Comparison of existing time-equivalence methods and the minimum load capacity method

Philip Xie, Anthony Abu, and Michael Spearpoint

Abstract

A fire resistance rating (FRR) is the minimum required ability of a building element to resist a fire. It is quantified as the time for which the element survives the exposure to the standard fire. One way of determining FRR is the time-equivalence (TE) approach which relates the destructive potential of a post-flashover fire to an equivalent duration under standard fire exposure. Many existing TE approaches use empirical correlations which account for fuel load, ventilation conditions, compartment size, lining materials and structural materials. Whilst they ease the determination of FRR, many parameters also affecting the structural failure are not explicitly considered such as load ratio, member size and reinforcement size in reinforced concrete (RC) members. A change in any of these will alter the survival duration of a member, however it is not reflected in the existing empirical correlations.

Increased understanding of fire behavior and structural response has made it possible to better analyze the behavior of structures at elevated temperatures and determine the minimum fire resistance using fundamental approaches. As part of a new research to redevelop TE methods in New Zealand, this paper presents an analytical comparison of selected TE methods and the minimum load capacity method. A close inspection of the sensitivities of varying ventilation, glazing fallout, load ratio, member size and reinforcement size in RC members to the prediction of FRR has been undertaken. The paper identifies limitations in the current New Zealand verification method and provides recommendations for improvement of the TE approach.

Keywords

Fire resistance rating • FRR • time-equivalence • C/VM2 • minimum load capacity

1 Introduction

To protect buildings in the event of fires their elements are provided with fire resistance which must be greater than the expected fire severity - the destructive potential of compartment fires [1]. The assigned fire resistance of building elements is usually expressed as fire resistance rating (FRR), which is the minimum required fire resistance of elements as determined in the standard fire test, to meet certain criteria including stability, integrity and insulation [2]. Accurate estimates of structural fire severity require thermal and structural failure analyses to determine the minimum requirements. This process is tedious for the day-to-day engineer; as such, simpler approaches are desirable. One common way of assessing fire severity is through time-equivalence (TE), which relates the fire severity of a post-flashover compartment fire to an equivalent duration (T_e) under the standard fire. This equivalent duration becomes the basis for selecting the FRR to ensure structural fire safety. As such it is important that the prediction of T_e is appropriately conservative.

In a recent re-structure of the fire design framework in New Zealand [3], the TE approach has been identified as one of three means of assessing the fire severity of post-flashover fires in a performance-based design approach [4]. The method, as adopted by New Zealand (C/VM2 method), is an empirical correlation based on the Eurocode TE method but is modified with a different set of lining factors [5], as recommended by Kirby et al. [6]. Through experimental investigations of a range of large scale compartment

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fires Kirby et al. found that the lining factors suggested by Eurocode 1 Part 1.2 [7] were not conservative, and recommended the use of an expanded set. To date, the C/VM2 method is the most current maximum-temperature based time TE method. It estimates T_e by simply multiplying factors that account for fuel load, ventilation conditions, compartment linings and structural material.

The other alternatives in the New Zealand design approach are the use of parametric time-temperature relationships, or heat release rate versus time curves. As these alternatives require significant time in creating the fires and structure thermal models, in order to assess fire severity, the TE approach is seen by many as the easiest option to determine FRR. Whilst the C/VM2 method provides an easy way of deriving FRR, the underlying simplification leads to unreliable results. Like other maximum-temperature based methods, the C/VM2 method is based on a single critical temperature. However critical (failure) temperatures are related to member load ratio and support conditions, which might not be the same as the one assumed in the C/VM2 method. In addition, for materials that develop non-homogenous temperatures within their cross-sections, a single uniform critical temperature is not realistic.

A more fundamental approach for determining T_e, called the minimum load capacity (MLC) method which considers failure of structural elements is used in this paper for comparison. As structural failure in fire can occur at different material temperatures, depending on the configuration of the element, the use of the MLC approach for comparison helps to identify the deficiencies in the C/VM2 approach for further improvement. A close examination of the impact of varying ventilation conditions (including glazing fallout ratio), member size, load ratio and reinforcement size in reinforced concrete (RC) members on the prediction of T_e is undertaken. This research also compares the MLC with other maximum-temperature based methods and energy methods. Recommendations for improvements of the C/VM2 method are then made.

