are relatively accurate away from the local vicinity of this edge. Accurate thermal modelling of the structure, particularly in this case by obtaining an accurate representation of the temperatures in the over-sprayed 1m zones at the outer ends of the primary beams, has a fault major effect compared with weakening of the slab at the location of the observed longitudinal crack, suggesting that the deflection pattern is more a function of temperature distribution than of structure loading and strength. The comparison between the modelling of basic cases and the test results shows very good correlation, indicating that such modelling is capable of being used to give a realistic picture of the structural behaviour of composite flooring systems in scenario-related performance-based design for the fire limit state. The advanced FE modelling of partially fire uprotected floors gives more freedom and economy in design Compaq to analytical models fixed to particular structural solutions.

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Design tool for membrane action in fire

Under the European RFCS project FRACOF was developed a technical document, design guide and design software based on Bailey’s analytical simple design method. A review of existing relevant fire tests carried out in full scale buildings around the world is described and the corresponding test data are summarized as well. Information is also included on observations of the behaviour of multi storey buildings in accidental fires. The document gives detailed explanation of the new large-scale fire tests of composite floor systems conducted under long duration ISO fire which provides more evidences about the validity of the simple design model. The conservativeness of the simple design model is also clearly illustrated through the comparison with the parametric numerical study conducted with help of advanced calculation models.

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FIRE RESEARCH AT THE LABORATORY OF STRUCTURAL ANALYSIS AND DESIGN, DEPARTMENT OF CIVIL ENGINEERING, UNIVERSITY OF THESSALY

Numerical simulation of the behavior of steel and composite structures under fire conditions after earthquake events

Normally, the design of structures according to the current design codes is performed independently for the seismic and thermal actions. In particular, many theoretical and experimental studies have been published in the last 20 years about the seismic behaviour of structures. The scientific knowledge in this field has been incorporated in the recent seismic regulations in Europe and elsewhere. Moreover, considerable research effort has been devoted during the same period to the study of the behaviour of steel and composite structures at elevated temperatures. Recently, the research interest has been extended beyond the behaviour of materials and structural members at elevated temperatures, to the overall behaviour of real structures. To this end, large-scale experiments have been conducted at European level (e.g. the Cardington full-scale composite building fire tests). These studies have led to the identification of additional mechanisms through which the structures may resist the design loads at elevated temperatures. Much of this research has been consolidated in the latest versions of design rules against fire. The interest of the research team of the University of Thessaly is focused on the following:

Numerical analysis of the behaviour of structural elements at elevated temperatures

Detailed numerical models are developed in order to simulate the behaviour of steel and composite structural components (beams, columns and slabs), which are designed according to the guidelines of Eurocodes, under fire conditions. The sophisticated three-dimensional finite element models are submitted to coupled thermo-mechanical analysis. All the nonlinearities that are present in the physical models (dependence of the thermal and mechanical properties of the material on temperature, nonlinear material behavior, cracking etc) are considered.

The further work is to consolidate the behaviour of the structural members in order to express it through marcroscopicreaction-displacement functions having temperature as a parameter. These functions would be suitable for using them in analysis with frame elements, in order to evaluate the response of real structures. It is expected that these functions will present descending branches due to the reduction of the strength of the materials when the temperature increases.

Definition of the requirements for the combined action of fire after earthquake

Fire after earthquake scenarios are developed which are based to the performance-based design concept. The starting point of the work is the standard matrices of required performance of buildings against earthquake events which consider the structural performance, the non-structural performance and the earthquake intensity. The new parameter that will be introduced here is the required fire resistance. Fire resistance requirements may be different for the various earthquake intensity levels considered. The combination of the above parameters results to 3-dimensional matrices.

Fire design and analysis of model structures for the combined scenarios of fire after earthquake

The proposed “fire after earthquake” scenarios lead to different temperature-time records for the structural and the non-structural members. The main objective is to study model structures for various thermal scenarios considering also the damages in the structural members induced by the seismic events. The “consolidated” results of the coupled thermo-mechanical analysis are profitably used to analyse full-size structures. Since the consequent numerical simulations will are relevant to single structural components or substructures, the detailed output of the detailed nonlinear finite element analysis are transformed into simplified analytical and numerical models useful for the analysis of more complex structural systems. The results of this procedure are the base for the evaluation of the limit resistance of the structures for this combined loading, the maximum fire resistance time and the nature of the failure.

Behaviour of composite slabs in elevated temperatures

The interest of the team of the University of Thessaly is also focused to the thermo-mechanical modelling of composite slabs with thin-walled steel sheeting in elevated temperatures.

The objective is to assess the thermal behavior of composite slabs through both simple and advanced calculation models and compare their results. More specifically, the results of the thermo-mechanical analysis, in terms of fire resistance, are compared with the expected fire resistance that results following the provisions of Eurocode 4, Part 1-2. Despite the significantly simplified procedure proposed by this norm, its application in the case of continuous composite slabs requires the involvement of a nonlinear iterative algorithm. The comparison is performed mainly in order to evaluate the effectiveness of simplified methods that are based on the proposals of Eurocode 4. Moreover the results of the thermal analysis which is conducted according to the principles of the heat transfer theory, applied through the finite element method, are compared with the temperature profiles for composite slabs proposed by Eurocode 4. Another objective is to study the fire performance of the steel-concrete slabs considering two structural systems: a simply supported and a continuous slab. The two systems are designed to have the same load bearing capacity at room temperature. Therefore, the objective is to evaluate the effect of static indeterminacy to the fire resistance of composite slabs.

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FIRE RESEARCH AT THE UNIVERSITY OF COIMBRA

The University of Coimbra, Faculty of Science and Technology (FCTUC) is a research and education organization located in central Portugal which was created in 1290. The Department of Civil Engineering is responsible for undergraduate teaching in Civil and Environmental Engineering and a large spectrum of postgraduate courses. It was established in 1972 and includes a staff of about 80 teaching academics covering structural engineering, hydraulics, geotechnics, construction materials and technology, urban planning, roads and transportation. The research unit ISISE (Institute for Sustainability for Innovation in Structural Engineering) is part of Structural Engineering. ISISE is organised in three research Groups: SMCT (Steel and Mixed Construction Technologies); HMS (Historical and Masonry Structures) and SC (Structural Concrete). Fire research is one of the research clusters of SMCT; the behaviour of steel and composite joints and the behaviour of restrained columns have been the main researches items of this cluster. SMCT comprises more than 50 people, including post-graduate students, plus a shared laboratory and modern equipment for mechanical testing and instrumentation.

