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Fire load energy densities for risk-based design of car parking buildings

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ABSTRACT

The time-equivalence method is one way to determine the appropriate fire severity in buildings. One of the input parameters required is the fire load energy density (FLED) and in a deterministic design this is taken to be a fixed value. This paper illustrates the use of a simple Monte Carlo tool that accounts for statistical variations in car energy content as a function of vehicle size to determine probabilistic FLED values for a risk-based calculation approach to the design of car parking buildings. The paper briefly discusses FLED values for car parking buildings that can be found in the literature and results from the Monte Carlo tool suggest that 260 MJ/m^2 could be used as an appropriate design value in lieu of using a probabilistic approach.

Introduction

Background

Currently there is debate in New Zealand regarding the design of steel structure car parks and the use of the time-equivalence calculations to determine appropriate severity for these buildings. Equations for calculating time-equivalence can be found in the New Zealand verification method C/VM2 [1]. These are based on equations from the Eurocode [2], but with an expanded set of factors to allow for adequate consideration of the contributions of different room lining materials [3].

In order to calculate fire severity using a time-equivalence method one of the parameters needed is the fire load energy density (FLED) which is the sum of all the energy available for release when the combustible materials are burned, divided by the total floor area of the compartment. The available energy content can be distinguished into permanent, variable, protected and unprotected loads [4]. Typically an 80th percentile variable fire load is used as a design value when using data from fire load surveys [4,5]. For a car parking building the variable load is essentially the vehicles and the calculation of FLED incorporates any floor areas used for vehicle lanes and ramps, pedestrian walkways, etc.

Typically time-equivalence calculations are carried out deterministically with fixed values assigned for FLED, compartment geometry, ventilation conditions, lining materials and the structural material being used for the design. The process considers that the compartment is uniformly heated throughout the fire exposure and for a car park fire scenario this effectively assumes the building is densely populated with vehicles and that they are on fire simultaneously. However in a densely populated car park it is possible that the fire will travel from vehicle to vehicle rather than assuming all are burning

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simultaneously. Recent work on travelling fires by Stern-Gottfried et al. [6] has introduced a new methodology using travelling fires to produce more realistic fire scenarios in large, open-plan compartments for structural fire design. Stern-Gottfried et al. examined the impact of FLED on their estimation of the peak structural member temperature. Their results show that local concentrations of dense fuel loads produce long-duration fires and have a significant effect on structural resistance. Alternatively in a sparsely populated car park, fires could be localised, may involve only a small number of cars and, depending on the location of the fire, they could be detrimental to the structure. Thus advanced calculation methods for the design of car parking buildings investigate localised fires of different sizes at different locations in the building and their resulting building structural response [7].

In order to provide adequate fire resistance there needs to be a realistic assessment of the response of the structure as a whole as deformations in one part of the building need to be resisted by other parts. As discussed by Moss et al. [8] a statistical approach to fire behaviour could be used in fire safety and structural engineering applications instead of using a deterministic methodology. As part of a statistical approach to find appropriate fire resistance ratings for car parking buildings the structural fire severity assessment needs to incorporate the variable fire load. This requires an investigation on how the FLED can vary depending on the energy content of cars, the occupancy of car parks, the area of parking spaces etc. and this paper illustrates an approach to this subject.

Static efficiency of car parks

As well as the space for each vehicle, a car parking area will also include lanes, ramps, pedestrian walkways, etc. Every parking layout has its own advantages and disadvantages depending on the functional design of the parking building. The spaces within a parking layout can be angled with 90°, 60°, 45° or 30° being typical. Large capacity parking areas give a better efficiency than smaller capacity areas since there has to be proportionally less room for ramps and accessways.

Chrest et al. [9] has a set of recommended values for designing a parking area. The recommendation considers the classification of the vehicles and the level of service (LOS). LOS is method developed by traffic engineers to classify the degree of congestion of traffic where the higher the degree of congestion, the lower the LOS. The highest LOS is Category A, which is considered as free flow and no delay, while the lowest LOS is Category F which is popularly called ‘gridlock’. From the set of recommendations, the static efficiency of a parking area could be as low as 16 m^2/space for a LOS D category while it could be as high as 40 m^2/space for a LOS A category. Chrest et al. note that efficiencies as low as 16 m^2/space are car park designs for 100% ‘small’ cars.

