



Research Article

Predicting and comparing the fire performance of a small-scale composite structure

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ABSTRACT

The purpose of this paper is to investigate a strategy for the fire testing of reduced scale structural models which will help engineers design safer structures and reduce the loss from fires. The concept of this work is how composite frame floor arrangements, beam-column connections might be modelled at a small scale suitable for fire testing. Testing full-scale is expensive, besides the testing of scaled model produces reasonable results which help us to understand the failure mechanism and all significant thermo-structural responses involved in a fire. Thermal effects within a structural element generate fire curve, thermal input and structural displacement output, in other words cause and impact. Dimensional analysis, which is a condition for dynamic similarity between prototype and model, can be achieved when all the dimensionless groups are set equal for both model and prototype. On the other hand, scaling rules are used to decide how much insulating material will be used on a structure. 5-storey composite building with composite floors and steel columns has been modelled at small scale with 1/5. The obtained results from various parametric investigations show that the reduced scale model fire test method would be a feasible way to investigate the fire performance of composite structures.

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1. Introduction

Structural models in other words reduced-scale structures sometimes called replica models have usually had an important role in structural engineering in terms of education, research and design. The physical modelling of a structure is an individual sample in which the model stands for a complete structure or some part of a structure. In other words, it is defined as any physical representation of a structure or assembly of structural elements, which is built by small scale compared with full size structures, is to be tested and the laws of resemblance must be applied to explain test results. However, it should be pointed out that the material of prototype can be used for the reduced-size structure. When these materials cannot be used for reduced-size structure, appropriate model materials must be taken place instead of prototype material and then the reduced-size structure is properly constituted a "model".

In terms of fire tests on reduced scale models, as an alternative to the more traditional analysis methods, the use of reduced model tests analysis will be explored in this paper. Fire tests on small scale models offer considerable saving in costs and resources. Scaled experiments offer an economical alternative to full-scale tests. In other words, these tests are repetitive to find the parametric investigations easily and understanding the behaviour of structures and structural members of varying geometries, shapes and end conditions would be readily attainable. Structural models might be classified in different ways such as elastic, indirect, direct, strength, dynamic and other models (Harris and Sabnis, 1999). Chat-taway et al. (1997) has described a procedure used in developing a small scale Class A fire threat (i.e. carbonaceous material such as wood, paper, etc.) by allowing easy scaling rules for the rate of a burning which is a function of surface area, temperature and other well-defined parameters. A methodology for the fire testing of

reduced scale structural model has been presented by O'connor et al. (1997) by applying the scale modelling principles to both structural testing and thermal modelling. In their model, steel and concrete columns, brickwork compartment walls and reinforced concrete floor slabs are used to apply the scaling methodology in standard fire condition. A water mist extinguishment design has been developed by Quintiere et al. (2007) using a quarter-scale model emphasizing scaling of flame radiation by varying the fuel radiative absorption coefficient. Cutter et al. (2009) have been proposed a new method for fire resistance testing of composite materials by developing composite panels subjected to combined fire and mechanical load in small scale. Radzi et al. (2016) has reviewed the complies methodologies, issues and challenges regarding small-scale fire tests on tunnel lining concrete including furnace tests on specimens of actual and reduced dimensions and the effects of loading, size reduction. Fire tests to cables at reduced scale have been performed by Girardin et al. (2016) only considering the external sheeting/jacket. Müllerová (2016) created a representative model of complete 3D structure model by reducing the time equation, energy equation, the border area and the fuel source through dimensionless groups. Krajčír and Müllerová (2017a, 2017b) have performed real 3D experiments in small-scale model representing the full-scale model in the effective way by exact calculation for suitable materials to represent real walls with certain thickness and fire resistance including wood cribs to represent the interior. A scaling method based on Froude scaling for the static fires has been examined by representing a gas burner, liquid pool, wood crib and polyurethane foam block (Quintiere et al., 2017). Bjørge et al. (2017) has aimed to develop a test concept for testing fire resistance of equipment protected with only air-gap and thermal insulation by demonstrating a conceptual methodology for small scale fire testing. Lannon et al. (2018) has followed a procedure based on gram-scale and/or milligram-scale standard testing to obtain relevant material properties which were employed to simulate the early stages of the room corner test, which was selected to represent the full-scale material performance. Wilson (2018) has developed numerical simulation of small-scale and full-scale fire experiments by firstly preparing a small-scale test apparatus for performing cone calorimeter test with a finite difference model and a CFD model. The compared results of this study show that 1D numerical model is not appropriate for the experimental configuration and heat transfer phenomena is found to be over-predicted through the non-degrading structural sections.

Based on the literature related to the scale modelling of fire tests, 5-story composite building involving composite floor systems and steel columns has been modelled at small scale with 1/5. The obtained results showed that choosing suitable scale factors for both structural elements' and insulation thermal properties including dimensions would reflect the similar behaviour with the full-scale.

2. Scale Modelling of Structures and Design Review Stage

The development of structural scaling introduces simple scaling rules to design the structural geometry, structural loading and boundary conditions. Every structural model must be designed due to the many similitude requirements that mean like connection between the model and the prototype structure. The theory of modelling relates to these similitude requirements which might be derived from a dimensional analysis (O'Connor and Silcock, 1992).

2.1. Theoretical development of structural scaling

Dimensional analysis will be used to develop the scale relations between important parameters which are involved in fire. In this study, “~” will be used to define the dimensional equality and “^” will be used to define the dimensionless variables. In other words, dimensionless variables will be showed as a ratio of the variables e.g. $\hat{T} = T/T_{\infty}$, $\hat{\rho} = \rho/\rho_w$ and $\hat{t} = t/t_r$ show the dimensionless of temperature, density and time respectively. ‘s’ is the scale factor or called the geometric length scale. In this work, the scale factor ‘s’ is considered as 1/5. The reason is not only to adopt a model size which can be used in fire tests using a fire oven but also to provide the heat transfer phenomenon in a correct way in terms of size. The required equations for structural scaling have been taken from Wang (2006).

If an object is subjected to a fire, the change of temperature can be related to the heat flux onto object;

$$mc \frac{dT}{dt} \sim \dot{q} \quad (1)$$

where c and \dot{q} represents the specific heat capacity and heat flux respectively. Herein, m is the mass which is related to density and volume of the object. As density's dimensionless factor is $\rho \sim s^0$, the dimensionless factor of mass is completely related to the dimensionless factor of volume as $m, V \sim s^3$ when the object is scaled by geometrically.

The heat generation rate and heat loss rate are scaled as;

$$\dot{Q} \sim s^{5/2} \quad (2)$$

$$\dot{q} \sim s^{5/2} \quad (3)$$

Since the same material is used in the small-scale models, the dimensional equality for c will be $c \sim s^0$. Hence Eq. (1) can be rewritten as;

$$s^3 s^0 \frac{dT}{dt} \sim s^{5/2} \quad (4)$$

where the temperature is independent from scale rules while the time scale can be invented as;

$$t \sim s^{1/2} \quad (5)$$

The structural scaling rule can be derived from the relevant equations, and the stress in one-dimensional form of structural member is used providing that there is no loss of generalization.

$$\varepsilon = \frac{\partial v}{\partial x} \quad (6)$$

where v is a deformation vector in x -direction and it is scaled like $v \sim s$, the scaled of strain will be $\varepsilon \sim s^0$. This corresponds that the strain value between prototype and model is a constant.