Behaviour of beam-to-column steel joints under natural fire

Traditionally, beam-to-column joints are assumed to have sufficient fire resistance due to cooler temperatures and slower rate of heating, caused by the concentration of mass on the joint area. However, observation of real fires shows that on several occasions steel joints fail, particularly from their tensile components (such as bolts or end-plates) because of high strains induced by the distortional deformation of the connected members. This research work dealt with the following subjects: i) the characterisation of the behaviour of beam-to-column joints in fire, and ii) their influence on the overall behaviour of the structure subjected to a natural fire. Special emphasis was directed to the cooling phase, because it induces an unwanted failure mode: brittle failure of the tensile components. The experimental results from a full-scale building fire test and six beam-to-column sub-frames fire tests under a natural fire were studied based on their temperature development, structural deformability and failure modes. The analytical approach of this research involved the proposal and validation of a design methodology for steel joints under fire loading. The model is based on the Eurocode 3 approach and includes the representation of all components to allow the application of any combination of bending moment and axial forces that characterise a fire situation.

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Fire resistance of steel and composite steel-concrete columns in buildings

The purpose of this work was to study steel and composite steel-concrete columns in buildings, under fire situation. The influence of several parameters such as the contact with brick walls, the stiffness of the surrounding structure, the load level, and the slenderness of the columns, were the target of the parametric study carried out in the present research. Five sets of experimental tests, were performed. Results of the experimental tests were compared with numerical studies reproducing the conditions used in the tests, with the purpose of providing valuable data for the development or improvement of analytical designing methods. The main goal was to reproduce as much as possible, in the laboratory, the conditions to which the column is subject in a real building.

An experimental set-up was constructed in the Laboratory of Structures and Testing Materials of the University of Coimbra, to allow fire resistance tests on columns with restraint to thermal elongation. It was composed of a 3D-steel frame, allowing different positions of the columns, to provide different values of stiffness of the surrounding structure. Mechanical loads constant during the tests were applied by a hydraulic jack, controlled by a central unit. Thermal actions were applied by a gas-burned and an electrical furnace. The experimental programme was composed of the following:

- Steel H Columns embedded on walls (14 experimental tests);
- Bare Steel H columns with restrained thermal elongation (14 experimental tests);
- Composite steel-concrete partially encased H columns with restrained thermal elongation (12 experimental tests);
- Bare steel circular hollow section columns (8 experimental tests);
- Concrete filled circular hollow section columns (32 experimental tests).

The numerical modelling of the tests was performed with the finite element computer package ABAQUS. A geometrical and material non-linear analysis with imperfections was performed. A very accurate modelling of the experimental tests was done, with a very good agreement between experimental and numerical results, both in terms of temperatures, forces and deflected shapes of the columns.

For the steel H columns embedded on walls, the main conclusions of this research were that the contact with the wall provides the column a huge thermal gradient within the cross-section. The column under fire situation will behave as a beam-column, failing by bending provoked by thermal bowing, instead of behaving as a column, failing by buckling.

For the bare steel H columns, the main conclusion was that for realistic values of slenderness of the columns in a building, the detrimental effect of the axial restraint is cancelled by the beneficial effect of the rotational restraint. These two restraints seem to cancel each other, and the restraint to thermal elongation is not so important.

For the composite steel-concrete H columns, the major conclusions were the great increase of fire resistance provided by the concrete between flanges, compared with bare steel columns. No local buckling was observed in these columns, and failure by buckling occurred with detachment of the stirrups from the web.

For the concrete filled and bare steel circular hollow section columns, the major conclusions were that the load level, the cross-sectional dimensions, the slenderness ratio and the type of material used to fill the column (i.e. concrete, reinforced concrete or fiber reinforced concrete) has significant influence in the fire resistance.

The major outcomes of this research work were proposals for the assessment of the temperature evolution within the cross-section of unevenly heated steel columns in contact with walls, as well as proposals for the calculation of the critical temperatures and fire resistance of steel bare columns.

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Robustness of open car parks under localised fire

This research work is part of the RFCS European ROBUSTFIRE project. A design philosophy aiming at the economical design of car parks exhibiting a sufficient robustness under localised fire is intended to be developed and practical design guidelines for the application of this design philosophy throughout Europe are expected to be derived. In other to reach this purpose, the work is divided into four main objectives: (i) A review of current practice and state of the art in the design and assessment of open car parks subject to localised fire and a state of the art on the behaviour of beam-to-column joints and steel columns in fire was performed; (ii) The required knowledge on the behavioural response of the individual frame structural elements directly affected by the localised fire and the resultant reduction of carrying capacity of the heated column should be acquired (by experimental tests and numerical simulations); (iii) Detailed numerical models as well as simplified analytical models of the fire response of critical structural components, including columns, connections and composite beams should be developed and validated; Finally (iv) a robustness assessment approach for steel composite car parks under fire, to be event-independent as far as possible should be developed and relevant and practical design guidance should be proposed.

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Composite joints for improved fire robustness

This research work is part of the RFCS European COMPFIRE project. The aim is to investigate and evaluate the behaviour of joints for improved fire robustness, particularly joints between beams and the most common composite columns (concrete-filled hollow sections). These composite columns are often assumed to possess inherently high fire resistance, yet there is very little knowledge on their joint behaviour in fire. The main outcomes of the work will consist in coherent performance-based design to steel and composite structures by focusing on the critical issue of the fire performance and robustness of joints. By developing practical methodologies for evaluating the full 3D behaviour of composite joints over the entire course of fire exposure, including the assessment of ductility limit, innovative fire engineering design solutions can be planned to avoid premature progressive collapse of a structure under fire attack.

