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STRUCTURAL FIRE DESIGN FOR STEEL FRAMED CARPARKS

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ABSTRACT

This paper presents a guide on a proposed performance based method for the structural fire design of steel framed carpark buildings. The current NZBC C/AS7 has stringent fire resistance rating requirements for structural elements of carparking buildings which would require the elements to be protected with passive fire protection. Using this proposed analytical method, it is possible to quantitatively demonstrate that the beams within a typical multi-bay steel framed carpark can be unprotected. The methodology involves the analysis of the capacities of composite steel beams under exposure to realistic vehicle fires. This approach removes the assumption of full compartment involvement that is assumed by other simpler methods. The localised thermal loading on parts of the structural beams, localised loss of strength of the beam and redistribution of actions to other beams are also included in the analysis. The method can also accommodate spread of fire from multiple cars and is flexible enough to accommodate different thermal loadings due to different types of vehicle fires.

INTRODUCTION

Overview

C/AS7 of the NZBC requires that carparking structures achieve a 60 minute FRR where sprinklers are not installed or a 30 minute FRR where sprinklers are installed within the building. For steel structures, a 30 or 60 minute FRR would typically require the structural framing elements to be protected with passive fire protection. This paper proposes an alternative method of assessment which can be applied to demonstrate a reduced fire resistance rating or no protection to steel beams in carparking structures, whilst satisfying the Performance Requirements of the NZBC. The proposed alternative method described here determines the capacity of steel beams within a carpark under exposure to realistic fires. The basis of the proposed methodology is from extensive research undertaken in Europe and Australia and is based on similar methodologies developed in Europe.

Scope of application

- The scope of application of the proposed method is limited to multi-storey steel framed carpark structures with structural steel beams supporting composite concrete floor systems. The beams are assumed to have composite action with the floor slab.
- The carpark structures (open or closed) are to be occupied for passenger vehicles cars, vans and utility vehicles. It is not intended to be used for car stackers, loading docks and parking structures for heavy goods vehicles.
- The scope of application for this method applies only for beams and bracing elements. The basis for this method is that fire damage to beams and braces are likely to be localised to a floor, or part of a floor, with less impact to other floors above. Steel braces can be unprotected if the building lateral stability can be shown not to be affected during fire exposure and after fire exposure.
- This method is currently not proposed to be applied to columns and requires that columns achieve the required Fire Resistance Rating either by passive fire protection, or if unprotected, by its inherent fire resistance. Beam connections are to be protected.

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- The method cannot be applied to cold formed structural elements.
- The method of calculation currently assumes that failure by lateral torsional buckling or webpost buckling of beams does not govern. In some types of structural systems, such as cellular beams, these failure modes may govern and hence may present a more onerous failure mode than can be predicted by this method.

FIRES IN CARPARKING BUILDINGS

Vehicle fires in carparking buildings primarily produce localised fires resulting in high temperatures in the close proximity area of the vehicle(s) on fire, but relatively temperatures further away from the fire. Based on statistics, full room involvement whereby all the vehicles in the carpark are burning simultaneously, is considered unlikely to occur. Joyeux et al (2001) provides a comprehensive summary of studies and statistics into vehicle fires in carparks which involved 327 fire fighter intervention reports in underground carparks, and 78 reports in above-ground car parks. Figure 1 summarizes the distribution of the categories of the reported car fires in underground carparks and open deck carparks, reported by Joyeux et al (2001).

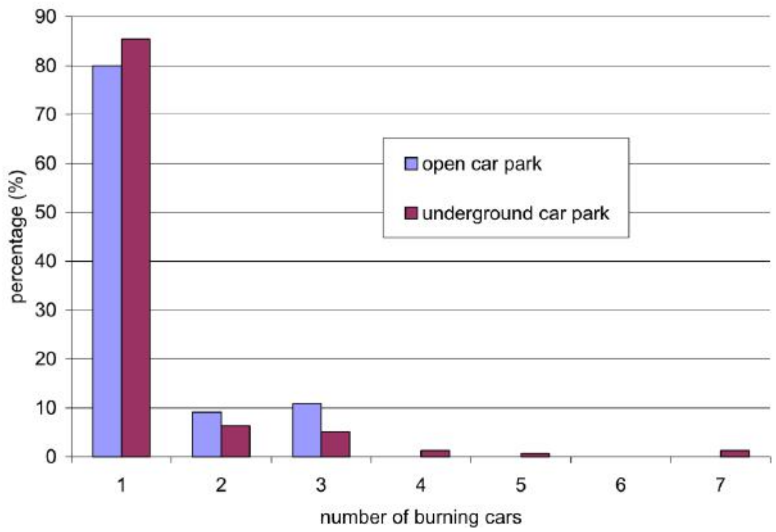

Figure 1: Distribution of numbers of vehicles involved in underground and open deck carpark fires

