



Fire design of carbon steel and stainless steel structural members by GMNIA with strain limits

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Abstract

A new fire design approach by Geometrically and Materially Nonlinear Analysis with Imperfections (GMNIA) and using strain limits is proposed for the fire design of carbon steel and stainless steel members in this study. The proposed method adopts computationally efficient beam finite elements to carry out the GMNIA of steel elements in fire. In the proposed fire design approach, the strength and stiffness deterioration of carbon steel and stainless steel at elevated temperatures, the spread of plasticity, global buckling behaviour, indirect fire actions and thermal expansion can be directly considered through GMNIA performed using beam finite elements, while strain limits which are determined on the basis of a modified Continuous Strength Method (CSM) base curve are used to capture the local buckling behaviour. The ultimate resistance of a steel member is determined by (i) the temperature level at which the strain limit is attained or (ii) the critical temperature at which the member is not able to withstand the applied loading, whichever occurs first. Due to the presence of neighbouring structural elements, structural members are typically axially and/or rotationally restrained at their ends. Thus, in this study, carbon steel and stainless steel members both with and without axial and/or rotational end-restraints are taken into account. The accuracy of the proposed new design method is verified against the benchmark results from shell finite element modelling. It is shown that the proposed fire design approach consistently provides accurate and safe capacity predictions for carbon steel and stainless steel members with and without axial and/or rotational end-restraints in fire.

1. Introduction

In fire, steel structures undergo significant strength and stiffness erosions which considerably reduce their ultimate loading capacities. In addition to considerable strength and stiffness reductions, in fire, individual members in steel structures are also typically subjected to additional compressive forces resulting from restrictions to thermal expansions due to the presence of neighbouring structural members, which are referred to as indirect fire actions. The material response of steel also becomes considerably nonlinear at elevated temperatures. Different types of steels such as carbon steel and stainless steel exhibit quite different elevated temperature material response and strength and stiffness retentions in fire. These factors all lead to quite complex behaviour of steel structures at elevated temperatures, which have to be carefully taken into consideration for accurate fire design of steel structures.

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Despite the complex behaviour of steel structures at elevated temperatures, the current approach widely adopted in practice and provided in structural steel fire design standards for the fire design of steel structures is the use of room temperature structural steel design methods with simple modifications and reduced elevated temperature material strengths and stiffnesses. However, this approach is based upon a high number of assumptions and neglects a number of important factors influencing the behaviour of steel structures in fire such as indirect fire actions and considerably more nonlinear stress-strain response of steel at elevated temperatures relative to the room temperature material response. It is clear that the development of bespoke design methods to accurately capture the behaviour of steel structures in fire is necessary. Considering the complex behaviour of steel structures in fire, bespoke fire design methods for steel structures should also effectively utilise the advanced computational resources currently available to structural engineers. This paper presents such fire design method which is currently under development and referred to as GMNIA with strain limits based fire design approach for steel structures. The development and verification of this method have been reported in Murtaza and Kucukler (2023, 2024) and Quan and Kucukler (2024). In this paper, the previous research for the development and verification of the method for individual structural steel members is outlined.

The GMNIA with strain limits based fire design approach developed in Murtaza and Kucukler (2023,2024a) and Quan and Kucukler (2024) is based upon the Geometrically and Materially Nonlinear Analysis with Imperfections (GMNIA) of steel structures in fire by using computationally efficient beam finite elements; the use of beam finite elements in the application of the method is essential for the sake of computational and modelling efficiency which makes the method applicable in practice. Since the standard beam finite elements cannot capture the detrimental influence of local buckling effects on the structural resistances of steel structures in fire, strain limits determined on the basis of a modified Continuous Strength Method (CSM) base curve are imposed on structural steel elements to account for the deleterious influence of local buckling effects. In the application of the proposed fire design approach, the GMNIA of a steel structure is performed by (i) first loading the structure at room temperature and then heating it on the basis of an appropriate fire scenario and (ii) monitoring the cross-sections of the members of the structure for the assessment of the attainment of the corresponding cross-section strain limits. The critical temperature or time is defined as (i) the temperature or time at which the strain limit is attained within a cross-section of a member of a structure or (ii) the temperature or time at which the structure is no longer able to carry the applied loading by exhibiting excessive deformations and deformation rates, whichever comes first. It should be noted the presented method is the extension of the room temperature second-order inelastic analysis with strain limits based design approach (Fieber et al., 2019, 2020, Quan et al., 2020, 2021 and Walport et al. 2021, 2023).