Stress may be related to force or strain as;

$$\sigma = \varepsilon E = \frac{\partial F}{\partial x \partial y} \quad (7)$$

Herein, elastic modulus (E), stress (σ) and force (F) are scaled by;

$$\sigma \sim s^0 \text{ and } F \sim s^2 \quad (8)$$

If a beam-column model can be modelled as Fig. 1, the bending resistance and external moment may be written as;

$$-EI \frac{d^2 y}{dx^2} = Py + M_1 + (M_2 - M_1) \frac{x}{L} \quad (9)$$

where y is the transverse deflection, E is the elastic modulus, and P is the axial force which occurred from the elevated temperature of the beam. M is the applied moment and L is the length of the beam. The deflection shape, which is shown in Fig. 1, should be similar to that of prototype providing that $dy/dx \sim s^0$. If the model is geometrically scaled ($x \sim s$), the scaling factor for transverse deflection will be ($y \sim s$).

Eq. (9) can be rewritten considering the geometrically scaling as;

$$-I \frac{d^2 y}{dx^2} = Py + M_1 + (M_2 - M_1) \frac{x}{L} \quad (10)$$

As can be worked out from Eq. (10) that, the scale factor for force and moment are $P \sim s^2$ and $M \sim s^3$.

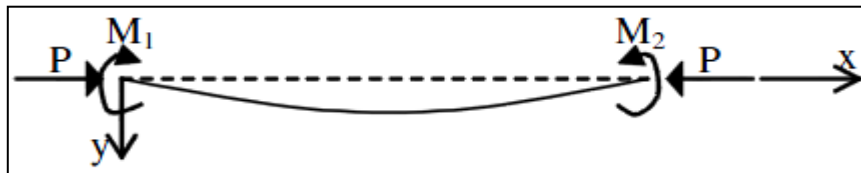


Fig. 1. Beam-column model (Wang, 2006).

When the same material is used for prototype and model, all those scaling rules can be summarized in Table 1.

Table 1. Summary of scale factor for structural scaling.

Quantities	Scale Factor
Length, L	s
Mass, m	s^3
Density, ρ	s^0
Heat generation rate, \dot{Q}	$s^{5/2}$
Heat loss rate, \dot{q}	$s^{5/2}$
Temperature, θ or T	s^0
Time, t	$s^{1/2}$
Strain, ε	s^0
Stress, σ	s^0
Elastic modulus, E	s^0
Force, F or P	s^2
Deformation, v	s
Area, A	s^2
Volume, V	s^3
Moment of inertia, I	s^4
Moment, M	s^3
Axial stiffness, K	s

2.2. Theoretical development of insulation scaling

After theoretical development of structural scaling, insulation for fire protection must be scaled due to the heat transfer through solids in compartment fires. Under these conditions, the equation can be shown as (Wang et al., 2008);

$$m_s c_s \frac{dT_s}{dt} + m_i c_i \frac{dT_i}{dt} \sim \frac{k_i}{\delta_i} A_s (T_f - T_s) \quad (11)$$

where s and i represent the structural materials and insulation respectively.

The structural materials (e.g. steel) and the insulation store the heat. The thermal conductivity of steel is higher than that in the insulation. Hence, the temperature may be considered as uniform in steel. On the other hand, there can be a simple assumption that the surface temperature of the insulation is equal to the hot gas temperature since thermal resistances of radiation and convection are small at the solid boundaries. Therefore, they are ignored in this study. To calculate the thickness of insulation in a small-scale model, Eq. (11) must be scaled with different scales. There are also different scaling approaches which can be derived depending on the heat capacity of insulation (Wang, 2006).

If the heat capacity of insulation is too important, the insulation properties can be obtained from Eq. (11) for scaled model by using dimensionless ratios. Using the insulation term, the scale modeling of insulation thickness must be $\delta_i \sim s^{1/4}$ (Wang, 2006).

Insulation materials are usually light-weight compared to the structural materials. Hence, the heat capacity of insulation may be ignored where the insulation thickness is thin. If the heat capacity is ignored, the scale modelling of insulation thickness is $\delta_i \sim s^{-1/2}$. The scaling rules for the design of wood cribs, fire compartment, insulation and structure considered in the paper are shown in Table 2. The fire compartment and the structure are both geometrically scaled, and the time is again scaled according to $t \sim s^{1/2}$.

3. Composite Beam Design and Modelling in Fire

3.1. Design of full-scaled composite beams

The calculations for full-scaled composite beams in terms of secondary and primary have been done and the section and insulation thicknesses have been determined by self-developed Fire Excel sheets. Plasterboard is considered as a protection material for full-scaled composite beams. The protected steel temperature has been checked against the critical temperature depending on the thickness of insulation. The standard fire is considered in the design of composite beams. Fire compartment is defined in terms of floor area, average windows height on all walls and total area of vertical opening and enclosure. The considered fire resistance time is 90 minutes. The design specifications such as insulation thickness and selected sections for beams can be shown

in Table 3. Fig. 2 shows the protected and unprotected steel temperatures of the primary and secondary beam types under the Standard (ISO) fire condition (ISO, 2014).

Table 2. Scaling rules for fire, insulation and structures.

Design parameters	Scaling rules
Scaling rules for fuel design wood cribs	
Thickness of wood sticks, b_c	$s^{1/3}$
Spacing between wood sticks, s_c	$s^{1/3}$
Length of wood sticks, L_c	$s^{7/6}$
Number of layers, N_c	$s^{1/3}$
Number of wood stick per layer, n_c	$s^{5/6}$
Scaling rules for compartment design	
Wall material, k_w and ρ_w	$s^{3/2}$
Thickness of wall, δ_w	$s^{1/4} \left(\frac{k_w}{\rho_w c_w} \right)^{1/2}$
Scaling rules for insulation on steel structures	
Properties of insulation, k_i and ρ_i	s^0
Thickness of insulation, δ_i	$s^{-1/2}$
Scaling rules for structures	
Structural loadings, P and M	$P \sim s^2, M \sim s^3$
Boundary constrain, K	s

Table 3. Design specifications of full-scaled composite beams.

Design Specification	Primary Beam	Secondary Beam
Selected section	UB 305×165×54	UB 305×102×28
Design load in fire (kN/m), q_{fi}	42	21
Critical temperature (°C)	646.2	652.4
Fire resistance time for unprotected steel (min), t	15.6	12.38
Protected steel temperature for 90 min (°C)	542.8	592.6
Properties of fire protection material		
Material	Plasterboard	Plasterboard
Thickness (mm) ($d_p \sim s^{1/2}$)	20	25

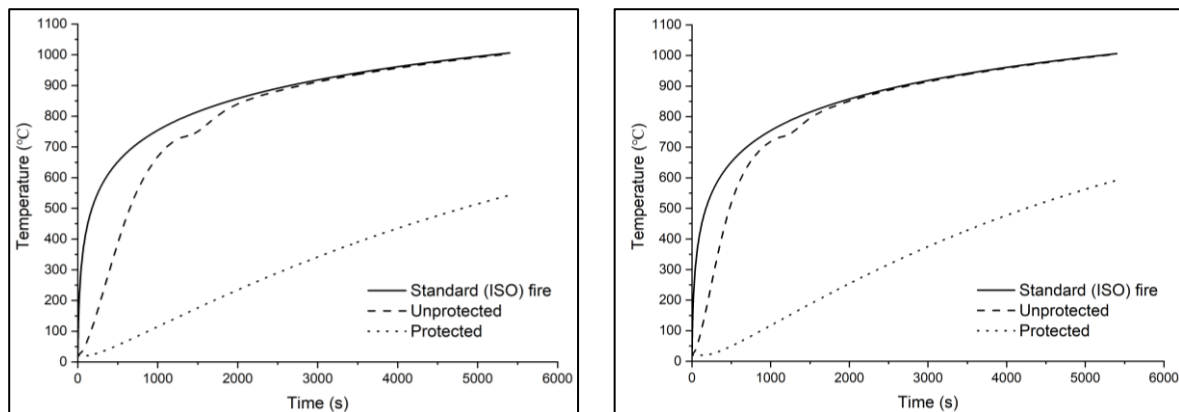


Fig. 2. Temperature distributions on full-scale primary beams and secondary beams.