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RESEARCH IN THE FIELD OF STRUCTURAL FIRE SAFETY ENGINEERING AT ETH ZURICH

Stability behavior of steel structures in fire

The structural resistance of steel members, in particular columns or beam-columns, under fire conditions is limited by three limit states and their interaction: First, full section yielding at elevated temperature (i.e. yield capacity) considering both axial compression-bending moment interaction and non-uniform temperature distributions (limit state 1); second, local and/or distortional buckling (limit state 2); and third, overall structural stability, especially flexural and lateral-torsional buckling (limit state 3). The reduction of steel strength during heating in fire as well as thermal gradients markedly affect the first limit state [1], while the reduced stiffness and the nonlinear stress-strain relationship of steel at elevated temperatures have a strong influence on the local buckling [2] – strongly affecting the cross-sectional capacity [3] – and overall buckling behaviour [4]. Several studies focusing on the flexural or lateral-torsional buckling resistance under fire conditions (for example [5], [6], [7], [8]) (limit state 3) implicitly consider section yielding (limit state 1). These studies assume that members without overall buckling effects, whose cross sections are classified as 'plastic' (Class 1), 'compact' (Class 2) or 'semi-compact' (Class 3), reach their full plastic or elastic capacity respectively without developing local buckling deflections even under fire conditions. However, elevated temperatures strongly influence the cross-sectional capacity and the local buckling behaviour of steel sections. Even cross-sections suitable for plastic design at ambient temperature may develop local buckling deflections in fire [2, 3], caused by large strains required to reach full section yielding due to the distinctly nonlinear stress-strain relationship of steel at elevated temperatures [9].

A comprehensive numerical parametric study (geometrically and temperature-dependent materially nonlinear analysis of the imperfect structure GTMNIA) using the finite element approach on the cross-sectional capacity of structural steel members in combined axial compression and biaxial bending under fire conditions has been carried out at ETH Zurich [3]. The cross-sectional capacity and local buckling behaviour of steel members in fire is strongly affected by the distinctly nonlinear stress-strain relationship of steel at elevated temperatures. The axial load has a marked effect on the cross-sectional capacity under fire conditions. Temperature-dependent normalized N-M interaction curves have been developed by means of the numerical results. These interaction curves for the cross-sectional capacity consider full section yielding (limit state 1) as well as local instability effects (limit state 2). A comparative study has shown that the simple adoption of the ambient temperature design rules in combination with temperature-dependent reduction factors for the yield strength reached at 2% strain does not lead to consistent results in many cases.

The interaction curves developed from the numerical results constitute an upper limit of the overall structural resistance considering member buckling effects (limit state 3). Comprehensive experimental and numerical studies on the flexural and lateral torsional buckling resistance of steel members as well as the local-global buckling interaction behaviour have been performed at ETH [4], [10], [11]. The experimental program comprised material tests at elevated temperatures as well as both cross-sectional capacity and slender column buckling furnace tests in concentric and eccentric compression at different temperatures and strain rates. The strain rate markedly influenced the stress-strain behaviour and the local and global buckling behaviour. A general analytical model for the slender column resistance has been developed. The model allows considering nonlinear stress-strain relationships, residual stresses, geometric imperfections and thermal creep effects.

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Fire safety of multi-storey timber buildings

In case of fire, combustible building materials like timber burn on their surface, release energy and thus contribute to the fire propagation and the development of smoke. The combustibility of wood is one of the main reasons why most building codes strictly limit the use of timber as a building material, in particular by limiting the number of storeys of timber buildings [12]. In Switzerland for example timber structures were mostly limited to low-rise buildings with 2 or less storeys, until 2005. Fire safety is the main precondition for the use of wood for multi-storey timber buildings and therefore an important criterion for the choice of material for buildings. Since the 90s, many research projects have focused on the fire behaviour of timber structures worldwide [for example 13, 14]. Some projects have been conducted by the Institute of Structural Engineering at ETH Zurich sponsored by the Swiss Agency for the Environment, Forests and Landscape (BAFU) and in collaboration with the Swiss Laboratories for Materials Testing and Research (EMPA) and different industrial partners (see Table 1). The research projects aimed at supplying basic data and information on the safe use of timber, in particular for multi-storey buildings. Further novel fire design concepts and models have been developed based on extensive theoretical studies, element and full scale testing as well as a large statistical data based on fires in buildings.

Research project	Testing type	Duration of fire tests
Fire resistance of timber-concrete composite slabs	Element tests under ISO-fire exposure	60 to 90 minutes
Fire resistance of timber slabs made of hollow core elements	Element tests under ISO-fire exposure	60 to 105 minutes
Fire resistance of light timber frame wall assemblies	Element tests under ISO-fire exposure	60 minutes
Fire resistance of timber block walls	Element tests under ISO-fire exposure	30 to 90 minutes
Fire resistance of multiple shear steel-to-timber connections	Element tests under ISO-fire exposure	30 to 70 minutes
Fire performance of wooden hotel modules	Full scale tests under natural fire conditions	4 minutes to burn-out

Table 1: Overview of some recent research projects on the fire behaviour of timber structures conducted at the Institute of Structural Engineering of ETH Zurich

Design models of timber structures in fire usually take into account the loss in cross-section due to charring of wood and the temperature-dependent reduction of strength and stiffness of the uncharred residual cross-section. Based on extensive experimental analysis novel fire resistance models for load-carrying structures like timber-concrete composites slabs and timber slabs made of hollow core elements were developed [15, 16]. For timber frame wall and floor assemblies with void cavities only a little information is available. In particular no detailed charring model exists for the calculation of the charring depth after the fire exposed claddings have fallen off. As a result of a comprehensive research project on the fire behaviour of timber frame assemblies performed at the ETH Zurich, a charring model for timber frame assemblies with void cavities was developed based on an extensive FE-thermal analysis [17]. The FE-thermal analysis showed that the main physical reasons for the increased charring rate observed after failure of the claddings is that, at that time, the fire temperature is already at a high level while no protective char layer exists to reduce the effect of the temperature (i.e. heat transfer). Thus the more that the protective cladding delays the start of charring, the more the charring rate increases after failure of the protective cladding. The charring model takes into account the influence of high temperature after failure of the fire protective claddings as well as the heat flux superposition on the charring rate of the timber beams exposed to fire on 3 sides. The FE-thermal analysis was verified by fire tests on protected specimens exposed to one-dimensional charring.