The proposed GMNIA with strain limits based structural steel fire design approach brings about significant advantages relative to simple fire design methods currently used in practice. During structural analysis, it enables the direct consideration of (i) the development and spread of plasticity, (ii) material nonlinearity, (iii) strength and stiffness reductions at elevated temperatures, (iv) thermal expansions, (v) indirect fire actions (i.e. additional compressive forces in steel members due to restrictions to thermal expansion), (vi) global and local instability effects and (vii) failure modes of steel structures, thereby furnishing a structural engineer a significant insight into the behaviour of steel structures in different fire scenarios. It also enables performance-based fire

design where the performance of a steel structure in fire can be enhanced by taking effective measures considering the overall response determined through the use of the proposed fire design approach. The following sections of this paper describe the proposed fire design approach and shows its application and verification for carbon steel and stainless steel structural members at elevated temperatures. Carbon steel and stainless steel members both without axial end restraints and with axial and/or rotational end restraints are considered. It is demonstrated that in all the considered cases, the proposed fire design approach furnishes consistent and safe resistance predictions for carbon steel and stainless steel structural members in fire.

2. GMNIA with strain limits based fire design approach for steel structures

In this section, the principles and application of the proposed GMNIA with strain limits based fire design approach are described. Following its introduction in this section, the following sections set out the accuracy assessment of the proposed GMNIA with strain limits based fire design approach for the fire design of carbon steel and stainless steel structural members.

2.1 Elevated temperature cross-section strain limits

The assessment of the attainment of strain limits within the cross-sections of steel members is essential in the application of the proposed GMNIA with strain limits based fire design approach. Thus, in the implementation of the proposed fire design method, the following condition has to be satisfied within each cross-section of a steel structure or member to consider that the structure or structural member is able to withstand the applied loading in fire:

$$\frac{\varepsilon_{Ed,\theta}}{\varepsilon_{csm,\theta}} \leq 1.0, \quad (1)$$

where $\varepsilon_{Ed,\theta}$ is the maximum compressive strain within the cross-section at temperature θ and $\varepsilon_{csm,\theta}$ is the elevated temperature strain limit at temperature θ calculated for the cross-section using a modified CSM base curve. The elevated temperature strain limit $\varepsilon_{csm,\theta}$ of a cross-section is dependent upon its elevated temperature cross-section slenderness $\bar{\lambda}_{p,\theta}$, which is determined as

$$\bar{\lambda}_{p,\theta} = \sqrt{\frac{f_y}{\sigma_{cr}}} \sqrt{\frac{k_{p0.2,\theta}}{k_{E,\theta}}}, \quad (2)$$

in which f_y is the yield strength for carbon steel and 0.2% proof strength for stainless steel, σ_{cr} is the elastic critical buckling stress of the full cross-section, $k_{p0.2,\theta}$ is the elevated temperature 0.2% proof strength reduction factor and $k_{E,\theta}$ is the elevated temperature Young's modulus reduction factor. For $k_{p0.2,\theta}$ and $k_{E,\theta}$, this study recommends the use of the values provided in the upcoming version of the European structural steel fire design standard prEN 1993-1-2 (2019). It should also be noted that the elastic critical buckling stress of a cross-section can be determined either analytically using the practical equations provided in Gardner et al. (2019) or numerically using computer software such the finite strip analysis software CUFSM (Adany and Schafer, 2006); the former method was used in this study owing to its practicality.