2 Time equivalence methods

In 1920s Ingberg [8] attempted to relate measured compartment fire temperatures and duration to an equivalent exposure to the standard fire. FRR was calculated by comparing the areas under the time-temperature curves of a standard fire and a compartment fire above a defined base temperature. His approach provided guidance for building code requirements and a design method for fire resistive construction to contain fire spread in buildings. However, Robertson and Gross [9] identified that fire severity would be largely affected by ventilation conditions which was not considered in Ingberg's method. As a result, that method was abandoned.

In 1970s Law [10] developed a different concept to determine the equivalent fire severity, which marked the birth of the maximum temperature concept. It defines the equivalent fire severity as the time of exposure to the standard fire that would result in the same maximum temperature in a protected steel member as would occur in a complete burnout of a fire compartment. Law also developed an empirical correlation to ease the determination of FRR which was a function of the fire load, the internal areas of the compartment and the ventilation area. The derivation was based on a range of fire experiments in small compartments with areas of 2-16 m^2 and a height of 1.5 m conducted by the Conseil International du Batiment (CIB) [10]. Law's work was then modified by Pettersson [11] and Thomas [12]. The latest versions of the maximum temperature methods, the Eurocode TE method and the C/VM2 method, account for a range of factors including the fuel load, the size of the compartment, the ventilation conditions, the type of linings and the type of structural material (i.e. protected steel, unprotected steel, concrete, or timber), and are in the form of a single equation. Although these two methods are quick to use, the actual mechanical response of structural members at elevated temperatures is not considered. Any change in structural properties would affect the failure time. As structural fire severity should relate to structural failure it is necessary to investigate time-equivalence with a comparative study using more fundamental approaches to help quantify the deficiencies of the C/VM2 method and explore options to improve predictions of FRR in an increasingly performance-based design environment.

In addition to the temperature-based approaches described above energy based methods have also been developed. These approaches focus on comparing the thermal energy released by a compartment fire and by the standard fire. In 1970s Hamarthy and Mehaffey [13] developed the concept of "normalized heat load" for quantifying the total heat penetrating compartment interior linings. They also provided a simplified empirical correlation to determine T_e for RC members. In late 2000s Nyman et al. [14] developed the "cumulative radiant energy" (CRE) method to determine T_e by comparing the radiative heat absorbed by plasterboard linings of a compartment. However their research focused only on the integrity and insulation failure of unloaded drywall systems - structural resistance was not considered. Kodur et al. [15] also developed a TE method based on energy balance for RC beams by accounting for both radiative and conventional heat transfer. Although these methods are material specific, they are included in comparisons in this paper to explore their applicability for alternative scenarios.

2.1 Minimum load capacity method

In order to assess the failure of a structure at elevated temperatures, two calculation models need to be considered. Eurocode 3 Part 1.2 [16] refers to these as “thermal response model” and “mechanical response model”. The thermal response model estimates the distribution of temperatures within the structural member, while the mechanical response model determines the behavior of the structural member by accounting for temperature dependent properties of materials and the effects of the adjacent joining structure.

During the heat cycle of a compartment fire, the load carrying capacity of a member decreases as the member temperature increases and reaches a minimum value before it starts to recover. The minimum load capacity (MLC) method derives T_e by comparing the minimum load capacity of a structural member attained under a compartment fire exposure to the load capacity attained by the same member exposed to the standard fire. As it accounts for both thermal and mechanical response, the MLC method produces more fundamental outcomes. Estimating structural failure is more representative of predicting fire severity than examining only the maximum temperature of a structural member. Therefore, the MLC method is compared against the existing TE methods to ascertain their accuracy and identify areas for improvement.

2.2 Investigated parameters

This study provides a general comparison of existing TE methods and the MLC method. As identified by Abu et al. [17], general design practice calculates T_e assuming 100% glazing fallout as the worst case scenario. However the true vent area is a fraction of the total glazing area plus any other permanent openings [18]. Lower glazing fallout ratios result in longer fires which would do more damage to massive or heavily protected structures. The current design assumption thus generates unreliable solutions. In order to quantify this uncertainty, the impact of varying glazing fallout ratios on the prediction of T_e has been selected as the first parameter under investigation of this research.