Hill [10] suggests that a ‘good’ parking efficiency ranges from 20 m^2/space for 300 parking spaces at 90° up to 35 m^2/space for 30 spaces at 45° while Butcher et al. [11] cited parking areas per vehicle in the range of 18.5–26.8 m^2. A survey of open top floors of 41 New Zealand multi-storey car parking buildings using Google Earth found typical static efficiencies are 28.9 ± 5.1 m^2/space. Assuming the top floor is representative, then a lower 80th percentile design value for calculating FLED of 25 m^2/space appears to be reasonable for New Zealand car parking buildings. If anything it is possible that there could be slightly more spaces on an open top floor than lower floors since there are no columns, etc. to take up some of the footprint and so the static efficiency might be slightly higher on lower floors.

Available FLED values

Research as far back as the late 1960s by Butcher et al. [11] found that the wood equivalent fire load density for a car park could be taken to be 17 kg/m^2 using an area per vehicle of 18.5 m^2. Using a heat of combustion for wood as 17–20 MJ/kg [4] gives a FLED of 290–340 MJ/m^2. Alternatively Gewain [12] suggested that the wood equivalent fire load density for a car park would generally be below 9.75 kg/m^2, equivalent to 166–195 MJ/m^2. A survey of fire loads cited by Thomas [4] suggests an average variable fire load density ($\bar{F}$) of 190 MJ/m^2 with a standard deviation of 105 MJ/m^2 for ‘Garaging, maintenance and exploitation of vehicles’. The survey gave 80%, 90% and 95% fractile values of 270, 340 and 420 MJ/m^2, respectively for this category. Thomas [4] also quotes Swiss data which gives an average FLED of 200 MJ/m^2 for ‘Parking buildings’. Thomas suggests that 80%-fractile and 90%-fractile values for well-defined occupancies can be found from $(1.45–1.75) \times \bar{F}$ and $(1.65–2.0) \times \bar{F}$ respectively, giving 250–300 and 270–330 MJ/m^2. A more recent study on the design of a car parking building as part of the rebuild of L’Aquila, Italy [7] used a FLED value of 268 MJ/m^2.

Clearly there are a range of suggested values for the FLED of a car park that start around 166 MJ/m^2 and reach an upper value of 420 MJ/m^2. Many of the results are based on data that is now several decades old and it might be argued does not account for any changes in the energy content of modern vehicles and the layout of modern car parks.

In terms of design guidance Eurocode 1 [2] contains a table of recommended FLED values but not for car parking occupancies. C/VM2 on the other hand gives a value of 400 MJ/m^2 for regular car parking buildings and a value of 400 MJ/m^2 per tier of car storage for car stacking systems. The C/VM2 FLED value of 400 MJ/m^2 is comparable to the work by Collier [13] which suggested that a FLED of 400 MJ/m^2 was reasonable. Collier’s value was obtained by using an upper value of 12,000 MJ for the energy content of a car from the range of values cited by Schleich et al. [14] and using a typical parking space area of 29 m^2/space as used by Li and Spearpoint [15] to give 414 MJ/m^2, comparable to the 95% fractile value given by Thomas [4]. Prior to the introduction of C/VM2 the earlier New Zealand compliance document for fire design (C/AS1 [5]) specified that the FLED for car parks are considered to be in the range 0–500 MJ/m^2 and consequently had a design value of $0.8 \times 500 = 400$ MJ/m^2.

Analysis

Monte Carlo modelling

Recent work by Tohir and Spearpoint [16] has investigated a probabilistic approach to examine how spaces in a car park might be populated. A relatively simple model has been developed that allows a specified number of parking spaces configured into a continuous double row be populated by a specified number of vehicles. The model allows for the possibility that vehicles might be preferentially parked at one end of the row. The model also allows the probability of each vehicle to correspond to a set of statistics such as size and energy content. By using the Monte Carlo capabilities of the model it is possible to generate distributions of FLED based on the input distributions.

Total energy content

Tohir and Spearpoint [17] completed a comprehensive survey of full-scale car fire experiments. This work uses the curb weight classification system given by ANSI [18] to categorise the vehicles and obtain values for the total energy released (Table 1). The ANSI classification system separately considers vans/MPVs and SUVs. However in this work these vehicles are integrated into the corresponding Passenger car classes by using the specified vehicle weight.