3.2. Design of small-scaled composite beams

The design of composite beams at 1/5th-scale ($s = 1/5$) follows the same procedure as design of full-scaled. However, the design loads are estimated from the resistance bending moment of the small-scaled section. It can be seen after all calculations that the loads for prototype (real-structure) are lower than that loads for model. Hence, it should be put more weights or loads (additional) on 1/5-scale model such as sand bags to obtain the same deflection under fire conditions. Moreover, wood cribs have also their self-weight leads to an additional load. Thus, the loads, which have been applied in the design of real structure, will increase in the design of model. After calculating the primary and variable loads, critical temperatures can be estimated, and the

resistance time can be modelled according to the time modelling rules. Besides, the thickness of protection must be modelled according to the rules of insulation scaling. Section properties of reduced scale model are worked out from geometrically modeling. The outputs from the developed model are shown in Table 4 in terms of section sizes, fire resistance time for unprotected steel and thickness of fire protection material. Fig. 3 shows the protected and unprotected primary and secondary beams at small scale. Without applying fire protection, primary beams can resist for 7 min against fire whereas this duration is 6.54 minutes for secondary beams due to their section area. Another outcome is those fire resistance times is almost half of the fire resistance times shown in Fig. 2 and Table 3 for full scale though there is no time scaling for the model.

Table 4. Design specifications of small-scaled composite beams.

Design Specification	Primary Beam	Secondary Beam
Selected section	UB 61×33×10.8	UB 61×20.4×5.6
Design load in fire (kN/m), q_{fi}	10.464	5.232
Critical temperature ($^{\circ}C$)	608.3	620.83
Fire resistance time for unprotected steel (min), t	7	6.54
Properties of fire protection material		
Material	Plasterboard	Plasterboard
Thickness (mm) ($d_p \sim s^{1/2}$)	45	56

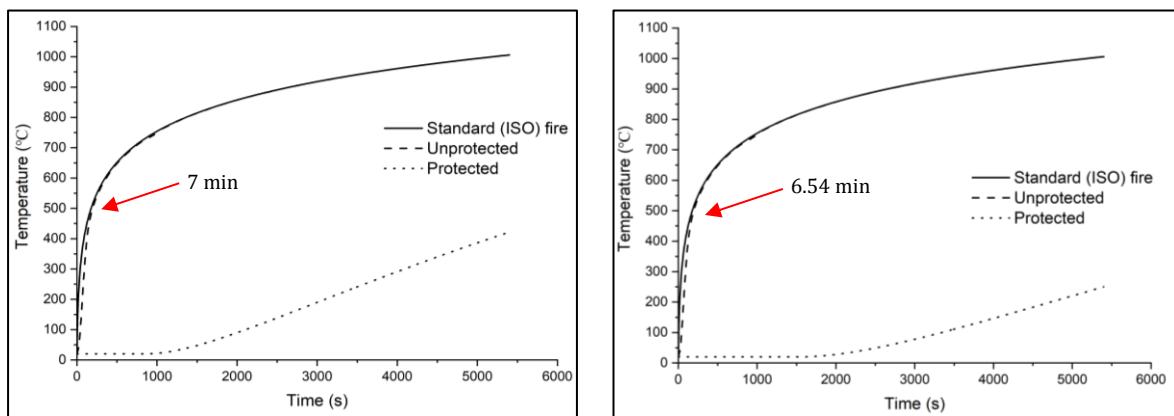


Fig. 3. Temperature distributions on small-scale primary beams and secondary beams.

4. Composite Slab Design and Modelling in Fire

4.1. Design of full-scaled composite slab

Firstly, the loads for full-scaled composite slab have been determined in terms of steel sheet load, concrete and finishes as the permanent loads and variable loads. Suitable steel decking has been chosen from Corus (Corus Pmf Comflor 51) (International, 2007). Effective thickness of the composite slab has been found based on steel decking properties using effective thickness method. After the determination of the effective thickness, design loads at ambient temperature has been calculated to estimate the design moments in terms of sagging

moment at span (M_{sag}) and hogging moment at mid-support (M_{hog}). However, applied sagging and hogging moments depend on the reduction factor related to the load combination factor ($\psi_{1,1}$). On the other hand, there is a limitation for steel sheet profile which needs to be checked according to EC4, Part 1.2, Annex D, Section D.5 (CEN, 2005b). This necessary check is shown below in Fig. 4.

The results of design at fire situation and ultimate limit state design at ambient temperature can be shown in Table 5. After all design calculations, this stage is to work out the fire resistance according to the thermal insulation criterion. As fire compartment, it is considered externally fully glazed over 3.0 m from floor to ceiling

height. Fire resistance time is considered as 90 minutes for this building. The temperature of rebars and the parts of steel decking such as lower flange, web and upper flange, and compressive resistance of concrete and plastic moment resistance of slab have been calculated.

Sagging moment resistance of slab should be compared with the design sagging moment. The calculation for hogging moment resistance follows the same procedure. However, the difference comes from using tension bar.

Scope of application		
EC4, Part 1.2, Annex D, Section D.5		
Field of application		Actual values
Re-entrant steel sheet profiles	Trapezoidal steel sheet profiles	
$70 \text{ mm} \leq l_1 \leq 135 \text{ mm}$	$80 \text{ mm} \leq l_1 \leq 155 \text{ mm}$	$l_1 = 112.5 \text{ mm}$ [OK]
$110 \text{ mm} \leq l_2 \leq 150 \text{ mm}$	$32 \text{ mm} \leq l_2 \leq 132 \text{ mm}$	$l_2 = 137.5 \text{ mm}$ [OK]
$38.5 \text{ mm} \leq l_3 \leq 97.5 \text{ mm}$	$40 \text{ mm} \leq l_3 \leq 115 \text{ mm}$	$l_3 = 40 \text{ mm}$ [OK]
$50 \text{ mm} \leq h_1 \leq 130 \text{ mm}$	$50 \text{ mm} \leq h_1 \leq 125 \text{ mm}$	$h_1 = 79 \text{ mm}$ [OK]
$30 \text{ mm} \leq h_2 \leq 60 \text{ mm}$	$50 \text{ mm} \leq h_2 \leq 100 \text{ mm}$	$h_2 = 51 \text{ mm}$ [OK]

[The slab is WITHIN the scope of application]

Fig. 4. Scope of application using developed EXCEL spreadsheet.

Table 5. Design specifications of small-scaled composite beams.