A report by Li et al (2004) stated that between 1995 and 2003, there were 93 incidents of vehicle fires in parking buildings in New Zealand of which 93 were single vehicle fires and three were multiple incident fires. The findings of this review were that fire can spread between vehicles especially in closed parking structures. All the fire tests reviewed in this study demonstrated the stability of the structure exposed to car fires. Tohir and Spearpoint (2014) have complied the likelihood of car fires in carparks, based on research by Joyeux et al (2001) and Li et al (2004), which is summarised in Table 1.

Table 1: Probability of car fire incidents (Tohir and Spearpoint (2014))

Number of vehicles involved	Number of incidents	Proportion of incidents	Cumulative proportion
1	344	0.858	0.858
2	27	0.067	0.925
3	21	0.052	0.977
4	4	0.010	0.987
5	3	0.007	0.994
6	0	0.000	0.994
7	2	0.005	0.999
> 7	0	0	0.999

In a US study by Denda (1993) of more than 400 parking garage fires, it was found that only 7% of the car fire incidents involved multiple vehicle fires, with fire mainly occurring between two adjacent vehicles, with one case involving three cars and another involving four cars. The study did not differentiate between sprinklered and unsprinklered carparking buildings.

Efficacy of sprinklers

Experimental tests undertaken by Bennetts et al (1997) have shown the efficacy of sprinklers in controlling car fires, which showed that with a functioning sprinkler system that operated automatically, there was no spread of fire from the originating car to adjacent cars. A statistical analysis of sprinkler protection records in Australia and New Zealand between 1886 and 1986 was undertaken by Marryatt (1988). With regards to car park facilities, the statistics indicate that 100% of 96 fires were controlled by the successful operation of the installed sprinkler systems.

METHODS OF REPRESENTING BURNOUT FIRES

To design for fire resistance of carparking buildings, C/VM2 (Clause 2.4) of the NZ Building Code permits three options for representing burnout design fires, which are:

A. Use a time equivalent formula to determine the equivalent fire severity (t_e) and to ensure that the Fire Resistance Rating (FRR) is equal to or greater than the $\geq t_e$.
B. Use a parametric time versus gas temperature formula to calculate the thermal boundary conditions (time/temperature) for input to a structural response model.
C. Construct a HRR versus time structural design fire as described in Paragraph 2.3.3 of C/VM2.

Methods A and B method assume that a compartment has reached flashover and assumes that the fuel load is uniformly distributed across the floor plate of the fire compartment. These methods do not consider the highly localised nature of the car fires which have high fire severity in the area of fire involvement, and low severities in the far-field region. Method C is considered the most appropriate for representing the thermal exposure of a carpark structure to a localised vehicle fire and therefore, the proposed method is based on the principles of C/VM2 Clause 2.4(c), by using a heat-release rate curve to represent an isolated fire.

PROPOSED METHODOLOGY

The proposed alternative method will consider the localised nature of vehicle fires in typical carparking buildings, followed by analysis of the structural capacities of the elements as a function of time of exposure during the fire. The steps of the proposed method are as follows:

Step 1: Definition of design fire

The design fire for carpark structures is proposed to be based on treating each vehicle fire as a localised fire which forms an axisymmetric fire plume.

- For a sprinklered carpark (open deck or enclosed carpark), a single Class 3 vehicle on fire is proposed as the design fire to determine its impact on the structure. The proposed design HRR-time is shown in Figure 2. The basis of this HRR curve is from calorimeter fire tests undertaken in Europe in the 1990's, based on a Class 3 car (Peugeot 406, Volkswagon Passat) which corresponds to a fuel load of about 9500MJ in the car (Joyeux et al, 2001). Compared with the data of reported vehicle fires in France and New Zealand, a single car fire has an 85 percent probability of occurrence. A single car fire is proposed based on studies by Bennetts et al (1987) which have shown that with a functioning sprinkler system, fire spread to other cars is mitigated.
- For an unsprinklered carpark (open deck or enclosed carpark): Three Class 3 vehicles or one utility vehicle on fire are proposed for the design fire. To consider multiple vehicle fires, the heat release rate of each vehicle is considered separately shown in Figure 3. The HRR curve for the first vehicle is identical to that of the one-car fire scenario. The growth in the HRR of the second and the third vehicles occur 12 minutes after the start of the first and second vehicles respectively. The HRR of the second and third vehicles are based on experimental data of fire tests (Cajot et al 1999).