Where sufficient data was available a Weibull distribution with parameters as shown in Table 1 have been assigned to the total energy content values to each classification. However, since Tohir and Spearpoint only found a single applicable dataset for Passenger car: Heavy, the distribution parameters for this classification are extrapolated from the distribution parameters for the lighter weight classes. The extrapolation uses the increasing trend in the mean of the total energy released as the curb weight class increases.

The previous work by Schleich et al. [14] proposed values for the total energy release for five different European car classifications and these were incorporated into the work by Joyeux et al. [19]. Other work by Shintani et al. [20] gives a trend line based on their experiments. Tohir and Spearpoint showed a close agreement with Shintani et al. whereas this is not the case with Schleich et al. (Fig. 1). It is clear that heavier vehicles have a greater total energy content than lighter vehicles.

Anderson and Bell [21] note that specific models of cars have increased in curb weight with one example of a 26% increase in weight between the equivalent 1985 and 2012 models. Tohir and Spearpoint [17] also investigated whether the energy content of vehicles has increased in newer vehicles however the analysis was inconclusive based on the available experimental data.

Vehicle fleet characteristics

Given that the total energy content can be related to vehicle curb weight it is then appropriate to investigate the proportion of curb weights within a vehicle fleet. Using data from the European Union, Tohir and Spearpoint [17] obtained a distribution of vehicle population curb weights shown in Fig. 2.

In addition a survey of almost 5000 vehicles in New Zealand by Anderson and Bell [21] is also shown in Fig. 2. Similar to the total energy content analysis, vans/MPVs and SUVs are included in the appropriate vehicle classification by using their known weight rather than by identifying them as separate categories.

As well as assessing the distribution of curb weights, it is useful to examine likely occupancy proportion of a car parking building. Anderson and Bell [21] carried out a survey of parking space occupancy in a New Zealand shopping mall covered car park over a two week period including weekdays and weekends. They found that the highest occupancy level was around 99% during the middle of the day and then values reduced during the morning and afternoon (Fig. 3). Their results found that on average the parking building was 90% occupied during the peak period although their study did not distinguish between weekdays and weekends which may have shown different trends.

A separate analysis of a 24 h car parking building in San Francisco that services nearby shops and offices [16] found a maximum occupancy value of 75% at around midday on a weekday, 55% at around 3 pm on the weekend and again the occupancy reduced other times. The results from the two surveys suggest that the expectation that a car park would be 100% full throughout its daily operation is unlikely and this variable could be included in a probabilistic analysis particularly if the time of day at which ignition occurs was being assessed. However from a general design perspective assuming a car park is 100% full is likely to be reasonable and for example this was the approach taken by Nigro et al. [7].

Probabilistic analysis of FLED

By assuming that all parking spaces are full, that each space contains a vehicle with the highest expected total energy content, where in Table 1 this value is 8000 MJ, and using the LOS range A–D then FLED values from 200 to 500 MJ/m^2 are obtained. This range of FLED values brackets the 400 MJ/m^2 given by Collier and C/VM2 even though the total energy

Table 1
Mean and standard deviation fire severity characteristics by curb weight classification, adapted from Tohir and Spearpoint [17].

Vehicle classification	Curb weight	Total energy released (MJ)				Distribution parameters	
		Mean	Standard deviation	Max. value	Min. value	α	β
Passenger car: Mini	1500–1999 lbs (680–906 kg)	2909	945	4090	1500	4.02	3222
Passenger car: Light	2000–2499 lbs (907–1134 kg)	4471	1677	8000	3000	2.93	5009
Passenger car: Compact	2500–2999 lbs (1135–1360 kg)	5288	692	6670	4860	7.49	5591
Passenger car: Medium	3000–3499 lbs (1361–1587 kg)	6386	695	7000	5960	14.53	6648
Passenger car: Heavy	⩾3500 lbs (⩾1588 kg)	7648	n/a	n/a	n/a	16.27*	7830*

n/a, insufficient data.
* Assumed values from the extrapolation of lighter weight classes.