Design Specification	
Characteristic floor loading	<p><u>Permanent Loads:</u> Steel sheet, $G_{p,k} = 0.20 \text{ kN/m}^2$ Concrete, $G_{c,k} = 2.80 \text{ kN/m}^2$ Finishes, $G_{f,k} = 1.00 \text{ kN/m}^2$</p> <p><u>Variable Loads:</u> Live load, $Q_{k,l} = 5.00 \text{ kN/m}^2$</p>
Material properties	<p><u>Steel Sheet:</u> Yield stress: $f_{p,y} = 255 \text{ N/mm}^2$ Geometry of cross section, $h_1 = 79 \text{ mm}$ Thickness, $t_p = 0.7 \text{ mm}$ Cross-sectional area, $A_p = 1296.8 \text{ mm}^2/\text{m}$</p> <p><u>Concrete:</u> Type, light-weight $f_{c,k} = 30 \text{ N/mm}^2$ Height, $h_c = 130 \text{ mm}$ Cross-sectional area, $A_c = 120803.3 \text{ mm}^2/\text{m}$</p>
Effective thickness of slab (mm), h_{eff}	120.8
Ultimate limit state design at ambient temperature (kNm/m)	$M_{sag} = 32.51$ $M_{hog} = 58.05$
Design at fire situation (kNm/m)	$M_{fi,Sd,sag} = 16.4$ $M_{fi,Sd,hog} = 29.3$
Sagging Moment Resistance of Slab	
Considered standard fire resistance time (min), R	90
Fire resistance time of slab (min), t_i	128.2
Sagging moment resistance (kNm/m)	$M_{fi,Rd,sag} = 43.3 > M_{fi,Sd,sag} = 16.8$ The composite slab is 'Satisfactory' against sagging moment
Hogging Moment Resistance of Slab	
Rebar diameter(mm), Φ	20
Tension bar cover, c	30
Normal force in hogging rebar, N_s (kN)	245.4
Hogging moment resistance (kNm/m)	$M_{fi,Rd,hog} = 77.3 > M_{fi,Sd,hog} = 29.2$ Satisfactory

4.2. Design of small-scaled composite slab

The response of compressive load is more important for any model concrete because the main property of concrete as a structural material is to carry the compression loads. The behaviour of prototype concrete under compression can be seen in a model concrete. Model concrete mixes must be designed properly and carefully to represent not only the tensile strength, time dependent behaviour but also the strength and the strain-stress relation under compression. In terms of materials included in model concrete mix, the cement is the same material in both prototype and model, but aggregates are different. For the model aggregates, ordinary well-graded concrete sand and sometimes fine crushed stone or pea gravel for larger-scale models are used with scaling of the particles. 'The finer particles in the model mix are limited to less than 10% passing the U.S. No. 100 sieve (0.149 mm mesh)' (Harris and Sabnis, 1999). The amount of aggregate, which is used in concrete mix, has a significant effect on the mechanical properties of model concrete.

A study about the influence of particle size distribution, shape and texture of the sand in micro concrete confirmed the earlier findings (Wijayasri, 1983).

The modelling of composite slab, the micro concrete can be used for concrete part. For the reinforcement part, to select and model the correct reinforcement for a concrete scaled model is the single and the most important step in the all process of modelling. For this modelling of composite slab, Black annealed wire can be considered as model reinforcement. Micro-concrete models may be reinforced with black annealed wire which can be found in the form of rolls. The wire is cold-drawn and annealed in the special factory. Before used in the models, it must be straightened by pulling. Hence this process strains the wire sufficiently to destroy the yield point. Stress-strain curve of prototype reinforcing steel should be chosen according to the reinforcing steel behaviour based on shape, diameter and their treatment under temperature conditions (Harris and Sabnis, 1999).

If the composite slab is modelled at 1/5-scale, the overall floor zone will be 150 mm including raised floor, slab, beam and services such as ceiling and lighting. The drawing for reduced-scale composite slab model can be shown in Fig. 5.

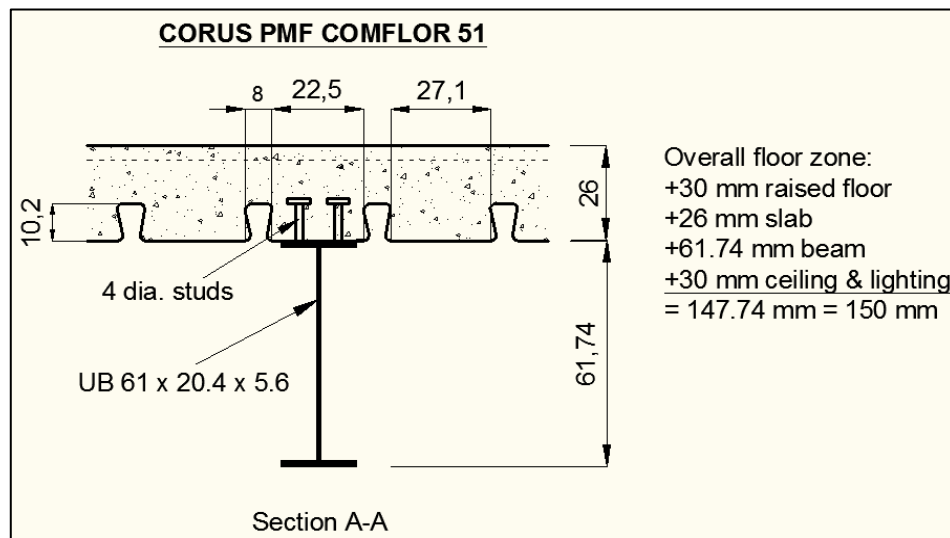


Fig. 5. The specifications of reduced scale composite beam and slab.

4.3. Design of wood cribs

A typical office fuel load is generally between 20 kg/m² and 60 kg/m² (Wang et al., 2007) and this fire loading condition should be scaled according to the heat loss and generation rate presented in Table 1. In the design of wood cribs, 40 kg/m² and 36 m² is assumed as the fuel load for a typical floor and floor area respectively. Therefore, the burning rate would be as,

$$m \approx \frac{m}{t} = \frac{40 \text{ kg/m}^2 \times 36 \text{ m}^2}{120 \text{ min} \times 60 \text{ s/min}} = 0.20 \text{ kg/s}$$

The average burning rate is scaled according to the $m \sim s^{5/2}$. Hence, the burning rate of the fuel for the 1/5-

scale is approximately 3.58 g/s and the burning time in the scaled model would be 53.7 minutes. Wood cribs are thought to be designed from pine whose density is 530 kg/m³. The total mass of the fuel load for a wood crib is calculated as,

$$3.58 \text{ g/s} \times 53.7 \text{ min} \times 60 \text{ s/min} = 11.53 \text{ kg} = 0.11 \text{ kN}$$

If this load converts into the uniform distributed load, it will be an additional load of 0.08 kN/m² per wood crib to the design of composite beam. Wood sticks have been designed as square cross-sections and scaled according to the scaling rules shown in Table 1. The design specifications can be given below in Table 6. Small-scaled wood crib model can be shown in Fig. 6.

Table 6. Design parameters of wood cribs.