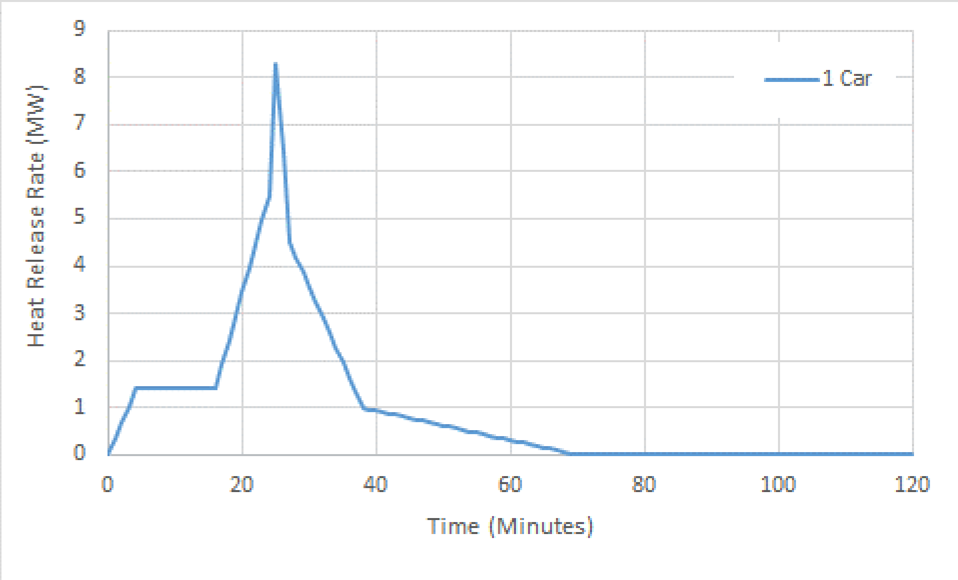

Figure 2: Design HRR curve for a single car fire – Sprinklered carpark

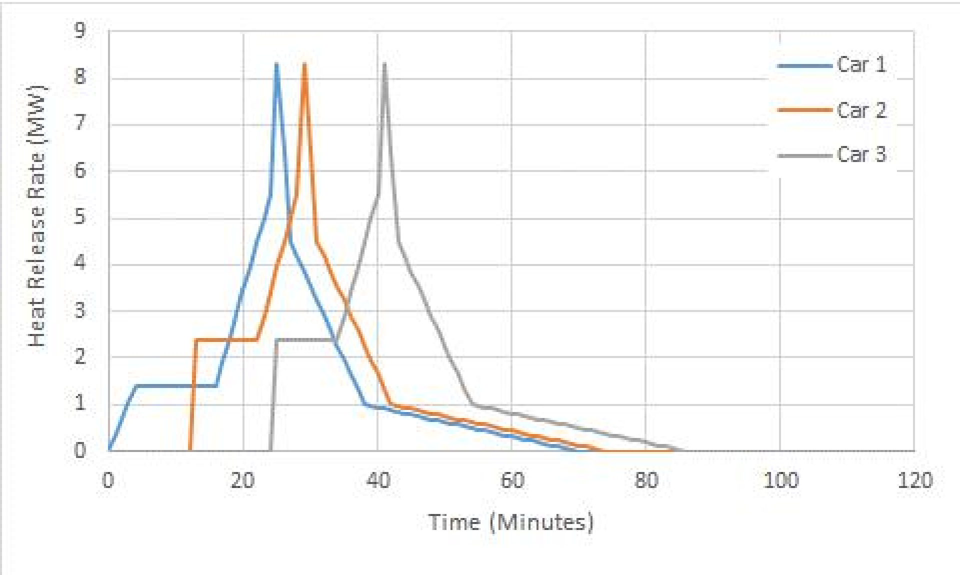

Figure 3: Separate HRR curves for three cars – Unsprinklered carpark

Step 2: Calculation of Plume and Beam Temperatures

The temperatures of the structure above can be calculated, depending on whether or not there is flame impingement on the structure above. Eurocode 1-2 (BSI 2009) provides equations for calculating the heat flux on the underside of a slab/beam, based on the Hasemi model. The equations consider the height of the ceiling above the fire, the heat release rate (HRR) and radial distance from the fire.