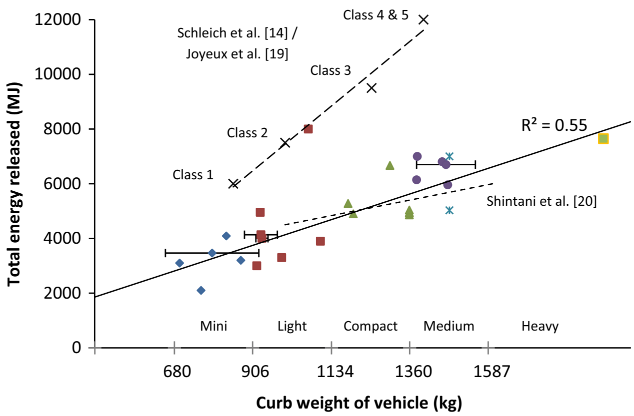

Fig. 1. The total energy released against curb weight of vehicles and associated classifications. (Solid symbols correspond to ANSI vehicle curb weight classifications; * symbol for ANSI MPV classification; and × symbol for Joyeux's European car classification, 1–5, adapted from Tohir and Spearpoint [17]).

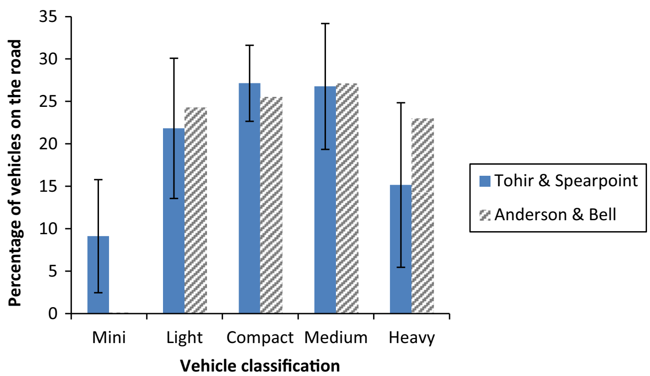

Fig. 2. Distribution of vehicle population curb weights, standard deviation indicated for Tohir and Spearpoint [17] values.

content used here is less than 12000 MJ used in Collier's previous work and also covers many of the values previously identified in the literature. However from a risk-based perspective it is unlikely that every available parking space would be populated by a car that would give the highest expected energy content. Therefore in this study distributions of FLED values are generated by using the measured energy content distribution of cars for each curb weight classification paired with vehicle curb weight population data, and specified values for the occupancy and number of parking spaces. For each analysis, using the Tohir and Spearpoint data for the distribution of vehicle population curb weights, 1000 iterations are applied for the distribution sample size and the results are shown in Fig. 4. An analysis using different static efficiencies is carried out to examine the resultant change in FLED values using the maximum limits for the static efficiency quoted by Chrest et al. [9]. From the analysis, at 16 m^2/space the FLED is 392 MJ/m^2 with a standard deviation of ±13.0 MJ/m^2. As the static efficiency is increased then the FLED decreases approximately linearly, as expected, so that at 29 m^2/space the FLED is 216 MJ/m^2 similar to Thomas [4] and at 40 m^2/space the FLED is 157 MJ/m^2 with standard deviations of ±6.8 and ±5.0 MJ/m^2, respectively. Thus the median FLED ($\tilde{F}$) can be estimated for a given static efficiency (SE) as $\tilde{F} = -9.9 \times SE + 536$ (MJ/m^2).

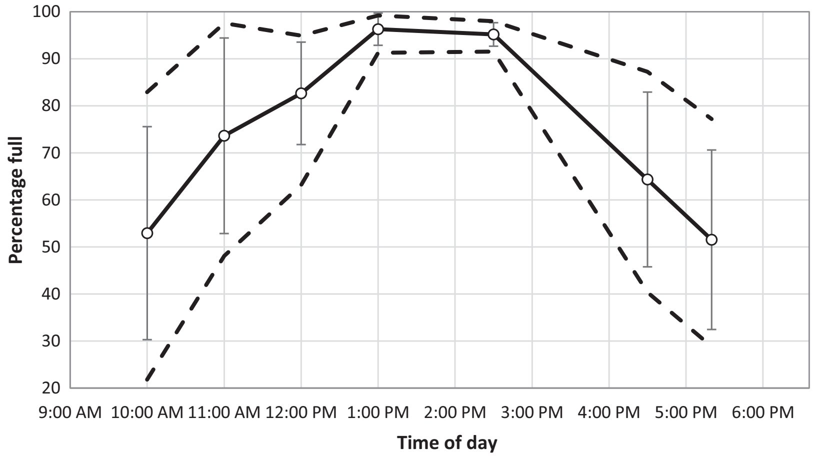

Fig. 3. Occupancy of car parking spaces, adapted from Anderson and Bell [21]. (Mean values with standard deviation shown; maximum and minimum recorded values shown by dashed lines).