Design Specification				
Scale	N_c	n_c	b_c (mm)	L_c (mm)
1	5	24	19.1	800
1/5	3	6	11	122

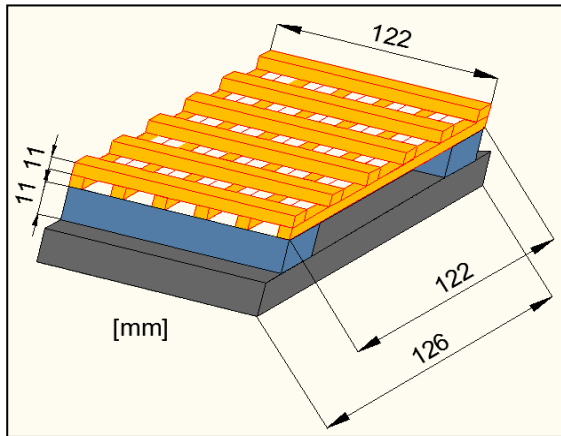


Fig. 6. Configuration of wood cribs.

5. Steel Column Design and Modelling in Fire

The very first important issue, which needs to be considered carefully, is the buckling resistance of column sections depending on the total design axial load. This loading changes based on the column position for instance edge, corner and internal. Columns are expected to be stable with or without fire protection under fire

conditions. The section classification according to the web and flange design has been done based on Eurocode 3 Table 5.2 (CEN, 2005a).

5.1. Design of full-scaled steel columns in fire

The loading conditions, floor and column sizes, and material properties are assumed to be identical for all type of columns in terms of internal, edge and corner. These properties are shown in Table 7.

All columns are protected by box protection and their properties are shown in Table 8.

5.1.1. Design of internal columns

Internal columns carry the maximum load compared to the corner and edge columns. The design of columns under fire condition follows the similar procedure with beam design. However, they should be checked against the ultimate limit state design at ambient temperature whether they will satisfy the lateral torsional buckling. Therefore, ultimate limit state design check at ambient temperature and design check at room temperature have been performed herein this study. The design specifications of full-scaled internal columns in fire are shown in Table 9.

After checking the buckling resistance of the section, the column can be designed at fire situation. Design loading condition is compared against the buckling resistance at time t with uniform temperature. For the fire compartment, it is considered externally fully glazed over 3.0 m from floor to ceiling height as sketched in Fig. 7.

The properties of the fire compartment have been presented in Table 10.

Table 7. The considered properties of columns and floors.

General Specifications of Columns	
Characteristic of floor loading	$G_k = 4 \text{ kN/m}^2$ $Q_k = 5.0 \text{ kN/m}^2$
Floor and column sizes	Span $B = 6 \text{ m}$, Span $L = 6 \text{ m}$ Column height = 4 m
Material Properties	Steel grade, $f_y = 275 \text{ N/mm}^2$ Elastic modulus, $E = 210000 \text{ N/mm}^2$

Table 8. Insulation properties of full-scaled columns.

Properties of Protection Material	Internal	Edge	Corner
Material	Plaster finish box protection	Plaster finish box protection	Plaster finish box protection
Thickness, d_p	25 mm	30 mm	35 mm
Density, ρ_p	1300 kg/m ³	1300 kg/m ³	1300 kg/m ³
Specific heat, c_p	1000 J/kg ^o K	1000 J/kg ^o K	1000 J/kg ^o K
Thermal conductivity, λ_p	0.50 W/m ^o K	0.50 W/m ^o K	0.50 W/m ^o K

Table 9. Design of full-scaled steel internal columns under fire condition.

Design Specifications of Internal Columns	
Selected section	UC 254×254×132
Floor area	36 m ²
Section classification	Web, $d/s = 15.6$ (Section is Class 1) Flange, $b/2t = 6.31$ (Section is Class 1)
Ultimate limit state design at ambient temperature	Partial factor, $\gamma_G = 1.35$ and $\gamma_{Q,1} = 1.5$ Design loads, $G_d = 194.4$ kN/m $Q_d = 270.0$ kN/m One floor total load = 464.4 kN Number of floors = 5 Design load from upper 4 floors = 1857.6 kN Extra factored dead load (cladding, etc.) = 45 kN Total design axial compression load, $N_{sd} = 2367.0$ kN
Design at room temperature	Buckling resistance, $N_{b,Rd} = 3381.84$ kN $N_{b,Rd} > N_{sd}$ (OK)

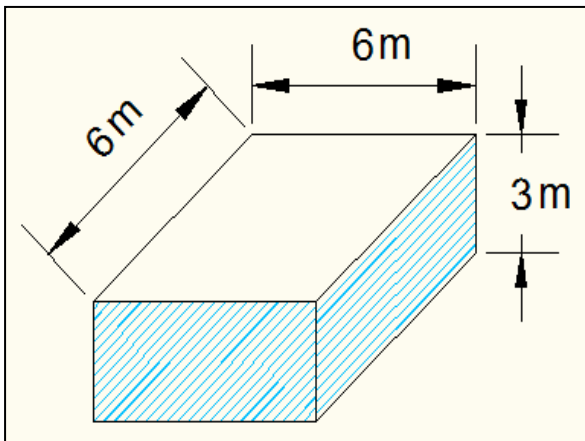


Fig. 7. Sketch of fire compartment.

Table 10. Fire compartment properties.

Opening and Enclosure	
Floor area, A_f	36.0 m ²
Total vertical opening, A_v	18.0 m ²
Average of windows height on all walls, h_{eq}	3.0 m
Total area of enclosure, A_t	168.0 m ²
Density of wall material, ρ_w	1600 kg/m ³
Specific heat, c_w	840 J/kg°K

The standard fire is considered herein this study and the steel temperature is around 990.2°C while maximum temperature is 1049.0°C after applying box protection for 90 minutes. The buckling resistance ($N_{bi,fi,t,Rd}$) at time t with uniform θ_a is 3361.5 kN while design loading in fire ($N_{fi,sd}$) is 1192.74 kN. Since buckling resistance is greater than the design loading, these internal columns can resist for 90 minutes under fire condition. The steel

temperatures have been presented in Fig. 8 with and without insulation.

5.1.2. Design of edge columns

The same procedure applied in the previous section for the design of internal columns has been applied to the design of edge columns. With the aid of developed fire excel spread sheets, the summary of the sections' properties can be shown in Table 11.

The same fire compartment properties shown in Table 10 has been used herein for edge columns. Edge columns has also been protected by box protection of which thickness is 10 mm. After 90 minutes' box protection, the steel temperature reaches to 994.6°C whereas the maximum temperature is 1049.0°C. The buckling resistance of edge columns ($N_{bi,fi,t,Rd}$) at time t with uniform θ_a is 1972.5 kN while design loading in fire ($N_{fi,sd}$) is 607.7 kN. The buckling resistance is also greater than the design loading in fire. Therefore, these edge columns can resist for 90 minutes under standard fire condition. Fig. 9 shows the protected and unprotected temperature distribution on edge columns.

5.1.3. Design of corner columns

For the corner columns in the real structure, floor area and axial compression load changes. However, the considered loads in terms of permanent and variable and the material properties are identical with the internal and edge columns. The design specifications are shown in Table 12. These columns have also been protected by box protection to resist against 90 minutes' fire. The predicted steel temperature is 999.2°C and the maximum temperature is 1049.0°C. For the buckling resistance check, the buckling resistance ($N_{bi,fi,t,Rd}$) at time t with uniform θ_a is 1142.2 kN whereas design loading in fire ($N_{fi,sd}$) is 315.2 kN. Hence, the corner columns can resist against fire for 90 minutes.

The temperature profiles for both protected and unprotected corner columns are given in Fig. 10.