The elevated temperature strain limit $\varepsilon_{csm,\theta}$ of a steel cross-section at temperature θ can be determined using the modified CSM base curve expressed using the following equations:

$$\frac{\varepsilon_{csm,\theta}}{\varepsilon_{y,\theta}} = \frac{0.25}{\bar{\lambda}_{p,\theta}^{3.6}} + \frac{0.002}{\varepsilon_{y,\theta}} \leq \Omega \quad \text{for } \bar{\lambda}_{p,\theta} \leq 0.68, \quad (3)$$

$$\frac{\varepsilon_{csm,\theta}}{\varepsilon_{y,\theta}} = \left(1 - \frac{0.222}{\bar{\lambda}_{p,\theta}^{1.05}}\right) \frac{1}{\bar{\lambda}_{p,\theta}^{1.05}} + \frac{0.002(\sigma/f_{p0.2,\theta})^{n_\theta}}{\varepsilon_{y,\theta}} \quad \text{for } 0.68 \leq \bar{\lambda}_{p,\theta} \leq 1.0, \quad (4)$$

in which, $\varepsilon_{y,\theta}$ is the elevated temperature yield strain determined through the division of the elevated temperature 0.2% material proof strength $f_{p0.2,\theta}$ by the elevated temperature Young's modulus E_θ (i.e. $\varepsilon_{y,\theta} = f_{p0.2,\theta}/E_\theta$), σ is the maximum compressive stress within the cross-section and n_θ is the material stress-strain response roundedness parameter. The modified CSM base curve is also graphically illustrated in Fig. 1. In eq. (3), the upper limit Ω to the normalized strain limit is set to 15 to avoid overestimations of the ultimate fire resistances of steel structures or members with stocky cross-sections in line with the ductility requirements set out in EN 1993-1-2 for carbon steel. The application range of the proposed fire design approach is also limited to the cross-sections with the elevated temperature cross-section slenderness $\bar{\lambda}_{p,\theta}$ of up to 1.0, covering the majority of the cross-sections encountered in practice. In Murtaza and Kucukler (2023, 2024a), the development and verification of the modified CSM base curve expressed using eqs. (3) and (4) are presented against the ultimate cross-section deformation capacities obtained from fire experiments on steel cross-sections with various cross-section geometries and slendernesses.

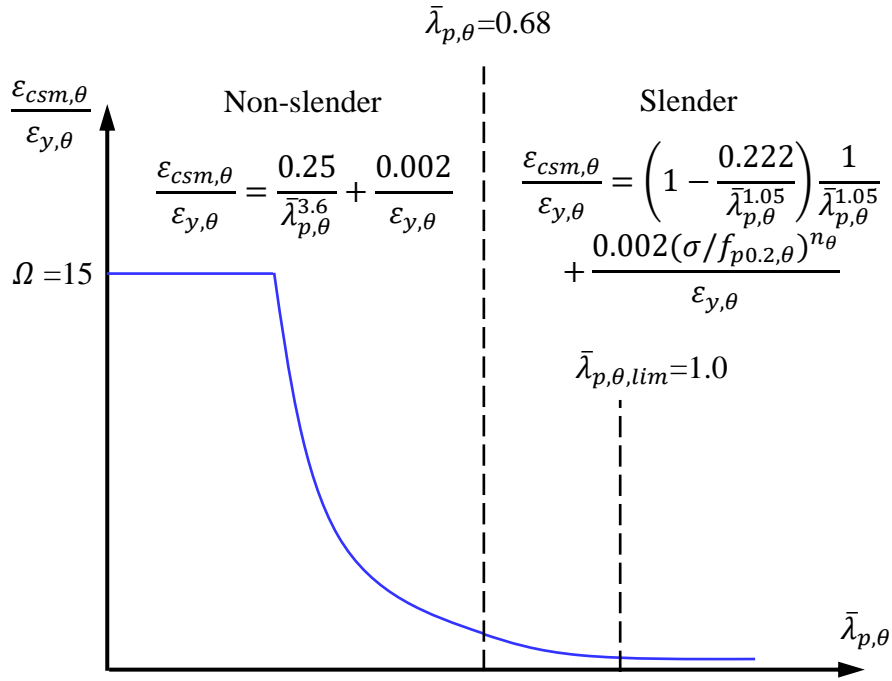


Figure 1: Modified CSM base curve for the determination of cross-section deformation capacities $\varepsilon_{csm,\theta}/\varepsilon_{y,\theta}$ using elevated temperature cross-section slenderness $\bar{\lambda}_{p,\theta}$

Table 1 also shows the proposed material stress-strain response roundedness parameters n_θ necessary for the determination of the elevated temperature strain limits of slender cross-sections

with $\bar{\lambda}_{p,\theta} > 1.0$. Similar to the material reduction factors $k_{p0.2,\theta}$ and $k_{E,\theta}$, n_θ should be interpolated for the temperatures between the provided values in Table 1.