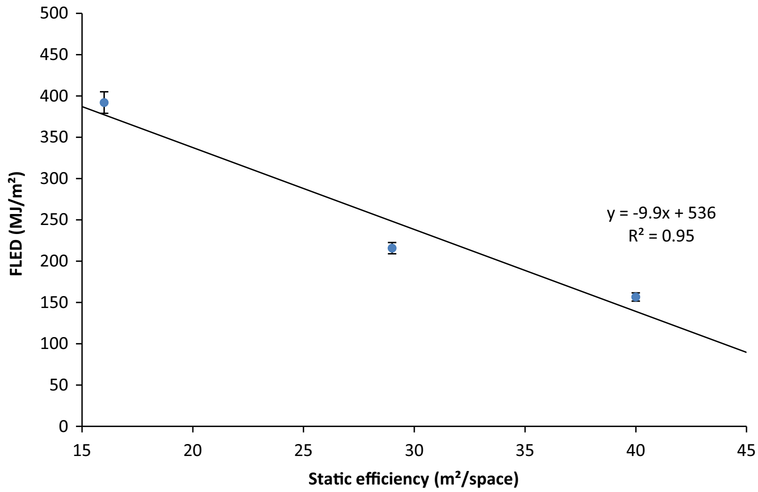

Fig. 4. Probabilistic model variation of FLED with static efficiency.

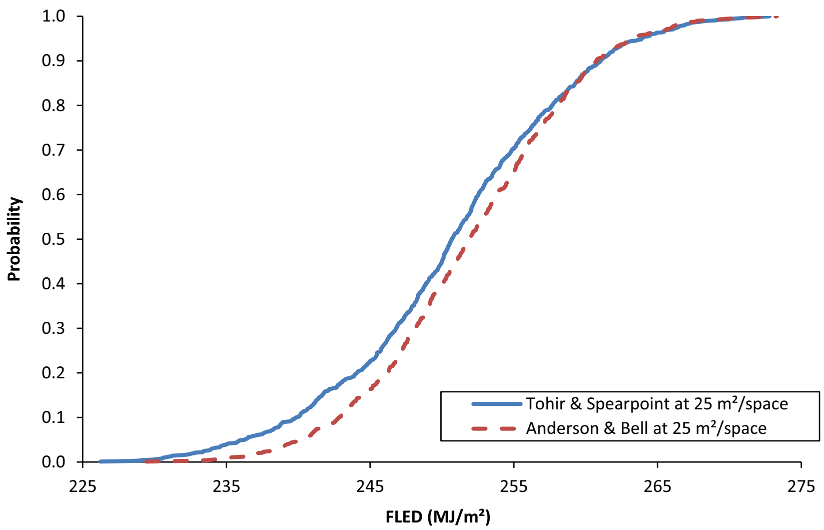

Fig. 5. FLED cumulative probability density curves for the Tohir and Spearpoint [17] and Anderson and Bell [21] vehicle curb weight distributions.