Given that the MLC method fundamentally assesses structural behavior at elevated temperatures, a number of parameters previously overlooked in existing TE methods, but are accounted for in the MLC method are investigated. They are member size, load ratio and reinforcement size in RC members.

Member size affects the behavior of a structure at fire conditions in many ways including its temperature evolution and residual strength. As such it affects both the thermal response and mechanical response of the structure.

Load ratio is defined as ratio of the applied loading at fire conditions to the capacity of a member at ambient conditions. The higher the load ratio, the quicker the member fails and vice versa.

Current tabulated data approach for fire design of RC beams in most modern codes (such as Eurocode 2 Part 1.2 [19]) only requires the beam width and the cover distance to be specified. However the strength of an RC member is also dependent on the amount of reinforcement in the member. This paper investigates the fire performance of two RC beams of identical beam width and cover distance but with different reinforcement size.

3 Analytical comparisons

The first step of the study is to generate a number of different compartment fire scenarios, by varying properties of the compartment, the ventilation, fuel load and lining materials, as shown in Table 1. The parameters are based on a survey of New Zealand. Two compartment sizes of 300 m^2 and 500 m^2 were chosen to represent an open plan office floor area in New Zealand. The 500 m^2 area is to allow the analyses to be performed with the Eurocode parametric fire equations [7].

Table 1 Parameters for compartment fire scenarios

Parameter	Value	Unit
Compartment floor area	300, 500	m^2
Compartment height	3.5	m
Vertical vent ratio (α_V)	2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5%, 20%, 22.5%, 25%	m^2 /m^2
Fire load energy density	250, 500, 750, 1000, 1250, 1500	MJ/m^2
Lining absorptivity	815.7	J/m^{2}s$^{1/2}$K

A floor height of 3.5 m is typical of office buildings in New Zealand. Ventilation is represented by the ratio of total vertical opening area to the floor area (α_V). The C/VM2 method has limits on the vertical vent ratio (α_V within 2.5% to 25%). The study evenly divides this range into nine intervals so that the ventilation conditions examined represent the overall spectrum of possible ventilation conditions allowed in the method. The fire load energy density is the total fuel load of the compartment divided by floor area of the compartment. The chosen values of fire load energy density are from 250 to 1500 MJ/m^2 which represents the normal range of design values in New Zealand for accommodation, office and retail type occupancies. The interiors of the compartments are assumed to be a combination of plasterboards and concrete floor and a lining absorptivity of 815.7 J/m^{2}s$^{1/2}$K is selected. A total of 120 compartment fire scenarios are generated from the selected range of parameters.

For each fire scenario, the existing methods predict a specific T_e value by using simple calculations. The MLC method on the other hand involves the construction of a compartment fire curve, heat transfer analysis and structural capacity analysis. The Eurocode parametric fire curves are used to represent the compartment fire curve. For steel members, the heat transfer analysis is performed in accordance with the steel temperature evolution equations described in Eurocode 3 Part 1.2. For concrete members, the heat transfer analysis cannot simply be done by a hand calculation due to the presence of temperature gradients across member cross-sections. A computer program FPRCBC-T [20] is used to perform the two-dimensional non-linear thermal analysis to predict the temperature histories of member cross-sections. Due to the significant simulation time required for the RC members, only 12 fire scenarios are investigated. The time-temperature histories of the structural members are then imported into a spreadsheet which calculates the temperature dependent load capacity of the member.

3.1 Structural members

Three different types of structural materials are investigated in the comparisons: protected steel, unprotected steel and RC. These three types are the most common types in New Zealand. Timber construction is not considered in this paper as there is insufficient data on predicting charring behavior in the decay phase of real fires.