Table 1: Material stress-strain response roundedness parameters n_θ

| Temperature (°C) | n_θ |
|---------------------|------------|
| 200 | 38.40 |
| 300 | 14.82 |
| 400 | 7.38 |
| 500 | 8.52 |
| 600 | 6.59 |
| 700 | 5.42 |
| 800 | 8.44 |
| 900 | 16.10 |
| 1000 | 16.15 |
| 1100 | 15.82 |

2.2 Elevated temperature material modelling

For the implementation of the proposed fire design approach, the Geometrically and Materially Nonlinear Analysis (GMNIA) of a steel structure or member in fire using computationally efficient beam finite elements is necessary. In the GMNIA of carbon steel and stainless steel structures, the use of the elevated temperature material models provided in the upcoming version of EN 1993-1-2 (2005) which is currently referred to as prEN 1993-1-2 (2019) is recommended. For carbon steel, the prEN 1993-1-2 (2019) elevated temperature material model can be expressed as

$$\sigma = \begin{cases} \varepsilon E_\theta & \text{for } \varepsilon \leq \varepsilon_{p,\theta} \\ f_{p,\theta} - c + \left(\frac{b}{a}\right) \sqrt{a^2 - (\varepsilon_{2,\theta} - \varepsilon)^2} & \text{for } \varepsilon_{p,\theta} < \varepsilon \leq \varepsilon_{2,\theta} \\ f_{2,\theta} & \text{for } \varepsilon_{2,\theta} < \varepsilon \leq \varepsilon_{t,\theta} \\ f_{2,\theta} [1 - (\varepsilon - \varepsilon_{t,\theta})] & \text{for } \varepsilon_{t,\theta} < \varepsilon \leq \varepsilon_{u,\theta} \\ 0 & \text{for } \varepsilon = \varepsilon_{u,\theta} \end{cases} \quad (5)$$

in which σ and ε are the stress and strain, E_θ is the elevated temperature Young's modulus, $f_{p,\theta}$ is the elevated temperature proportionality limit stress, $f_{2,\theta}$ is the elevated temperature material strength at 2% total strain, $\varepsilon_{p,\theta}$ is the strain value at the proportional limit calculated as $\varepsilon_{p,\theta} = f_{p0.2,\theta}/E_\theta$, $\varepsilon_{2,\theta}$ is the 2% total strain (i.e. $\varepsilon_{2,\theta} = 0.02$), $\varepsilon_{t,\theta}$ is the limit strain equal to 0.15 (i.e. $\varepsilon_{t,\theta} = 0.15$) and $\varepsilon_{u,\theta}$ is the ultimate strain taken as 0.20 (i.e. $\varepsilon_{u,\theta} = 0.20$). It should be noted that the elevated temperature Young's modulus E_θ is determined by multiplying the room temperature Young's modulus E by the elevated temperature Young's modulus reduction factor $k_{E,\theta}$ (i.e. $E_\theta = k_{E,\theta}E$), whereas the elevated temperature proportional limit stress $f_{p,\theta}$ and material strength at 2% total strain $f_{2,\theta}$ are determined by multiplying the room temperature yield strength f_y by the elevated temperature proportionality limit stress reduction factor $k_{p,\theta}$ and elevated temperature yield strength reduction factor respectively (i.e. $f_{p,\theta} = k_{p,\theta}f_y$, $f_{2,\theta} = k_{2,\theta}f_y$). In the proposed design method, the material property reduction factors for strength and stiffness (i.e. $k_{p,\theta}$, $k_{p0.2,\theta}$,