The load-carrying capacity of timber structures is often limited by the resistance of the connections. Thus, highly efficient connections as multiple shear steel-to-timber connections with slotted-in steel plates and steel dowels are needed for an efficient design. The load-carrying capacity of multiple shear steel-to-timber dowelled connections with slotted-in steel plates in fire primarily depends on the temperature-dependent reduction of embedment strength of the timber members. In order to accurately predict the fire resistance of the connection, knowledge on the temperature distribution in the cross-section as well as the influence of steel elements (slotted-in steel plates and steel dowels) on the charring of the timber members is essential. Based on an extensive experimental and numerical analysis, a design model for the calculation of the load-carrying capacity in fire of multiple shear steel-to-timber dowelled connections with slotted-in steel plates subjected to tension was developed [18, 19]. The design model is in analogy with the "Reduced Cross-Section Method" according to EN 1995-1-2 commonly used for the fire design of timber members. The proposed design model takes into account different geometries of the connection and the influence of the steel elements on the temperature distribution in the cross-section.

In order to limit fire spread by providing adequate fire compartmentation, elements forming the boundaries of fire compartments are designed and constructed in such a way that they maintain their separating function during the required fire resistance time (insulation and integrity criteria). While fire tests are still widely used for the verification of the separating function of light timber frame assemblies, design models are becoming increasingly common. A comprehensive research project on the separating function of light timber frame wall and floor assemblies with cladding made of gypsum plasterboards and wood-based panels was carried out at ETH Zurich in collaboration with the EMPA. As result of the research project, a design method was developed based on physical submodels for each layer and the interaction between the layers forming the assembly [20]. Thus, the total fire resistance is taken as the sum of the contributions from the different layers (claddings, void or insulated cavities). The design method takes into account the influence of adjacent materials on the fire performance of each layer according to their function (protection and insulation values) and their interaction (position coefficients). The coefficients of the design method (basic protection and insulation values as well as position coefficients) were calculated by extensive finite element thermal simulations based on physical models for the heat transfer through separating multiple layered construction. The coefficients of the design method were then simplified by general equations. The material properties used for the finite element thermal simulations were calibrated and validated by fire tests performed on unloaded specimens at EMPA using ISO fire exposure. The design method was verified with full-scale fire tests, showing that the model is able to predict the fire resistance of timber assembly safely. The developed design method significantly extends the application range of the design method according to EN 1995-1-2 by giving additional data as well as physical models for the basic protection and insulation values as well as the position coefficients and permits the verification of the separating function of a large number of common timber assemblies.

The better knowledge in the area of fire design of timber structures from the research projects, combined with technical measures, especially sprinkler and smoke detection systems, as well as well trained and equipped fire brigade allow the safe use of timber and a wider field of application of timber for buildings. As a result the Swiss fire regulations of 2005 allow the use of timber structures in multi-storey medium-rise residential buildings up to 6 storeys. Many other European countries have also liberalized the use of timber for buildings or introduced fire regulations that permit the use of timber on the basis of performance.Text devoted to second subject prepared in length of about 10 lines.

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STRUCTURAL FIRE ENGINEERING RESEARCH AT THE UNIVERSITY OF MANCHESTER

Main areas of expertise:

- Post-flashover fire dynamics
- Heat transfer analysis
- Thermal and mechanical properties of construction materials at elevated temperatures
- Behaviour of steel, concrete and composite structures in fire
- Tensile membrane action
- Catenary action
- Behaviour of joints in fire
- Concrete filled tubular columns
- Behaviour of thin-walled steel structures
- Dissemination and education

Post-flashover fire dynamics

Work in this area includes assessment of rate of heat release in post-flashover compartment fires, assessment of accuracy of parametric fire curves in Eurocode, CFD simulation of post-flashover compartment fires, development of glass breakage model for compartment fire.

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Heat transfer analysis

The emphasis of research in this area is on development of analytical and design calculation methods to enable temperature distributions to be easily calculated in a number of common situations, including different components of steel beam/column connections with different methods of fire protection, connections to concrete filled tubular columns, concrete filled tubular columns, thin-walled steel structures.

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Thermal and mechanical properties of construction materials at elevated temperatures

Accurate prediction of structural fire resistance critically depends on supply of reliable input data of thermal and mechanical properties of materials, particularly at elevated temperatures. Work in this area include development of experimental, analytical and numerical procedures to quantify thermal conductivity, specific heat, stress-strain relationship of a number of construction materials, including intumescent coating, gypsum, foamed concrete and structural composites.

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Behaviour of steel, concrete and composite structures in fire

The University of Manchester researchers started research on structural behaviour in fire more than 20 years ago. This research covers all major aspects of structural behaviour in fire and ranges from structural members to whole structures. Research methodology includes experiments, numerical simulations, and the development of analytical and design methods. A large number of scientific papers have been published and only a selection is included in the reference.

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Tensile membrane action

Tensile membrane action is now a major load carrying mechanism to enable unprotected steelwork to be used. This mechanism was first researched in the 1960s. However, it was during the Cardington structural fire research programme that the potential of this load carrying mechanism was first identified. The University of Manchester researchers played the most important role in first identifying this load carrying mechanism and subsequently in conducting detailed research and development to enable this load carrying mechanism to be beneficially used by fire engineering practitioners.

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Catenary action

Catenary action describes the load carrying mechanism in a beam whereby the applied load on the beam is resisted by tensile action in the beam acting upon the deflection of the beam. Full development of catenary action has the potential to enable fire protection to be eliminated in steel beams. The Manchester researchers began work in this area some 10 years ago, covering numerical simulation and development of analytical methods. This topic has now emerged as the key in understanding structural robustness in fire. Related research includes joints in fire.