The temperature evolution in a steel member is related to its section factor (H_p/A). Section factor is a measure of the ratio of the heated perimeter to the area of the cross section of the member. A DD9999 Task Group [21] conducted a time-equivalence study on the fire severity of steel members which used a triangular distribution set of section factors between 70 and 220 m^{-1}. A median value of 145 m^{-1} was found to have the highest frequency in the distribution. For this reason, a UK UB305×127×48 steel beam member with a section factor of 143 m^{-1} is chosen for the comparisons of both protected and unprotected steel beams in this paper. As columns have smaller section factors as compared to beams, a UK UC203×203×71 steel column with a section factor of 93 m^{-1} is selected for the analyses. For the RC construction, two beams of rectangular cross section (400×600 mm^2) are chosen with details shown in Fig. 1. The cross-sections are based on an RC beam example used by Kodur et al. to describe their energy based TE method. It is assumed that the two beams are made of concrete with a compressive strength of 40 MPa and reinforced with rebars having yield strength of 400 MPa. One beam is reinforced with six tensile rebars while the other one is reinforced with two tensile rebars. Both beams have the same number and size of compression reinforcement. It is also assumed that all the members used in the comparisons are isolated, simply supported members and are not affected by the adjacent structure of the compartment.

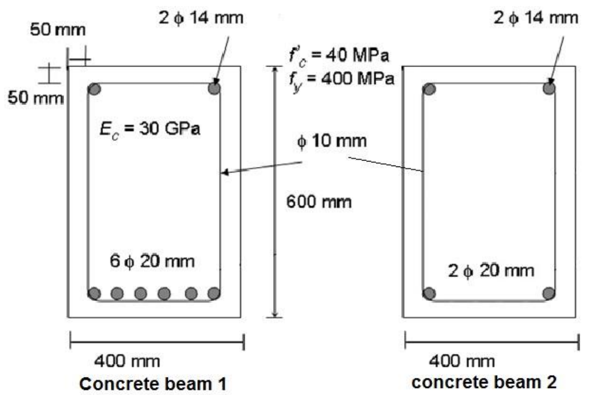

Fig. 1 Concrete beam cross-sections.

4 Results

Comparisons for protected steel and concrete members are shown in Figs. 2-4. Only results falling within four hours are presented here to correspond to the limits in C/VM2 method.

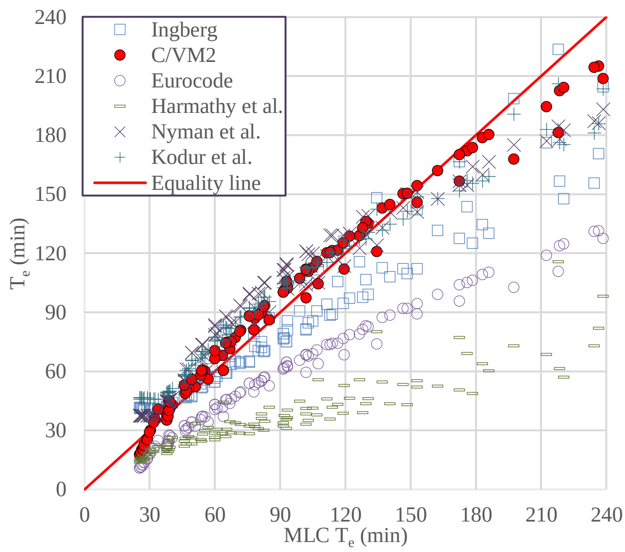

Fig. 2 Comparisons for the protected steel beam UB305×127×48.

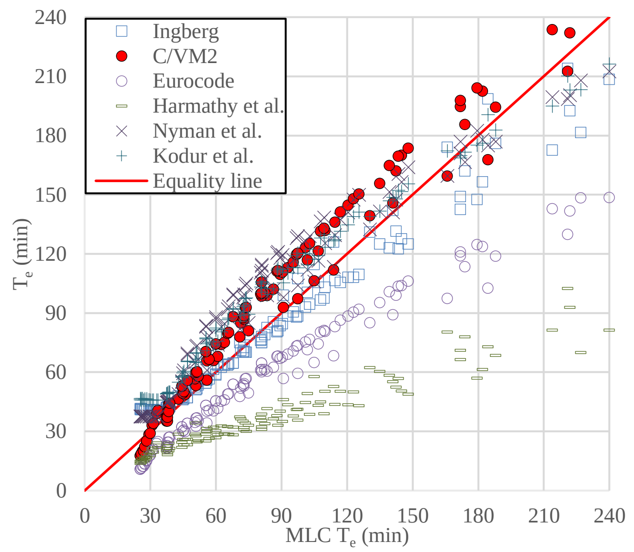

Fig. 3 Comparisons for the protected steel column UC203×203×71.