$k_{y,\theta}$ and $k_{E,\theta}$) recommended in prEN 1993-1-2 should be adopted. Moreover, the auxiliary coefficients a , b and c in eq. (5) are calculated as given in prEN 1993-1-2 (2019):

$$a = \sqrt{(\varepsilon_{2,\theta} - \varepsilon_{p\theta})(\varepsilon_{2,\theta} - \varepsilon_{p\theta} + c/E_\theta)}, \quad (6)$$

$$b = \sqrt{c(\varepsilon_{2,\theta} - \varepsilon_{p\theta})E_\theta + c^2}, \quad (7)$$

$$c = \frac{(f_{2,\theta} - f_{p\theta})^2}{(\varepsilon_{2,\theta} - \varepsilon_{p\theta})E_\theta - 2(f_{2,\theta} - f_{p,\theta})}. \quad (8)$$

In the case of the elevated temperature material modelling of stainless steel, prEN 1993-1-2 (2019) recommends the use of the two-stage Ramberg-Osgood material model which is expressed as

$$\varepsilon = \frac{\sigma}{E_\theta} + 0.002 \left(\frac{\sigma}{f_{p0.2,\theta}} \right)^{n_\theta} \quad \text{for } \sigma \leq f_{p0.2,\theta}, \quad (9)$$

$$\varepsilon = \frac{\sigma - f_{p0.2,\theta}}{E_{p0.2,\theta}} + \left(\varepsilon_{u,\theta} - \varepsilon_{p0.2,\theta} - \frac{f_{u,\theta} - f_{p0.2,\theta}}{E_{p0.2,\theta}} \right) \left(\frac{\sigma - f_{p0.2,\theta}}{f_{u,\theta} - f_{p0.2,\theta}} \right)^{m_\theta} + \varepsilon_{p0.2,\theta} \quad \text{for } f_{p0.2,\theta} \leq \sigma \leq f_{u,\theta} \quad (10)$$

in which $E_{p0.2,\theta}$ and $\varepsilon_{p0.2,\theta}$ are the tangent modulus and total strain corresponding to $f_{p0.2,\theta}$ respectively, $f_{u,\theta}$ and $\varepsilon_{u,\theta}$ are the ultimate tensile strength and strain at temperature θ and n_θ and m_θ are the strain hardening exponents. For the determination of the elevated temperature material strengths $f_{p0.2,\theta}$, $f_{2,\theta}$ and $f_{u,\theta}$ and the elevated temperature ultimate strain $\varepsilon_{u,\theta}$, the multiplication of the standardised room temperature material properties (f_y , f_u and $\varepsilon_{u,\theta}$) for stainless steel adopted in Quan and Kucukler (2023a) by the corresponding strength (i.e. $k_{p0.2,\theta}$, $k_{2,\theta}$ and $k_{E,\theta}$) and ductility reduction factors (i.e. $k_{\varepsilon_{u,\theta}}$) provided in prEN 1993-1-2 (2019) is recommended (i.e. $f_{p,\theta} = k_{p,\theta}f_y$, $f_{2,\theta} = k_{2,\theta}f_y$).

2.3 Equivalent geometric imperfections

In the application of the proposed fire design approach, equivalent bow imperfections which consider the detrimental influence of both actual member out-of-straightnesses and residual stresses on the resistances of steel members in fire should be modelled in GMNIA. In line with Murtaza and Kucukler (2023), the magnitudes e_0 of the equivalent bow imperfections should be calculated as follows

$$e_0 = \alpha\beta L \geq L/1000 \quad \text{with} \quad \beta = \frac{1}{250} \quad (11)$$

where α is the imperfection factor equal to $\alpha = 0.65\sqrt{235/f_y}$ from prEN 1993-1-2 (2021), $\beta = 1/250$ is the reference bow imperfection and L is the member length; the lower bound to the equivalent imperfection is defined as 1/1000 of the member length L (i.e. $e_0 = L/1000$) as this is the maximum permissible member out-of-straightness provided in the European standard for the execution of steel structures EN 1090-2 (2008). It should also be noted for the cases where the

membrane residual stresses are quite low and their influence on the member resistances is immaterial such as for cold-formed stainless steel hollow section members, the equivalent imperfections can be taken as 1/1000 of the member lengths L (i.e. $e_0 = L/1000$) to avoid conservative estimations of the ultimate resistances. Moreover, for the case of steel members subjected to pure bending and fully laterally restrained against lateral-torsional buckling (i.e. fully laterally restrained beams), the modelling of equivalent bow imperfections is not necessary.