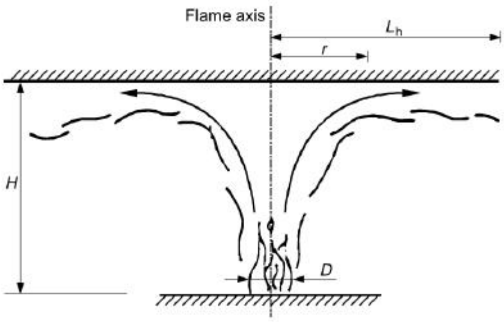

Figure 4: Localised fire – for flames which impinge on the slab /beam above

The heat flux, q” (kW), received at the underside of a beam/slab is:

$q'' = 100$ if $y \leq 0.30$
$q'' = 136.3 - 121y$ if $0.3 < y < 1.0$
$q'' = 15y^{-3.7}$ if $y \geq 1.0$

where:

$y = (r+H+z')/(L_H+H+z')$
$Q_H^* = Q/(1.11\times10^6.H^{2.5})$
$Q_D^* = Q/(1.11\times10^6.D^{2.5})$
L_H = horizontal flame length = $2.9H(Q_H^*)^{0.33}-H$
$z' = 2.4D(Q_D^{*2/5} - Q_D^{*2/3})$ for $Q^*_D < 1.00$
$z' = 2.4D(1.0 - Q_D^{*2/3})$ for $Q^*_D \geq 1.00$
Q = Heat release rate (W)
$H = H_a - H_s$ (m)
H_a = Height of lower flange of beam from the floor (m)
H_s = Height of fire source from the floor (m)

To consider the effect of multiple vehicles, the heat release rate of each vehicle will need to be determined and the heat flux for each vehicle (at different radial distances to the subject element) will need to be considered and added, as shown below:

$$q'' = q''_{car1}(r) + q''_{car2}(r) + q''_{car3}(r) + \ldots \qquad \text{Equation 1}$$

The net heat flux is calculated as follows:

$$h_{net} = q'' - \alpha_c (\theta_m - 20) - \Phi\varepsilon_m \varepsilon_f \sigma[(\theta_m+273)^4 - 293^4] \qquad \text{Equation 2}$$

The temperatures of the structural elements can be calculated using an iterative spreadsheet method, assuming a homogenous temperature across the steel section, shown by the following equation (BSI 2005):

$$\Delta\theta_{a,t} = k_{sh}(A_m/V)/(c_a.\rho_a)\, h_{net}\, \Delta t \qquad \text{Equation 3}$$

Where:

$\Delta\theta_{a,t}$ = Increase of temperature in an unprotected steel member during a time interval Δt
Δ_t = Time interval (recommended not greater than 60s)
k_{sh} = Shadow factor = $0.9\,[A_m/V]_b / [A_m/V]$
A_m/V = Section factor for unprotected steel member (1/m) (not to be less than $10m^{-1}$)
$[A_m/V]_b$ = Box value of the section factor
A_m = Surface area of member per unit length (m^2/m)
V = Volume of the member per unit length (m^3/m)
$c_{a=}$ = Specific heat of steel (m^3/m)
h_{net} = design value of the net heat flux per unit area (W/m^2)

Calculation of member capacity

The residual capacities (Moment, shear and/or axial) of the elements can be determined based on the calculated steel temperatures. The residual capacities of the elements (R_F) are compared with the fire limit state actions (U^*_{fire}) so that:

$$R_F \geq U^*_{fire}$$

- If the capacity (R_F) is greater than the action (U^*_{fire}), then the structural element is considered to be able to resist the fire limit state actions.
- If the capacity (R_F) is less than the action (U^*_{fire}), then the size and/or strength of the structural element would need to be increased. Alternatively, other load resisting mechanisms (load redistribution or two-way slab behaviour via tensile membrane action) would need to be considered.
- This method of comparison is based on the assumption of one-way action and does not consider other mechanisms such as two-way action (tensile membrane action) that can be expected in a real multi-bay steel framed carpark structure. Two-way action in the slab is not covered in this paper but can be covered by a more advanced analysis method, e.g.: finite element analysis.
- The proposed method assumes that composite action is provided between the beams and slab. The method does not allow for failure by lateral torsional buckling of the beams.