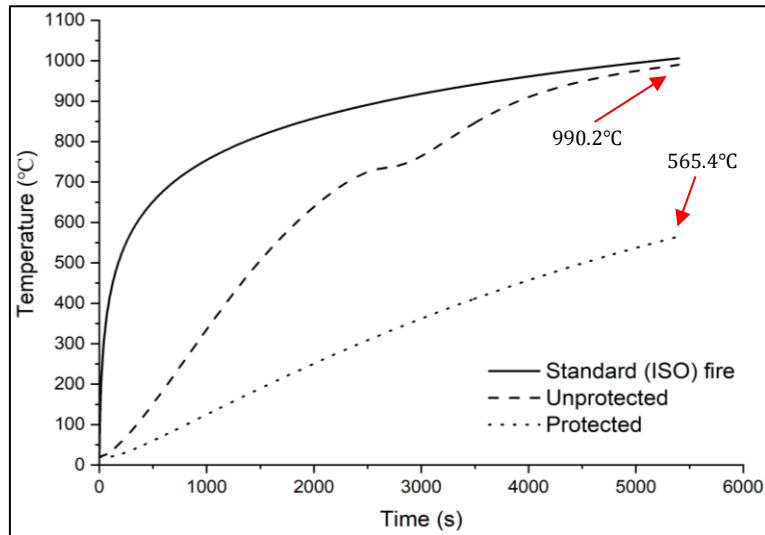


Fig. 8. Temperature distribution for internal columns.

Table 11. Design of full-scaled edge columns under fire condition.

Design Specifications of Edge Columns	
Selected section	UC 203×203×86
Floor area	18 m ²
Section classification	Web, $d/s = 12.7$ (Section is Class 1) Flange, $b/2t = 5.1$ (Section is Class 1)
Ultimate limit state design at ambient temperature	Partial factor, $\gamma_G = 1.35$ and $\gamma_{Q,1} = 1.5$ Design loads, $G_d = 97.2$ kN/m $Q_d = 135.0$ kN/m One floor total load = 232.2 kN Number of floors = 5 Design load from upper 4 floors = 928.8 kN Extra factored dead load (cladding, etc.) = 45 kN Total design axial compression load, $N_{sd} = 1206.0$ kN
Design at room temperature	Buckling resistance, $N_{b,Rd} = 1881.53$ kN $N_{b,Rd} > N_{sd}$ (OK)

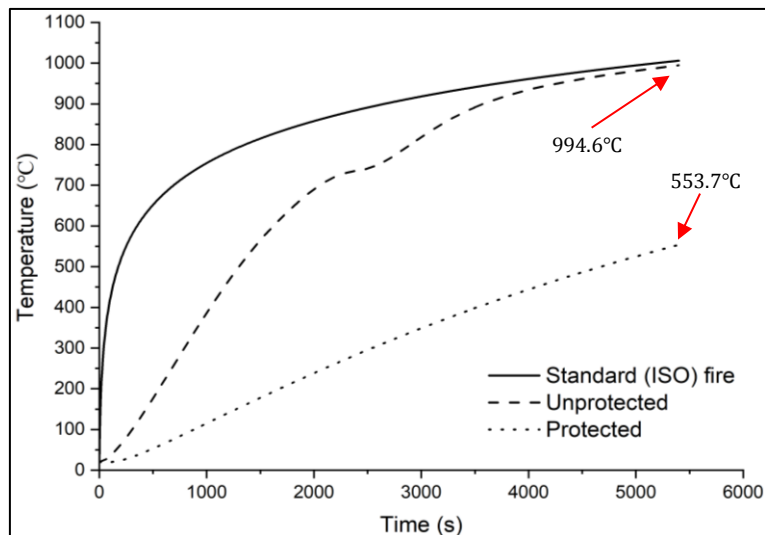
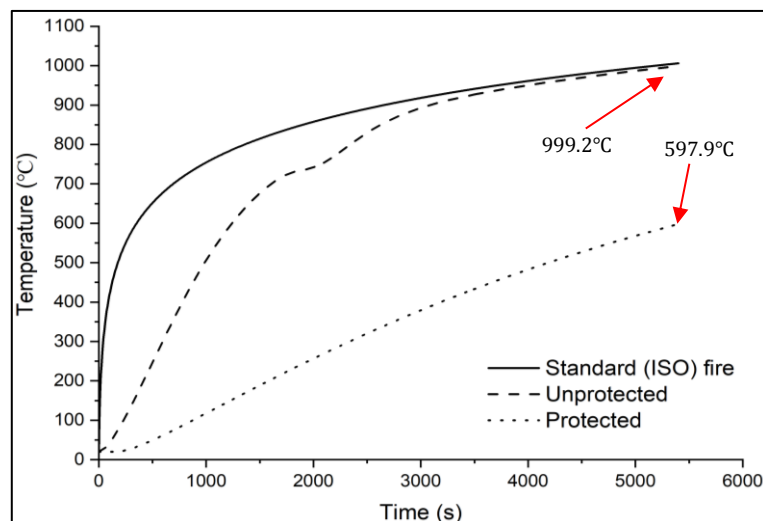


Fig. 9. Temperature distribution for edge columns.

Table 12. Design of full-scaled corner columns under fire condition.

Design Specifications of Corner Columns	
Selected section	UC 203×203×52
Floor area	9 m ²
Section classification	Web, $d/s = 12.7$ (Section is Class 1) Flange, $b/2t = 5.1$ (Section is Class 1)
Ultimate limit state design at ambient temperature	Partial factor, $\gamma_G = 1.35$ and $\gamma_{Q,1} = 1.5$ Design loads, $G_d = 948.6$ kN/m $Q_d = 67.5$ kN/m One floor total load = 116.1 kN Number of floors = 5 Design load from upper 4 floors = 464.4 kN Extra factored dead load (cladding, etc.) = 45 kN Total design axial compression load, $N_{sd} = 625.5$ kN
Design at room temperature	Buckling resistance, $N_{b,Rd} = 1105.17$ kN $N_{b,Rd} > N_{sd}$ (OK)

**Fig. 10.** Temperature distribution for corner columns.

5.2. Design of small-scaled columns in fire

All type of columns (internal, edge and corner) have been modelled at 1/5-scale. However, axial compression load has been worked out depending on the characteristic floor loading of composite floor. The section properties can be shown in Table 13.

The characteristic floor loading, floor and column sizes and material properties are identical for all type of columns. They have been also scaled according to the scaling rules with a scaler of 1/5. They are presented in Table 14.

The insulation properties of small scaled columns are identical with the prototype. However, the thickness of the box protection has been scaled according to the scaling rule presented in Table 2. The scaled properties of the box protection are shown in Table 15.

5.2.1. Design of small-scaled internal columns

The estimations of the compression load for all type of columns have been performed by using MATLAB. The same procedure in terms of buckling resistance check implies herein though. The summary of modelling of internal columns is shown in Table 16.

As can be seen from Table 16, the total design axial compression load (N_{sd}) is 130.8 kN while this load for the prototype was 2367.0 kN. This can be concluded that the load is not proportional with the scaling factor ($P \sim s^2$). However, the loads on the composite floor have been increased to prevail the deflection (i.e. G_k has been increased from 4 kN/m² to 7.44 kN/m²). Infact, this load has not been increased, the total design axial compression for 1/5-scaled model would be 92.88 kN which is close to the scaling rule's result.

Fire compartment, which was considered externally fully glazed over 3.0 m height for the prototype, is also been scaled down. The properties of it are shown in Table 17.

Table 13. The section properties of small-scaled columns.