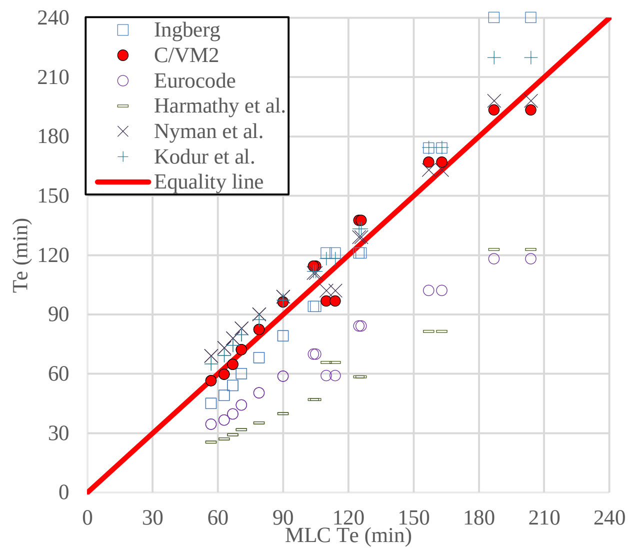

Fig. 4 Comparisons for the RC beams.

The results show that when T_e is below 150 min the C/VM2 method predicts slightly higher values as compared to the MLC method for protected steel beams, protected steel columns and RC beams with maximum differences of 13 min, 26 min and 13 min respectively. Figures 2 and 3 show that the C/VM2 method predicts lower values when T_e is lower than 30 min. Given that most fire rated systems start from an FRR of 30 min, this shortfall of the C/VM2 method is not practically important. As T_e gets higher than approximately 150 min, the C/VM2 method starts to under-predict the results for protected steel beams. The greatest difference between the C/VM2 and the MLC method is 30 min when T_e is between 150 and 240 min. This difference means that the C/VM2 method becomes increasingly less conservative beyond 150 min.

It can also be seen that various methods produce considerably different predictions of T_e. The energy methods, by Nyman et al. and Kodur et al., predict very close T_e values to the MLC method. However both of them also start to under-predict T_e beyond 150 min. The results show that the application of the two energy methods could be extended to protected steel members.

For all three types of materials, the Eurocode method, Ingberg's method and the one by Harmathy and Mehaffey under-predict T_e for almost the entire range of comparisons. The greatest shortfalls of the Eurocode method and the one by Harmathy and Mehaffey compared to the MLC method are 90 min and 110 min respectively (for T_e within 240 min).

Figure 5 presents comparisons of the C/VM2 method, the Eurocode method and the MLC method for the unprotected steel beam and column. Both the C/VM2 method and the Eurocode method tend to significantly under-predict T_e beyond approximately 70 min. Between 30 and 60 min, both methods again under-predict T_e. It appears problematic to use either the C/VM2 method or the Eurocode mode to predict T_e values for unprotected steel members. It is also important to note that below 70 min there are cases where the Eurocode and C/VM2 methods predict changes in T_e while MLC predictions hardly vary, suggesting the occurrence of structural failure. This confirms that the Eurocode and C/VM2 methods are unreliable for predicting FRR of unprotected steel structures.

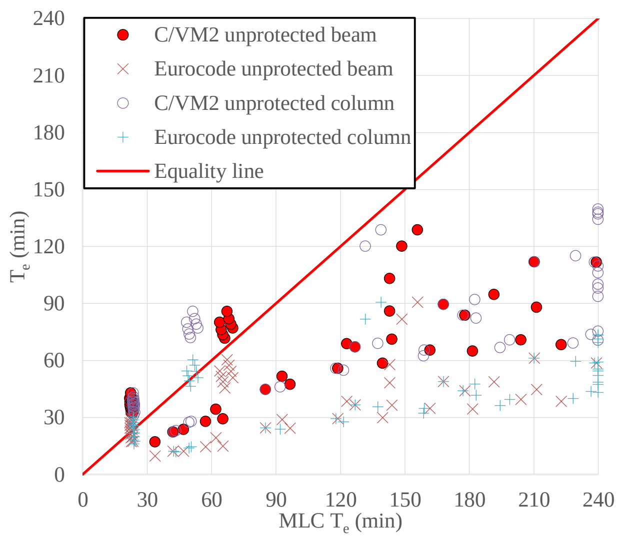

Fig. 5 Comparisons for the unprotected steel beam and column.