Locations of Design Checks

For composite beams in a carpark, the following checks should be carried out**Error! Reference source not found.**:

1. The bending and shear checks of the beams at the location of highest likely fuel loads. This is likely to be the carparking bays.
2. The bending capacity check of the beam at the location of highest bending moment (E.g.: midspan of the beam).
3. The residual shear strength of the beam at the location of highest shear force.

WORKED EXAMPLE

A worked example is shown below for based on a typical multi-storey carparking building in New Zealand. The carpark is sprinkler protected. The structure has a uniform grillage of beams with long span beams (17m) which span across the carparking spaces located on the two sides of the driveway. The beams are simply supported. The beams support a 150mm thick Comflor 80 composite steel-concrete slab. It is assumed that the columns will be protected. The inter-storey height is 3.0m. The details of the structural elements are as follows:

Section size	Depth (mm)	Flange width (mm)	Flange thickness (mm)	Web thickness (mm)
Secondary beams - 600WB190	600	350	25	12
Primary beams - 250UC72.9	260	256	17.3	10.5
Columns - 310UC158	327	311	25	15.7

Material properties

- Structural Steel: 300MPa
- Reinforcing: 9mm diameter at 200mm grid spacing - Grade 500 E Mesh
- Concrete compressive strength: 30MPa

Description of Fire Scenario

To demonstrate the method, a single car fire is considered, as shown below in Figure 5, which is a single car along the driveway directly beneath a beam. This is an unlikely scenario because the driveway is typically not occupied but it could be due to a vehicle fire on the driveway could be due to an accident. This location has the highest bending moment on the beam.

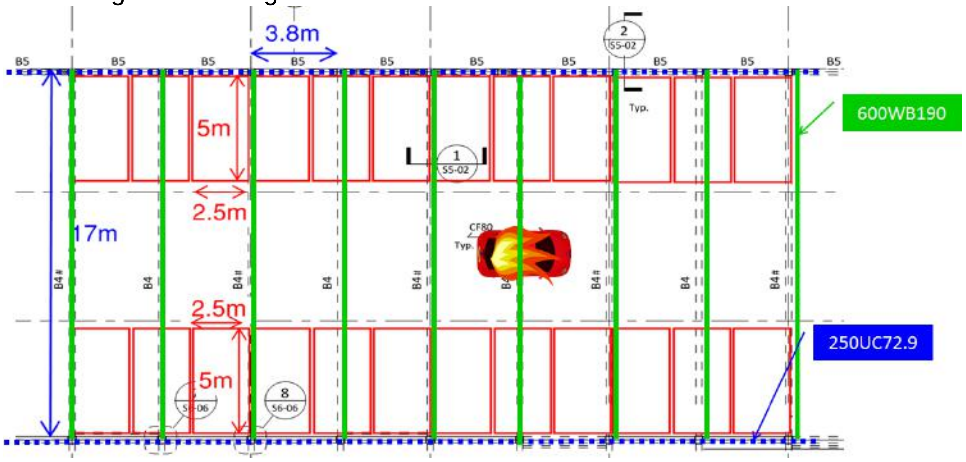

Figure 5: Design Fire Scenario

The design heat release rate for each of the single car fire scenario is shown in Figure 2. The radial distance of the beam (600WB190) from the fire, r, is zero. Solving Equation 2 by setting h_{net} = 0 and assuming a steady state condition the steel temperature is equal to the flame temperature ($\theta_m = \theta_F$), the flame temperature (θ_F) can be solved. Applying an incremental method of the analysis, the flame temperature impinging on the steel can solved for the whole fire duration and applied in a spreadsheet, shown in Figure

6.