Section properties	Internal	Edge	Corner
Depth of section "h" (mm)	55.26	44.44	41.24
Width of section "b" (mm)	52.26	41.02	40.86
Thickness of web "s" (mm)	3.06	2.54	1.58
Thickness of flange "t" (mm)	5.06	4.10	2.50
Root radius "r" (mm)	2.54	2.04	2.04
Depth between fillets "d" (mm)	40.06	32.16	32.16
Ratios for local buckling of flange "b/2t"	5.16	5.00	8.17
Ratios for local buckling of web "d/s"	13.10	12.66	20.35
Second moment of area for axis x-x "I _x " (cm ⁴)	36.05	15.12	8.41
Second moment of area for axis y-y "I _y " (cm ⁴)	12.05	5.00	2.85
Elastic modulus of axis x-x "Z _x " (cm ³)	13.05	6.80	4.08
Elastic modulus of axis y-y "Z _y " (cm ³)	4.61	2.39	1.39
Plastic modulus of axis x-x "S _x " (cm ³)	14.95	7.82	4.54
Plastic modulus of axis y-y "S _y " (cm ³)	7.02	3.65	2.11
Area of section "A" (cm ²)	6.72	4.40	2.65

Table 14. General specification of columns.

General Specifications of Columns	
Characteristic of floor loading	$G_k = 7.44 \text{ kN/m}^2$ $Q_k = 5.0 \text{ kN/m}^2$
Floor and column sizes	Span $B = 6 \text{ m}$ Span $L = 1.2 \text{ m}$ Column height = 0.8 m
Material properties	Steel grade, $f_y = 275 \text{ N/mm}^2$ Elastic modulus, $E = 210000 \text{ N/mm}^2$

Table 15. Scaled properties of insulation for small-scaled columns.

Properties of Protection Material	Internal	Edge	Corner
Material	Box protection	Box protection	Box protection
Thickness, d_p	55.9 \approx 55 mm	67 \approx 70 mm	78 \approx 80 mm
Density, ρ_p	1300 kg/m ³	1300 kg/m ³	1300 kg/m ³
Specific heat, c_p	1000 J/kg ^o K	1000 J/kg ^o K	1000 J/kg ^o K
Thermal conductivity, λ_p	0.50 W/m ^o K	0.50 W/m ^o K	0.50 W/m ^o K

Table 16. Design properties of small-scaled internal columns.

Design Specifications of Internal Columns	
Selected section	1/5-scaled of UC 254×254×132
Floor area	1.44 m ²
Section classification	Web, $d/s = 13.1$ (Section is Class 1) Flange, $b/2t = 5.16$ (Section is Class 1)
Ultimate limit state design at ambient temperature	Partial factor, $\gamma_G = 1.35$ and $\gamma_{Q,1} = 1.5$ Design loads, $G_d = 14.46$ kN/m $Q_d = 10.8$ kN/m One floor total load = 25.26 kN Number of floors = 5 Design load from upper 4 floors = 101.04 kN Extra factored dead load (cladding, etc.) = 4.5 kN Total design axial compression load, $N_{sd} = 130.8$ kN
Design at room temperature	Buckling resistance, $N_{b,Rd} = 135.27$ kN $N_{b,Rd} > N_{sd}$ (OK)
Buckling resistance at time t with uniform θ_a ($N_{b,fi,t,Rd}$) and design load in fire ($N_{fi,sd}$)	$(N_{b,fi,t,Rd}) = 123.95$ kN $N_{b,fi,t,Rd} > N_{fi,sd} = 65.92$ kN (OK)
Fire resistance time	$t = 40.25$ minutes ($t \sim s^{1/2}$)

Table 17. Scaling of fire compartment.

Opening and Enclosure	
Floor area, A_f	1.44 m ²
Total vertical opening, A_v	0.72 m ²
Average of windows height on all walls, h_{eq}	0.6 m
Total area of enclosure, A_t	6.72 m ²
Density of wall material, ρ_w ($\rho_w \sim s^{3/2}$)	143.11 kg/m ³
Specific heat, c_w ($c_w \sim s^{3/2}$)	75.13 J/kg°K

Fig. 11 shows the protected and unprotected internal columns' temperature at small scale. For the small-scale model, there is no temperature change until almost 15 min due to the modelled insulation thickness.

The protected steel temperature reaches around 512°C whereas unprotected temperature for the same internal column reaches to almost Standard fire temperature at the end of 90 minutes.

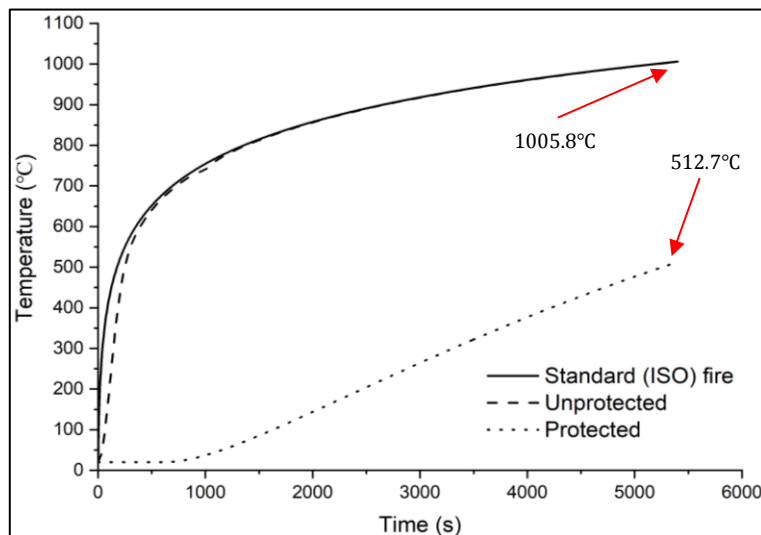


Fig. 11. Temperature distribution for internal columns at small scale.

5.2.2. Design of small-scaled edge columns

Except the axial compression load from 4 upper floors which is the half of the design loads of internal columns due to the design floor area, entire properties are identical with the small-scaled internal columns. The summary of modelling of edge columns is shown in Table 18.

This modelling results show that the differences between the buckling resistance at time t with uniform θ_a and the design load value increases for edge columns compared to the internal columns which results in reduce on the thickness of fire protection material. Hence;

when the section size gets smaller, the differences between the buckling resistance of columns and design axial compression will be higher. The same fire compartment with its properties has been considered herein.

Fig. 12 presents the temperature distribution on small scaled edge columns. Because of scaling of insulation thickness, the lower protected temperature results have been obtained. The final temperature for the protected steel sample is around 320°C at the end of the 90 min. This means that there is almost no strength change of the steel material as the steel properties change dramatically after around 500°C.

Table 18. Design properties of small-scaled edge columns.