4.1 Glazing fallout

C/VM2 method design FRR values of 60, 90 and 120 min are used to examine the impact of glazing fallout on the prediction of T_e for protected steel members. A similar analysis for RC beams uses a design FRR of 60 min. The comparison employs the MLC method to predict T_e associated with the different glazing fallout ratios and the results are illustrated in Figs. 6 and 7. The C/VM2 method's prediction is still conservative if the glazing fallout ratio is no less than 70% for the protected steel beam and is no less than 65% for the protected steel column. Figure 9 indicates that a 95% glazing fallout ratio is required to allow the C/VM2 method and the MLC method to produce comparable results for RC beams.

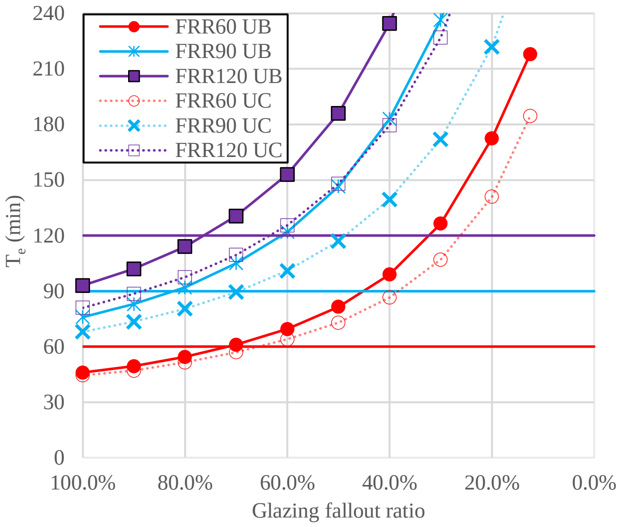

Fig. 6 Impact of varying glazing fallout on minimum FRR values for the protected steel beam and column.

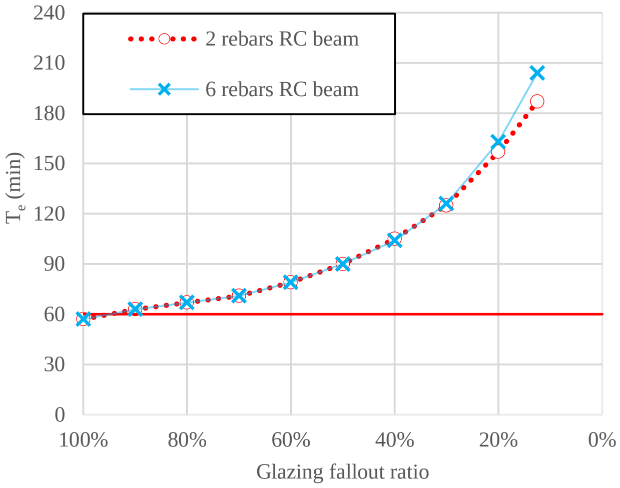

Fig. 7 Impact of varying glazing fallout on minimum FRR values for RC beams for the C/VM2 60 min design scenario.

4.2 Ventilation

Ventilation plays an important role in the determination of T_e. Figure 8 shows when the vertical vent ratio (α_V) is lower than 7.5%, most T_e predicted by the C/VM2 method are lower than the MLC method for T_e of no more than 150 min. It suggests that the C/VM2 method is problematic for α_V values lower than 7.5%.

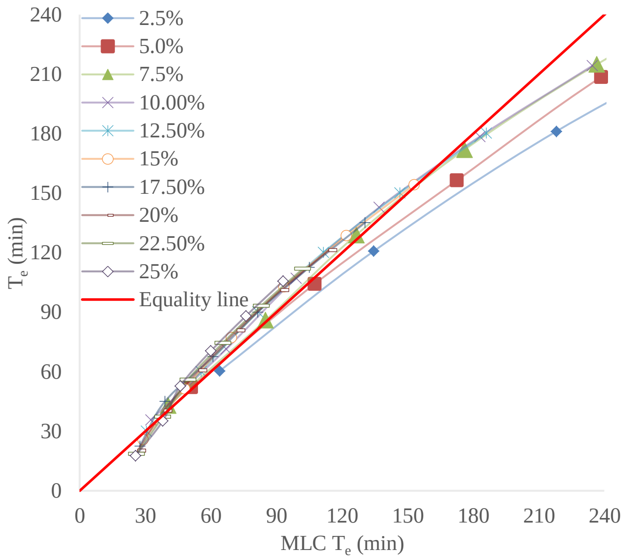

Fig. 8 Comparisons of the C/VM2 method and the MLC method at various vertical vent ratios (α_V).