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Behaviour of joints in fire

Joint behaviour is one of the most important current topics of structural fire engineering research. The research goes beyond the traditional approach of quantifying connection moment-rotation-temperature relationships because there is significant presence of axial force in joints in fire. Joint behaviour has critical influence on structural robustness in fire. The Manchester researchers are engaged in research studies to develop methods of calculating temperatures in different joint components, joint component behaviour and effects of joints on structural behaviour. Research methods include fire tests, numerical simulations and development of analytical methods.

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Concrete filled tubular columns

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Behaviour of thin-walled steel structures

Thin-walled structures have much more complicated modes of behaviour than normal steelwork. This is a relatively poorly understood area of structural fire engineering research, perhaps due to the use of thin-walled steel structures as secondary structural members. Work by the University of Manchester researchers includes single compression elements and panel construction.

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Dissemination and education

In addition to conducting extensive research on various topics of structural behaviour in fire, the Manchester researchers are also actively engaged in dissemination and education. A fire engineering undergraduate and postgraduate course has been taught at the University of Manchester since 1998. The one-stop shop www.structuralfiresafety.com represents a major initiative in web based dissemination of information in this area.

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FIRE RESEARCH AND DESIGN AT THE "POLITEHNICA" UNIVERSITY OF TIMISOARA, ROMANIA

The fire research at the Department of Steel Structures and Structural Mechanics of the "Politehnica" University of Timisoara is numerical and design oriented. The team is the drafter of the actual Romanian Regulation for Fire Design of Steel Structures (aligned to ENV 1993-1.2), was involved in the translation of the corresponding fire parts of EN1993-1- 2 and EN1994-1-2 and in the elaboration of the corresponding National Annexes, and also applied modern fire engineering in practice for design projects. Fire design of composite steel concrete structures Lately, there is a growing demand in Romania for steel structures, especially for industrial and commercial objectives, where erection speed is critical in the choice of the structural solution. The main problem of steel structures is their low fire resistance. Composite steelconcrete solutions have the advantage of increased resistance of the structural element, in the case of fire, as well as in normal conditions. One example of application of the advanced methods for composite steel- concrete buildings in Romania, using the SAFIR computer program, comprise the verification of the fire resistance of 150 minutes for the columns of a multi-storey steel-concrete building which is the tallest building in Bucharest, Romania (106 m). The columns are made by partially concrete encased section with crossed I hot rolled European profiles, in order to increase strength, rigidity and fire resistance. Another example is the verification of the fire resistance for the columns of a three-storey framed building structure for the LINDAB-Romania Company Headquarters, in Bucharest. Taking into account the specific of LINDAB – Romania (systems of steel industrial buildings) the special demand was that the resistance structure must be visible steel, made by circular columns. Because for this type of building, according to Romanian fire regulations, the columns must have 120 minutes of fire resistance, the solution of reinforced concrete filled CHS columns was chosen.

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Fire after earthquake

Fire following earthquake can cause substantially loss of life and property, added to the destruction already caused by the earthquake, and represents an important threat in seismic regions. On the other hand, even when no fire develops immediately after an earthquake, the possibility of later fires affecting the structure must be adequately taken into account, since the earthquake induced damages make the structure more vulnerable to fire effects than the undamaged one. The numerical research developed at the "Politehnica" University of Timisoara evaluates the fire resistance time for unprotected steel moment resisting frames, in the hypothesis that they are already damaged by the earthquake, using advanced methods for earthquake and subsequent fire analysis, and using both standard and natural fire scenarios. The natural fire scenarios consider the situation before earthquake, for which all active fire fighting measures are available, and the situation after an earthquake, for which all or part of the fire fighting measures are no more available and the fire load density is consequently modified. Moderate and severe seismic actions are used for designing the steel structures. The influence of the damage level induced by the earthquake on the fire resistance is emphasized.

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Numerical modelling of membrane action of composite slabs in fire situation

Membrane action in fire is now an intensively researched area, for which more improvement is always necessary. The numerical research, in collaboration with the University of Liege, Belgium, was done with the SAFIR program, in order to derive more simple models for representing the partially protected composite floors in fire situation. The numerical models are calibrated using the results of three full scale tests that have been performed in recent years. A complete and detailed numerical modelling of the membrane effect is quite complex and CPU time consuming, due to the simultaneous presence of beams and of orthotropic shells. If such a numerical simulation can be done in research centres and universities, it is not practically applicable for real projects that have to be analyzed in shorter time. The first objective of the research was to derive more simple models for representing the partially protected composite floors in fire situation that, on the price of simplifications and approximations, would nevertheless yield a sufficiently close to reality representation of the structural behaviour and a safe estimate of the load bearing capacity. The second objective was to highlight the influence of some critical parameters on the behaviour and fire resistance of composite slabs such as the amount of reinforcing steel in the slab, the thickness of the slab, the load level and the flexibility of the protected edge beams.

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FIRE RESEARCH IN POLAND

The main purpose of this state-of-the-art report is to present and summarize the actual knowledge about who is who in the field of fire research and fire engineering in Poland.

General division

The fire engineering activity sector in Poland can be divided in several groups of participants, out of which four main groups can be distinguished, i.e. state institutions, universities & academia, research units and others (mainly private sector, consortia of Polish private or public partners, PPP, etc.).

State Institutions

The leading role is played by the National Headquarters of State Fire Service (KG PSP) and its units which are mainly focused on the fire prevention with related directions and regulations aimed at increasing the global safety level of buildings, their users and rescue teams. It participates in conducting many research projects, majority of which are financially supported by the Ministry of Science and Higher Education, but some of them are managed within national or international consortia and using European funds as well. More detailed information about the activity of the National Headquarters of State Fire Service and examples of projects currently being done can be found on http://www.straz.gov.pl/.