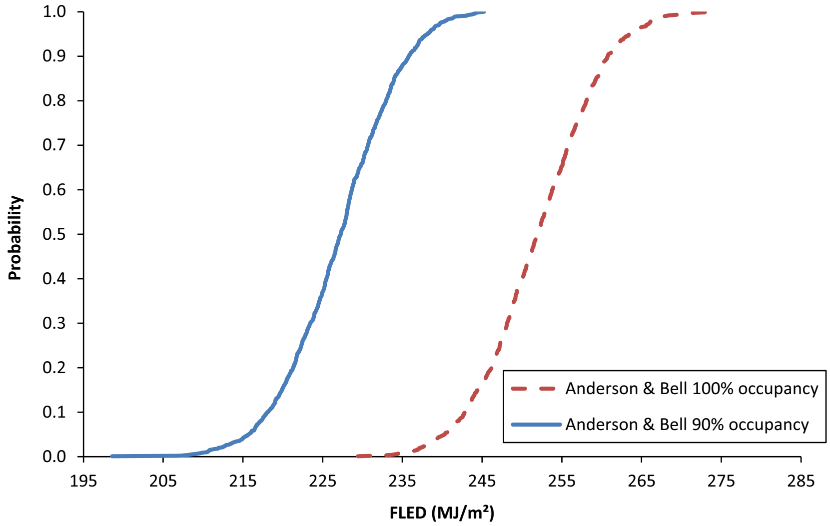

Fig. 6. FLED cumulative probability density curves for 100% and 90% occupancy and the Anderson and Bell [21] vehicle curb weight distributions.

It is useful to investigate how the FLED varies with the distribution of vehicle population curb weights obtained by Anderson and Bell [21] using the suggested static efficiency for New Zealand parking buildings of 25 m^2/space. Fig. 5 shows that the median FLED increases from 251 MJ/m^2 with the Tohir and Spearpoint data to 252 MJ/m^2 when the Anderson and Bell data is applied. At a 100% occupancy for the Anderson and Bell data, the 80%, 90% and 95% fractile FLED values are 258, 261 and 263 MJ/m^2, respectively. The fractile bands that result from the probabilistic model are less than those given by Thomas [4] even though the median values are similar. As such this study suggests that the ratio of the median FLED to the 80%, 90% and 95% fractile values are 1.024, 1.036 and 1.047, respectively. Thus to determine a specified percentile FLED (F_p) for a given static efficiency (p) then $F_p = f \times \tilde{F}$ (MJ/m^2) where f is the appropriate fractile value given above.

Finally Fig. 6 shows the effect of reducing the parking occupancy from 100% to 90% for the Anderson and Bell distribution of vehicle population curb weights at 25 m^2/space static efficiency. As expected the median value proportionally reduces from 252 MJ/m^2 at 100% occupancy down to 227 MJ/m^2 at 90% occupancy. Similarly at a 90% occupancy the 80%, 90% and 95% fractile FLED values are 233, 236 and 238 MJ/m^2.

Conclusions

The paper demonstrates how a probabilistic approach to obtaining FLED values can be applied by bringing together a number of recent studies related to car parking buildings. The application of the Monte Carlo model allows for a future reassessment of FLED values for car parking buildings should there be new energy content measurements for cars or changes in the composition of a vehicle fleet. The approach could also be modified to account for the occupancy of car parking spaces as a function of the time of day.

Since the change in FLED from the Monte Carlo tool is directly related to the static efficiency then deciding what is an appropriate value becomes important. However the linear relationship from the probabilistic model means results can be easily applied to any static efficiency that is deemed suitable. In addition the ratio of the median FLED to the 80%, 90% and 95% fractile values allows fractile values to be estimated for a given static efficiency. Therefore a simple calculation method is presented in the paper to estimate the median FLED and associated percentile values for a given static efficiency in lieu of performing a Monte Carlo analysis. Using a static efficiency of 25 m^2/space, a 100% parking space occupancy, the distribution of curb weights obtained by Anderson and Bell [21] and the vehicle energy content distributions from Tohir and Spearpoint [17], the 80% fractile FLED is 260 MJ/m^2 (rounded up to the nearest 10 MJ/m^2).

It is interesting to compare the FLED values from the Monte Carlo model to values quoted in the literature given this work has used energy content values from vehicles subsequent to the 1980s and also adjusts for the apparent higher percentage of heavier vehicles in modern fleets. Thomas [4] gives an average FLED value for 'Garaging, maintenance and exploitation of vehicles' as 190 MJ/m^2 and 200 MJ/m^2 for 'Parking buildings' which are of the order of 20% less than median values obtained in this study. However the method proposed by Thomas to obtain 80% fractile values means values of 270 MJ/m^2 for 'Garaging, maintenance and exploitation of vehicles' and 250–300 MJ/m^2 for 'Parking buildings' are comparable with the 260 MJ/m^2 value suggested in this study.

Using a time-equivalence calculation for the structural fire design of car parking buildings may not always be the only approach that should be considered and the effects of travelling fires and/or severe localised fire in the vicinity of structural elements may also need to be investigated.

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