4.3 Member size

In the thermal response analysis of the MLC method, the only parameter that is related to the member size is the section factor (H_p/A). This section picks three C/VM2 FRR values of 60, 90 and 120 min from the 120 design scenarios and examines the impact of member size on the prediction of T_e by only varying the value of H_p/A.

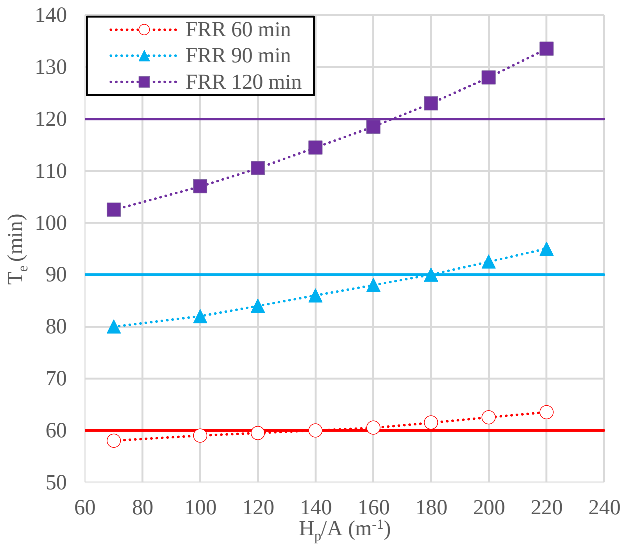

Fig. 9 Impact of varying member size of protected steel beams on minimum FRR values.

Figure 9 shows that the MLC method predicts lower T_e than the C/VM2 method for low H_p/A values of up to 145 m^{-1}, 180 m^{-1} and 165 m^{-1} for the selected scenarios of FRR values of 60, 90 and 120 min respectively. The results suggest that the C/VM2 method tends to under-predict T_e for members with large section factors.

4.4 Load ratio

The load ratio of a member directly impacts on how soon it fails in a fire. A structural member loaded with a higher load as compared to its minimum capacity fails. The critical (failure) load ratio is identified as the minimum load capacity attained in each fire. Figure 10 presents the critical load ratio of the protected steel beam and column in the 120 scenarios. It can be seen that the critical load ratios spread between 32% and 76%, and between 23% and 67% for the steel beam and column respectively. The results show that load ratio is an important consideration of fire severity, as a variation in the fire significantly affects the failure load ratio, even under a given FRR.

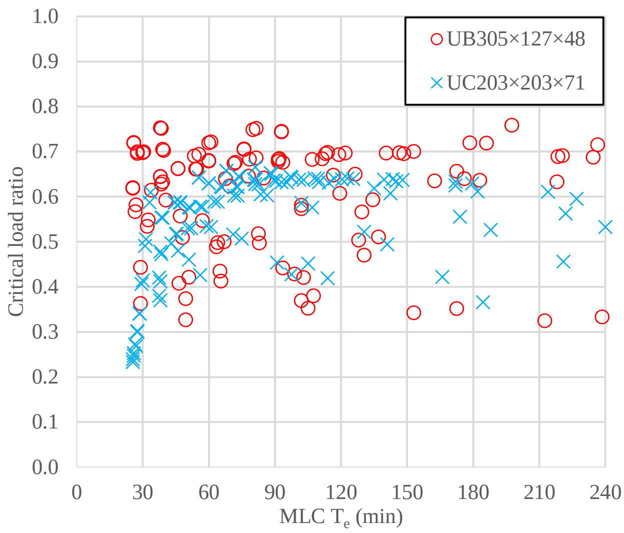

Fig. 10 Critical load ratio for the protected steel members.