Design Specifications of Edge Columns	
Selected section	1/5-scaled of UC 254×254×86
Floor area	0.72 m ²
Section classification	Web, $d/s = 12.66$ (Section is Class 1) Flange, $b/2t = 5.002$ (Section is Class 1)
Ultimate limit state design at ambient temperature	Partial factor, $\gamma_G = 1.35$ and $\gamma_{Q,1} = 1.5$ Design loads, $G_d = 7.23$ kN/m $Q_d = 5.4$ kN/m One floor total load = 12.63 kN Number of floors = 5 Design load from upper 4 floors = 50.52 kN Extra factored dead load (cladding, etc.) = 4.5 kN Total design axial compression load, $N_{sd} = 67.65$ kN
Design at room temperature	Buckling resistance, $N_{b,Rd} = 75.26$ kN $N_{b,Rd} > N_{sd}$ (OK)
Buckling resistance at time t with uniform θ_a ($N_{bi,fi,t,Rd}$) and design load in fire ($N_{fi,sd}$)	$(N_{bi,fi,t,Rd}) = 112.56$ kN $N_{bi,fi,t,Rd} > N_{fi,sd} = 31.83$ kN (OK)
Fire resistance time	$t = 40.25$ minutes ($t \sim s^{1/2}$)

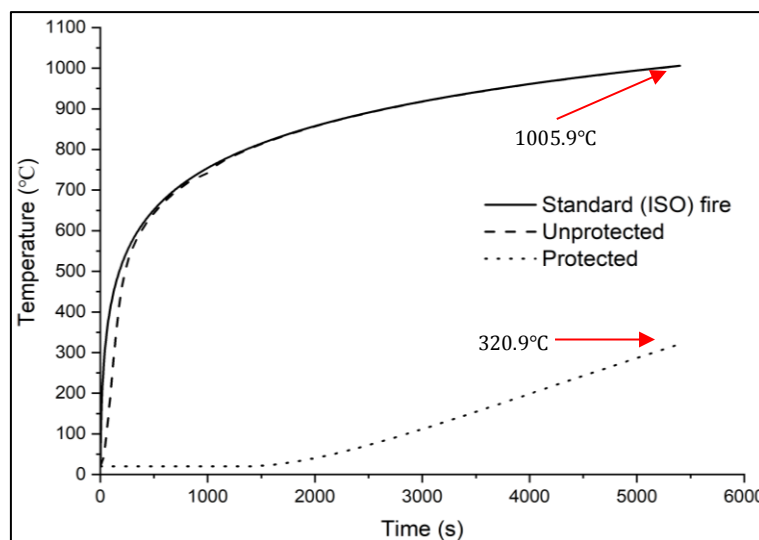


Fig. 12. Temperature distribution for edge columns at small scale.

5.2.3. Design of small-scaled corner columns

Small-scaled corner columns have been modelled with the same procedure of internal and edge columns. The properties are shown in Table 19.

Figs. 11-13 present the steel temperature on internal, edge and corner columns at small scale respectively. Although it has been mentioned in the Section 2.2 as the changing the insulation property in terms of density and

thermal conductivity is impracticable and unpredictable because of non-existence of light-weight insulation materials in the design procedure, using the same insulation thermal properties with the full-scale produced very lower temperatures since the insulation thicknesses are scaled according to the “ $s^{-1/2}$ ” (Wang, 2006) resulting in thicker insulation material for the reduced scale models. Therefore, an important outcome from the study is to scale the insulation thermal properties.

Table 19. Design properties of small-scaled corner columns.

Design Specifications of Corner Columns	
Selected section	1/5-scaled of UC 254×254×52
Floor area	0.36 m ²
Section classification	Web, $d/s = 20.35$ (Section is Class 1) Flange, $b/2t = 8.17$ (Section is Class 1)
Ultimate limit state design at ambient temperature	Partial factor, $\gamma_G = 1.35$ and $\gamma_{Q,1} = 1.5$ Design loads, $G_d = 3.62$ kN/m $Q_d = 2.7$ kN/m One floor total load = 6.32 kN Number of floors = 5 Design load from upper 4 floors = 25.28 kN Extra factored dead load (cladding, etc.) = 4.5 kN Total design axial compression load, $N_{sd} = 36.1$ kN
Design at room temperature	Buckling resistance, $N_{b,Rd} = 80.8$ kN $N_{b,Rd} > N_{sd}$ (OK)
Buckling resistance at time t with uniform θ_a ($N_{bi,fi,t,Rd}$) and design load in fire ($N_{fi,sd}$)	$(N_{bi,fi,t,Rd}) = 70.71$ kN $N_{bi,fi,t,Rd} > N_{fi,sd} = 15.92$ kN (OK)
Fire resistance time	$t = 40.25$ minutes ($t \sim s^{1/2}$)

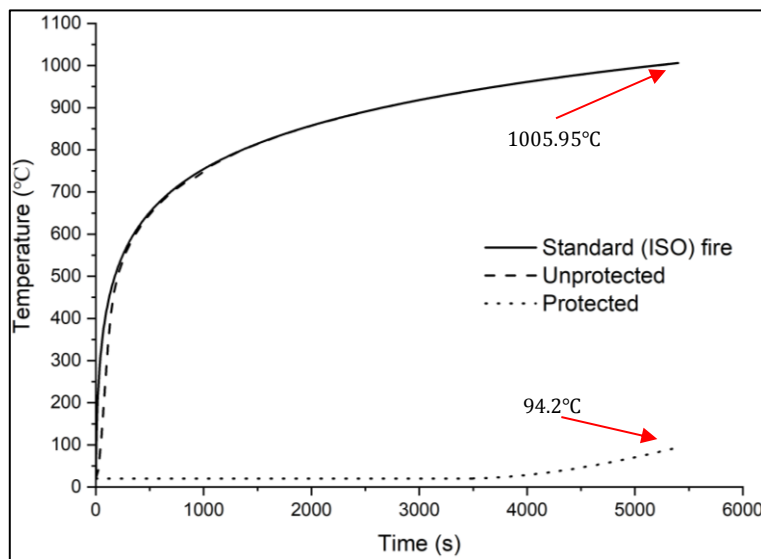


Fig. 13. Temperature distribution for corner columns at small scale.

6. Conclusions

The feasibility of using small-scale models to investigate the fire performance of composite structures has been explored in this paper. The physical scaling rules for the composite structures in general and insulation have been presented. Reduced scale model testing is a significantly economical way compared with the full-scale tests. Providing proper and correct scaling conditions, these small-scale models can represent the behaviour of real structures under a fire condition. The modelling results in terms of beam, slab and column according to the presented scaling rules have been predicted by using developed Fire Excel Spreadsheets and MATLAB. The following inferences can be made from this study:

- The scaling factor ($s = 1/5$ – scale) geometrically has been applied to all structural members, fire compartment and insulation. The section sizes and the insulation thicknesses has been modelled according to scaling rules.
- The insulation thermal properties including density and thermal conductivity should also be scaled rather than considering it as light-weight material with ignoring the scaling. This results in very lower temperatures for the small-scaled steel samples.
- The comparisons of results between different types of columns, and effective and appropriate strategy for partial scaling have been presented.
- The required protection material in the reduced scale model, box protection herein this study, is more than that required in the real structure to resist the structure to the proposed fire resistance time.
- The loads used in the real structure have been increased by including additional sand bags to ensure the same deflection in prototype.
- Temperature results of steel profiles in the model are close to the temperatures of real structure. This makes the small-scale modelling methodology an economical way to guess the behaviour of real structures under fire condition.
- The comparison of critical temperatures of beams between small-scale and full-scale is quite good and promising. The relative difference is within 6%. This leads to that failure mechanism, failure time (fire resistance time for unprotected sections) and failure temperature can represent the prototype.
- A small-scale composite slab is designed with micro concrete and black annealed wire. However, the fabrication of wires is a complex process since they are so thin. Therefore, they need to be produced carefully to represent the similar behaviour with the full-scaled composite slab.

The scaling rules are applied to open sections herein this study. However, those mentioned rules can also be easily applied on the closed sections such as rectangular hollow sections (RHSs).

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