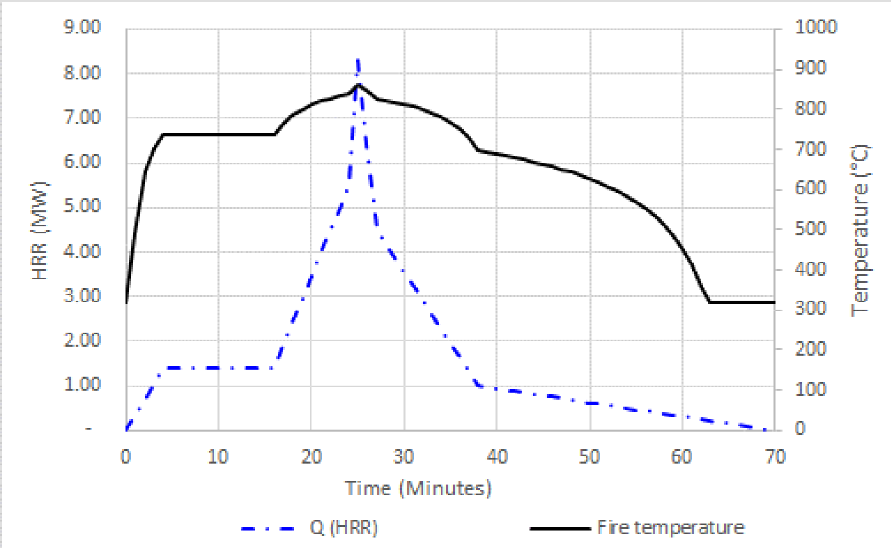

Figure 6: Calculated fire temperature above at the soffit of beam above the fire.

The temperature of the steel beams can be calculated iteratively using Equation 3. For the 600BW190 beam, the heat transfer calculation is undertaken for the top flange, bottom flange and web whereby the section factor for each element can be determined separately. The corresponding steel temperatures are shown in Figure 7.

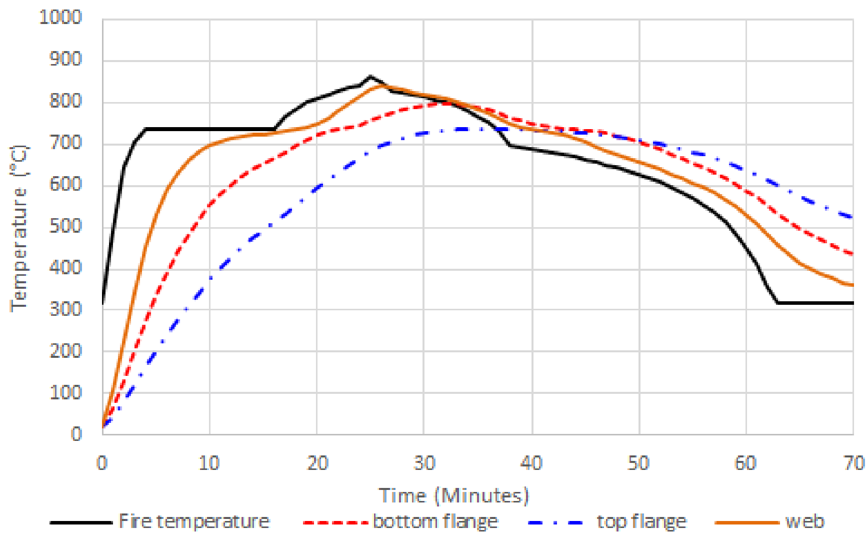

Figure 7: Calculated steel temperatures of beam located directly above the fire.

Structural Calculations

Using the temperatures calculated in Figure 7, the flexural capacity of the 600WB 190 beam can be calculated and compared with the applied bending moment.

Loading

Dead load, DL = Slab + metal deck + SDL = 2.54 + 0.15 + 0.5 = 3.19kPa
Live load, LL = 2.5 kPa
Fire limit state load = DL + 0.4 LL = 4.19kPa
Tributary width = 3.8m
W = UDL load + SW of beam = 4.19kPa x 3.8 m + 2kN/m = 17.9kN/m

The applied bending moment is calculated at midspan (8.5m from the end support of the beam) is calculated as:

$M^*_{fire, midspan} = W.x/2.(L-x) = 647kNm$

Where:
L = full length of beam = 17m
x = distance at point of interest from end support = 8.5m

The variation of the flexural capacity of the composite beam as a function of temperature is summarised in Figure 8**Error! Reference source not found.**, calculated based on Eurocode 4-1-2 (BSI 2005). The variation of the flexural capacity changes as a function of temperature, based on the material properties from Eurocode 3-1-2 (BSI 2005), shown below in Figure 9.

As shown in Figure 8**Error! Reference source not found.**, the flexural capacity of the beam exceeds the applied moment at approximately 22 minutes; a plastic hinge forms at the beam midspan at this time. This means that the beam would not be able to support the applied moments if the strength of the beam continues to decrease. However, it must be noted that the fire is localised. Therefore, the flexural capacity of the two adjacent beams on either side of the heated beam is considered for resisting the moments that cannot be resisted by the main heated beam. This is shown schematically in Figure 10, whereby the adjacent beams are marked in blue.