Universities and Academia

Amongst the large number of Polish technical universities one can recognize 6 universities which seem to be the most active players in this group. One of them is the Main School of Fire Service (SGSP) in Warsaw, http://www.sgsp.edu.pl/, which as a university is partly subordinate to the Ministry of Science and Higher Education but also is dependent on the Ministry of Interior and Administration as the separate organisational unit of the national State Fire Service (PSP). This is the only one such organization in Poland and one out of the few state technical universities in the world which trains the fire service officers, educates civilian specialists in the fire safety and civil safety engineers at the same time. The laboratories of the Main School of Fire Service are pretty well equipped with stands for evaluation of strength parameters of constructional materials in fire conditions. One of the currently conducted research projects is oriented to the impact of heating rate on parameters of structural steel under fire conditions, which seems to play the crucial role for correct assessment of load-carrying capacity of structural members subjected to elevated temperatures and as the input data in case of advanced numerical analyses of structural systems.

The next significant representative amongst universities is the Cracow University of Technology, http//www.pk.edu.pl/. The university is represented in our COST action by Dr Mariusz Maślak, who is the member of WG1. The main topics of research currently conducted in the university concentrate mainly on safety problems of concrete structures and some reliability aspects of structures subject to fire conditions.

The next one is the oldest technical university in Poland, the Warsaw University of Technology with its Faculty of Civil Engineering, http://www.pw.edu.pl/. The university is widely represented in our action by Dr Lesław Kwaśniewski, and Dr Paweł A. Król, who are the members of WG2 and Dr Robert Kowalski – member of WG3. Our main scientific interests are dedicated to different aspects of load-carrying capacity of concrete and steel structures as well as virtual testing and computer modelling of structures in fire conditions.

The last on the list of universities is the University of Warmia and Mazury in Olsztyn, http://www.uwm.edu.pl/. The University of Warmia and Mazury is relatively very young unit as it was founded on the 1 September, 1999 after merging three educational institutions. The University of Warmia and Mazury is represented in our COST action by Dr Zenon Drabowicz, member of WG3, whose scientific interests concentrate on the evaluation of the capacity of structures after fire and approximate models for analysis of structures under fire loading. Dr Drabowicz cooperates with Prof. Wojciech Skowroński, currently employed in the Wroclaw University of Environmental and Life Sciences, Institute of Building, http://www.up.wroc.pl/, who has been the author of the first Polish monograph on fire safety issued in English.

It's also a good opportunity to mention another individual personality - Prof. Dariusz Gawin, of the Łódź University of Technology, Faculty of Building, Architecture and Environmental Engineering, http://www.p.lodz.pl/, who is a distinctive specialist on modelling thermo-hydro-mechanical coupling phenomena in concrete and other porous building materials.

Research Units

The last part of this report is dedicated to research units and scientific centres from among which the distinctive position belongs to the Building Research Institute (ITB) in Warsaw, http://www.itb.pl/. Since 1 May, 2004 the Building Research Institute has become the Notified Body to the European Commission and to the other member states of EU designated for the task concerning the assessment of building products conformity, according to the requirements of European Directive. The Department of Fire Research which is the separate unit of the Building Research Institute has about 40 years of experience in the field of fire research. The Fire Research Department consists of the Division of Fire Resistance and Smoke Control and the Division of Fire Development and Material Testing. With the Fire Research Department works jointly the Certified Fire Testing Laboratory, formally the separate unit within the structure of the Building Research Institute. The Fire Testing Laboratory is equipped with stands and furnaces allowing for fire tests on separated structural members, floor and wall structural systems, building products, etc. The other notified body, but working under supervision of the National Headquarters of State Fire Service and the Ministry of Interior and Administration is the Fire Protection Research Centre – State Research Institute (CNBOP) in Józefów, Mazovia province, http://www.cnbop.pl/. The Centre has authorization of ministry and notification of European Commission in scope of Directive 89/106/EEC "Construction Products" as well as Directive 89/686/EEC "Personal Protective Equipment". Moreover, the Fire Protection Research Centre takes actively part in elaboration and revising standards and other standardization documents in the scope of: Personal Protective Equipment Technical Committee No. 21, Floor Coverings and Textile Materials Combustibility Technical Committee No. 27, Fire Safety of Buildings Technical Committee No. 180, Rescue and Extinguishing Equipment Technical Committee No. 244 and Fire Alarm Systems Technical Committee No. 264. The Fire Protection Research Centre is represented in our action by Mr Krzysztof Biskup, who is the member of WG1.

Others

There is no technical possibility to mention all the projects being currently conducted within the private sector for research and development, but there are at least several examples that could be presented and discussed. One of them is the project concerning development of complete building system based on perlite and vermiculite aggregate, allowing for thermal insulation of structural members, passive fire protection of existing structures and erecting new low residential buildings.

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RECENT FIRE SAFETY RESEARCH AT THE CHAIR FOR METAL STRUCTURES, TECHNISCHE UNIVERSITÄT MÜNCHEN

Utilisation of Membrane action for Fire Design of Composite-Beam-Slab-Systems

The use of membrane action for the design of composite-beam-slab-systems in fire can reduce the costs of fire protection measures considerably. For most of the secondary beams no fire protection is necessary. Several research projects in the last years were run to investigate this issue. But there are still questions remaining. E.g. it has to be clarified if the edge beams between two slab panels can be designed like a composite beam or if only the steel beam can be taken into account. The reason is that huge cracks appear at the edge beams due to large rotations of the concrete slab. Therefore it is not sure that the shear studs can transfer the shear forces over the cracks.

A research programme (IGF 16142 N) in cooperation between the Technische Universität München and the Leibniz Universität Hannover recently started to clarify the remaining issues and enable the use of membrane action in Germany. The project is mainly sponsored by the German Bundesministerium für Wirtschaft und Technologie and many industry partners. The research project includes two large scale fire tests which were performed in 2010 near Munich.

Intumescent Coating Systems on Steel Columns in Interaction with Industry Claddings

Intumescent coating systems are indeed a good method to protect steel members in case of fire. The disadvantage of these paints is that nobody can predict the behaviour of joints, crossings or partly protected areas. This is the reason why the Technische Universität München wants to explore these important subjects.