4.5 Reinforcement size

Only the cover distance and member width are required to determine the FRR of a RC beam using tabulated data. However the failure of the RC beam at elevated temperatures is also affected by the amount of reinforcement present. Figure 11 illustrates the minimum load capacities attained by the two RC beams with identical cover distance and beam width but different amount of reinforcement. It can be seen when T_e is below 90 min, the minimum load capacities attained by both beams under various fire scenarios are above 0.80. However as T_e increases, the difference in minimum load capacities attained by the two members increases as well. At 150 min, the RC beam with six rebars attains a minimum load capacity of 0.62 whereas the one with two rebars only attains a minimum load capacity of 0.3. This significant difference means that the member with a less reinforcement is likely to fail sooner at elevated temperatures. If this effect is not recognized by the designer when predicting T_e, the members solely designed to the minimum requirements of cover distance and member width may not achieve their intended fire resistance.

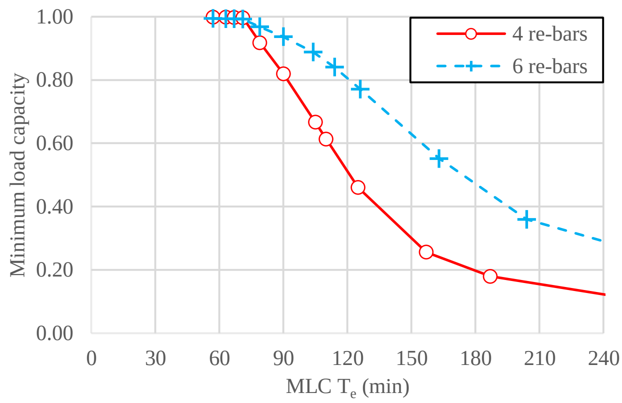

Fig. 11 Minimum load capacities attained by the two RC beams.

5 Discussion

The analytical comparisons presented in this article have only examined a few parameters that affect the prediction of T_e while a number of other parameters such as support conditions and the interaction of adjacent structure are not investigated. Many more complicated structural failure modes have also not been considered such as buckling of a RC columns, lateral torsional buckling and shear failure. When the member is not isolated but is part of a structure, additional forces may be imposed on the member. This may significantly shorten the predicted failure time as compared to those of isolated members. All these raise further questions for the use of a simple calculation approach such as the C/VM2 method for deriving FRR.

It is observed that it is difficult to assign fixed values for many factors affecting the prediction of T_e, such as member size, the load ratio and the glazing fallout ratio. The first two may have different values even inside a single compartment. The glazing fallout can vary depending on the design scenarios, or even with time during a fire. As a result it might not be realistic to use a pre-defined or fixed value to represent these parameters and it is considered that a statistical distribution will be more appropriate.

There is yet another factor that has been overly simplified in the C/VM2 method. This is the assumption of uniform heating inside the compartment. For larger open area spaces, a travelling fire may be observed instead of a fully involved compartment fire [22].

6 Conclusions

This article has identified a number of parameters previously overlooked in the maximum temperature-based TE methods. The parameters are related to the mechanical response of structural members at elevated temperatures, which directly influence failure, and hence their T_e predictions. The effect of load ratio, member size and reinforcement size of RC members have been investigated. The study also looks at the impact of varying ventilation conditions on the prediction of T_e. It is found that all these parameters have considerable influence in either the prediction of T_e or the confidence in relying on existing design methods. The results show that:

- for protected steel beams, the C/VM2 method tends to predict lower T_e values than the MLC method beyond 150 min.
- glazing fallout ratios of 70%, 65% and 95% should be expected when using the C/VM2 method for protected steel beams and columns, and RC beams respectively.
- for both protected steel beams and columns, the C/VM2 method tends to predict lower values than the MLC method when α_V is lower than 7.5%.
- when the steel member section factor H_p/A is greater than 140 m^{-1}, the C/VM2 method may predict lower T_e than the MLC method.
- a lower reinforcement size for RC beams may lead to an earlier failure than expected.

It is observed that the MLC method provides a more fundamental way of assessing structural failure. To ensure that the current methods provide adequate design solutions, a large number of uncertainties will need to be investigated. It is also found that some parameters that affect the prediction of T_e need to be represented statistically rather than the conventional pre-defined values. It is recommended that a risk-based statistical approach should be investigated for future design.

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