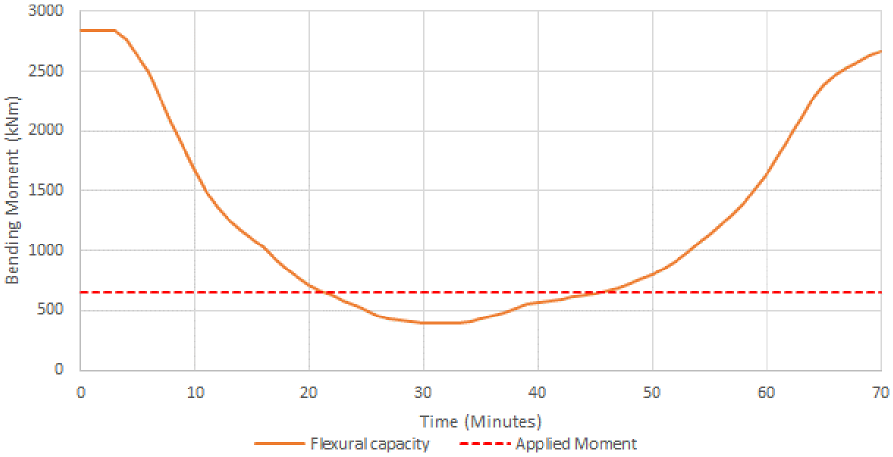

Figure 8: Comparison of flexural capacity and applied bending moment

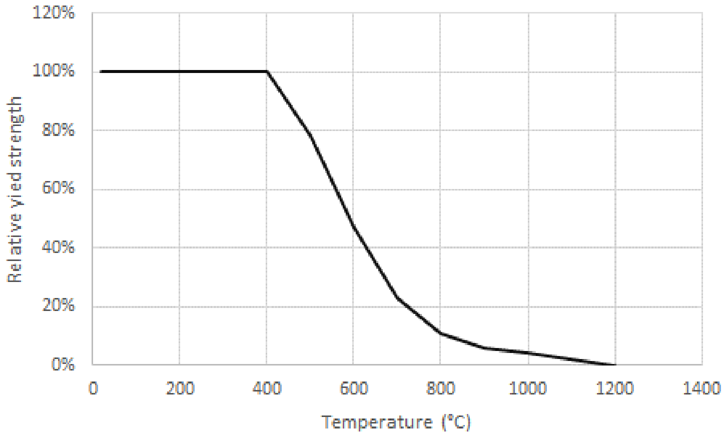

Figure 9: Yield strength of structural steel as a function of temperature (Eurocode 3, BSI (2005))

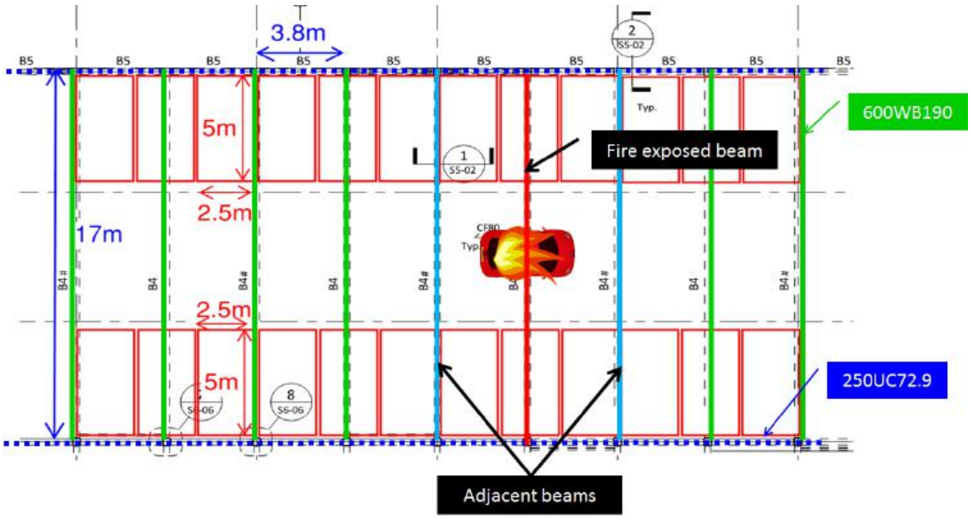

Figure 10: Location of adjacent beams relative to main fire-exposed beam.

The temperatures of the adjacent beams is checked using the same procedure as outlined previously but using R (radius) as 3.8m from the centreline of the fire plume. The calculated steel temperatures of the top flange, web and bottom flange of the adjacent beams located 3.8m from the plume centreline are shown in Figure 11.