The research project "Intumescent coating systems on steel columns in interaction with industry claddings" contributes to answer various questions. This project is about three H-profiles (usually used as steel columns) on one side planked with a usually used steel cassette-cladding and on the three other sides painted with intumescent coating. Thermocouples fixed by point welding were mounted to sev-eral points on and in the steel columns and on the metal facade – profiles. The test was run with the ISO fire curve.

Simultaneous with the fire tests numerical simulations were realized. The comparison of the measured and the computed results is quite good. The implementation of the exact processes during the impact of fire in the intumescent layer must be approved.

Patch Loading under Fire Conditions

This research deals with the local buckling of steel plates subjected to patch loading at elevated temperatures. In case of fire, both yield stresses and elasticity modulus fall depending on the steel temperature. Thus higher limited strains (2% instead of 0.2%) are permitted by construction design. The lateral buckling of the web of girders under patch loading is also influenced by the fire.

The practicable approach to the above described phenomenon is the yield line theory which is ex-tended with the consideration of the higher deformations. Our task is to take out the description of the stability problem of the girders webs under patch loading and fire. Available approaches could be used and then usefully developed. The theoretical investigations would be substantiated with finite element simulations.

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PRACTICAL ACTIVITY OF FIRE ENGINEERING AROUND PROBLEMATIC OF EUROCODES IN SLOVAK REPUBLIC.

Official standpoint Ministry of interior Slovak Republic for Fire resistance of building structures in the Slovak republic under Eurocodes:

Fire resistance of building structures in accordance with § 8 promulgation MV SR no. 94/2004 statute is determined:

- on the basis of initial type testing (act no. 90/1998 statute about building products as amended),
- by calculation according to technical standards (in cases where it is possible to express all the relevant factors by calculation , for example under the so-called „Eurocodes for the design of constructions to the effects of fire “),
- by test and calculation (in those cases where the examination is not possible to express and show all the relevant factors affecting the fire resistance test of building construction).

The decisive factors:

- all the important building-physical properties, thermal and mechanical parameters depending on the temperature, at which the known dimensions and for the construction element (structure) allow to simplify the determination of fire resistance.

Reviewed building construction is designed to:

- effects of mechanical loading at normal temperature ambient according to Eurocodes,
- the various factors in the tables for each building elements,
- the temperature curve,
- to determine the fire resistance of structural element.

Theoretical – experimental estimation of the supporting external wall fire resistance of the wood constructional system Φ- HA STANDARD

Expertise was elaborated for the supposed fire resistance of the construction:

- Wall: REI 45 (o → i) – by the effort of the wall by the fire from the outside according to the STN EN 1363 - 2;
- Wall: REW 45 (i → o) – as fire closed area by the fire exposition from the inside according to the STN EN 1363 – 1.

Expertise was elaborated:

- According to terminal condition of the fire resistance R, E, I, W;
- With the application of the theoretical calculation according to the line STN EN 1995-1-2:2004 – R, E;
- With the application of theoretical calculation of thermal field (Fourier partial differential equation of the non stationary heating conduction) I.

It was proved that: wooden supporting circumferential wall of the constructional system Φ- HA STANDARD by the fire exposition from the outside according to the STN EN 1363-2 suits to the fire resistance REI 45 (o

→i) and by the fire exposition from the inside according to the STN EN 1363-1 suits to the fire resistance REW 45 (i →o).

Theoretical – experimental estimation of the constructional system fire grading (REW 60) for the steel arc halls.

Expertise was elaborated for the supposed fire resistance of the construction:

- REW 60 (i → o) – as fire closed area by the fire exposition from the inside according to the STN EN 1363-1.
- Expertise was elaborated:
- according to the terminal conditions of the fire resistance R, E, W;
- with the application of the theoretical calculation according to the line STN EN 1995-1-2:2004;
- with the application of theoretical calculation of thermal field (Fourier partial differential equation of the no stationary heating conduction)W, I.;
- with the application of the simulation of the virtual model of the building construction joined with static and thermal analysis.

It was proved that: frameless steel constructional system for the arched halls HUPRO by the fire exposition from the inside according to the STN EN 1363-1 suits to the fire resistance REW 60 (i →o).

Estimation of equivalent fire time period duration of family house - model of fire according STN EN 1991-1-2. Combination of 1-zone model and 2-zone model.

Results:

Maximal temperature in fire area - 1284 °C, at 74. minute. Minimal temperature in fire area - 195,37 °C at 130. minute. Maximal rate of heat release in fire area - 13,50 MW at 18,4. minute. Zones interface elevation h = 1,85 m at 2,00. minute.

Next subsidiary results:

temperature of cold zone - 21 °C at 2,00. minute;

pyrolysis rate - 0,84 kg/s at 18,4. minute and next duration to 75,2. minute, total duration of fire - 130 minute;

expansion of fire area 54,00 m2 at 14,00. minute;

oxygen mass of fire are - minimum mass 1,09 kg at 73,00. minute.

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STN EN 13501-2 Fire classification of construction products and building

elements - Part 2: Classification using data from fire resistance tests, excluding ventilation services

STN EN 1363-1 Fire resistance tests - Part 1. General requirements Requirements of fire grading the external wall

STN EN 1363-2 Fire resistance tests – Part 2: Alternative and additional procedures

STN EN 1365-1 Fire resistance tests for load bearing elements– Part 1: Walls

STN EN 1990 Eurocode: Principles of construction projection (E)(including Attachment A1: Buildings (S))

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FIRE RESEARCH AT THE UNIVERSITY OF COIMBRA

The University of Coimbra, Faculty of Science and Technology (FCTUC) is a research and education organization located in central Portugal which was created in 1290. The Department of Civil Engineering is responsible for undergraduate teaching in Civil and Environmental Engineering and a large spectrum of postgraduate courses. It was established in 1972 and includes a staff of about 80 teaching academics covering structural engineering, hydraulics, geotechnics, construction materials and technology, urban planning, roads and transportation. The research unit ISISE (Institute for Sustainability for Innovation in Structural Engineering) is part of Structural Engineering. ISISE is organised in three research Groups: SMCT (Steel and Mixed Construction Technologies); HMS (Historical and Masonry Structures) and SC (Structural Concrete). Fire research is one of the research clusters of SMCT; the behaviour of steel and composite joints and the behaviour of restrained columns have been the main researches items of this cluster. SMCT comprises more than 50 people, including post-graduate students, plus a shared laboratory and modern equipment for mechanical testing and instrumentation.