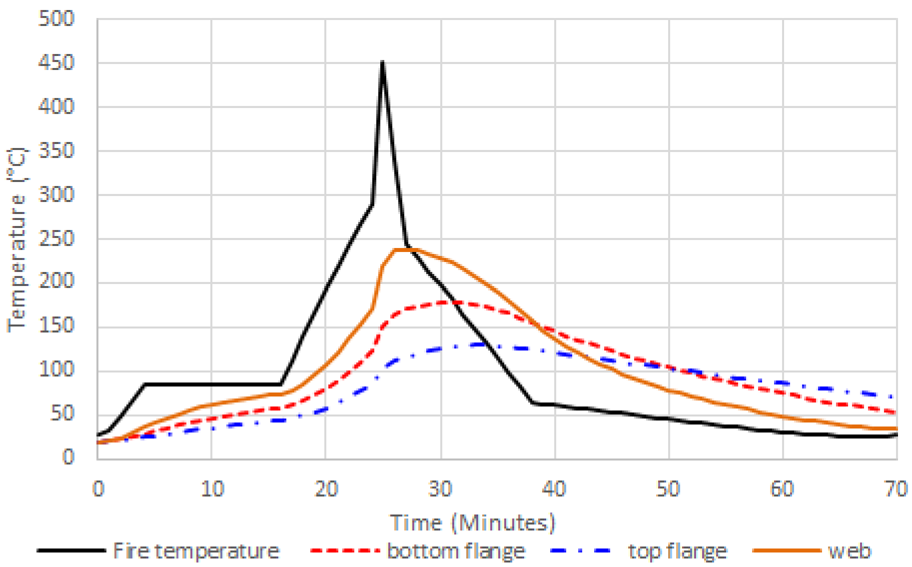

Figure 11: Calculated steel temperatures of beam located radially 3.8m from fire.

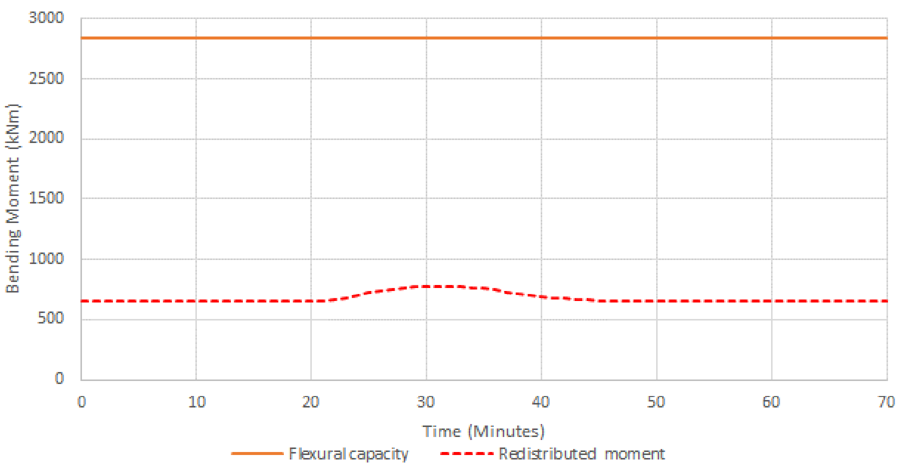

Figure 12: Comparison of flexural capacity and applied bending moment for each secondary beam located 3.8m from the fire location.

The calculated bending capacity of each of the adjacent beams is shown in Figure 12. The flexural capacity of the beam does not reduce with time. This is because the steel temperatures are relatively low (Under $250^{o}C$) and the yield strength of the steel has not reduced. As shown in Figure 12, the applied moment on each of the beams increase after 20 minutes due to the moments that are transferred from the beam above the fire that is directly heated above the fire. Therefore, the analysis shows that even if one of the beams forms a plastic hinge, the adjacent beams can resist the applied loads.

SUMMARY

This paper has proposed an alternative design method for assessing the fire resistance of steel beams under localised fires, for application in carparking buildings. The proposed method is dependent on the vehicle design fires, beam spacings and the distance of the fire source to the beams. The proposed method shows that due to the nature of vehicle fires in carparking buildings which only have a local impact onto the structural beams, it is shown that the beams can be unprotected on the basis that other beams that are located further from the fire source have sufficient residual strength to resist the applied loads when the actions can be redistributed. The proposed method can be applied with other types of modern and future vehicles such as hybrid and electric vehicles, when the HRR data is obtained.

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