Behaviour of beam-to-column steel joints under natural fire

Traditionally, beam-to-column joints are assumed to have sufficient fire resistance due to cooler temperatures and slower rate of heating, caused by the concentration of mass on the joint area. However, observation of real fires shows that on several occasions steel joints fail, particularly from their tensile components (such as bolts or end-plates) because of high strains induced by the distortional deformation of the connected members. This research work dealt with the following subjects: i) the characterisation of the behaviour of beam-to-column joints in fire, and ii) their influence on the overall behaviour of the structure subjected to a natural fire. Special emphasis was directed to the cooling phase, because it induces an unwanted failure mode: brittle failure of the tensile components. The experimental results from a fullscale building fire test and six beam-to-column sub-frames fire tests under a natural fire were studied based on their temperature development, structural deformability and failure modes. The analytical approach of this research involved the proposal and validation of a design methodology for steel joints under fire loading. The model is based on the Eurocode 3 approach and includes the representation of all components to allow the application of any combination of bending moment and axial forces that characterise a fire situation.

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Fire resistance of steel and composite steel-concrete columns in buildings

The purpose of this work was to study steel and composite steel-concrete columns in buildings, under fire situation. The influence of several parameters such as the contact with brick walls, the stiffness of the surrounding structure, the load level, and the slenderness of the columns, were the target of the parametric study carried out in the present research. Five sets of experimental tests, were performed. Results of the experimental tests were compared with numerical studies reproducing the conditions used in the tests, with the purpose of providing valuable data for the development or improvement of analytical designing methods. The main goal was to reproduce as much as possible, in the laboratory, the conditions to which the column is subject in a real building. An experimental set-up was constructed in the Laboratory of Structures and Testing Materials of the University of Coimbra, to allow fire resistance tests on columns with restraint to thermal elongation. It was composed of a 3D-steel frame, allowing different positions of the columns, to provide different values of stiffness of the surrounding structure. Mechanical loads constant during the tests were applied by a hydraulic jack, controlled by a central unit. Thermal actions were applied by a gas-burned and an electrical furnace. The experimental programme was composed of the following:

- Steel H Columns embedded on walls (14 experimental tests);
- Bare Steel H columns with restrained thermal elongation (14 experimental tests);
- Composite steel-concrete partially encased H columns with restrained thermal elongation (12 experimental tests);
- Bare steel circular hollow section columns (8 experimental tests);
- Concrete filled circular hollow section columns (32 experimental tests).

The numerical modelling of the tests was performed with the finite element computer package ABAQUS. A geometrical and material non-linear analysis with imperfections was performed. A very accurate modelling of the experimental tests was done, with a very good agreement between experimental and numerical results, both in terms of temperatures, forces and deflected shapes of the columns. For the steel H columns embedded on walls, the main conclusions of this research were that the contact with the wall provides the column a huge thermal gradient within the cross-section. The column under fire situation will behave as a beam-column, failing by bending provoked by thermal bowing, instead of behaving as a column, failing by buckling.

For the bare steel H columns, the main conclusion was that for realistic values of slenderness of the columns in a building, the detrimental effect of the axial restraint is cancelled by the beneficial effect of the rotational restraint. These two restraints seem to cancel each other, and the restraint to thermal elongation is not so important.

For the composite steel-concrete H columns, the major conclusions were the great increase of fire resistance provided by the concrete between flanges, compared with bare steel columns. No local buckling was observed in these columns, and failure by buckling occurred with detachment of the stirrups from the web.

For the concrete filled and bare steel circular hollow section columns, the major conclusions were that the load level, the cross-sectional dimensions, the slenderness ratio and the type of material used to fill the column (i.e. concrete, reinforced concrete or fiber reinforced concrete) has significant influence in the fire resistance.

The major outcomes of this research work were proposals for the assessment of the temperature evolution within the cross-section of unevenly heated steel columns in contact with walls, as well as proposals for the calculation of the critical temperatures and fire resistance of steel bare columns.

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Robustness of open car parks under localised fire

This research work is part of the RFCS European ROBUSTFIRE project. A design philosophy aiming at the economical design of car parks exhibiting a sufficient robustness under localised fire is intended to be developed and practical design guidelines for the application of this design philosophy throughout Europe are expected to be derived. In other to reach this purpose, the work is divided into four main objectives: (i) A review of current practice and state of the art in the design and assessment of open car parks subject to localised fire and a state of the art on the behaviour of beam-to-column joints and steel columns in fire was performed; (ii) The required knowledge on the behavioural response of the individual frame structural elements directly affected by the localised fire and the resultant reduction of carrying capacity of the heated column should be acquired (by experimental tests and numerical simulations); (iii) Detailed numerical models as well as simplified analytical models of the fire response of critical structural components, including columns, connections and composite beams should be developed and validated; Finally (iv) a robustness assessment approach for steel composite car parks under fire, to be event independent as far as possible should be developed and relevant and practical design guidance should beproposed.

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Composite joints for improved fire robustness

This research work is part of the RFCS European COMPFIRE project. The aim is to investigate and evaluate the behaviour of joints for improved fire robustness, particularly joints between beams and the most common composite columns (concrete-filled hollow sections). These composite columns are often assumed to possess inherently high fire resistance, yet there is very little knowledge on their joint behaviour in fire. The main outcomes of the work will consist in coherent performance-based design to steel and composite structures by focusing on the critical issue of the fire performance and robustness of joints. By developing practical methodologies for evaluating the full 3D behaviour of composite joints over the entire course of fire exposure, including the assessment of ductility limit, innovative fire engineering design solutions can be planned to avoid premature progressive collapse of a structure under fire attack.

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