2.4 Application of the proposed GMNIA with strain limits based fire design approach

The application procedure of the proposed GMNIA with strain limits based fire design approach is shown in Fig. 4.

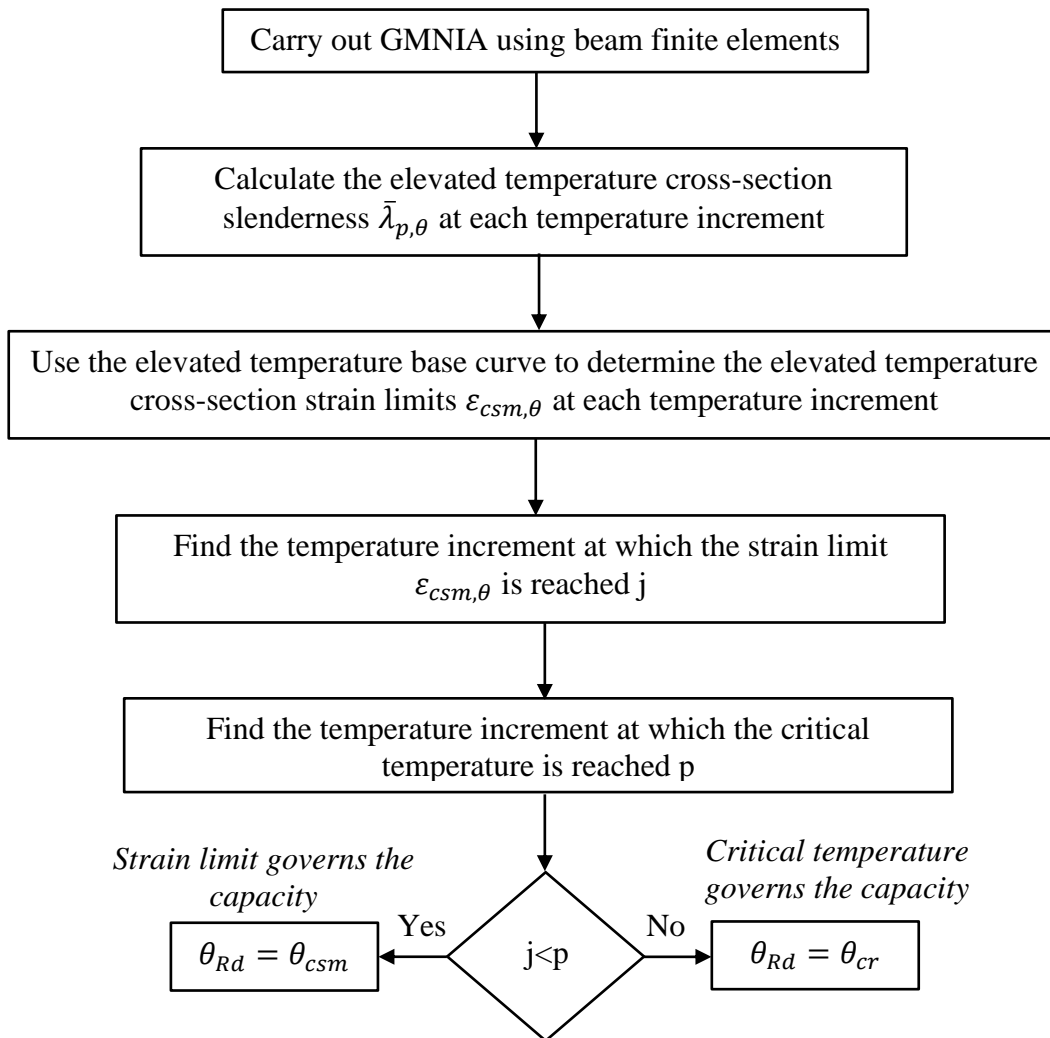


Figure 4: Application procedure of the proposed GMNIA with strain limits based fire design approach

In the implementation of the proposed fire design approach, the anisothermal analysis technique can be used where the structural steel member is first loaded at room temperature and then heated by adopting an appropriate heating profile with respect to time for a fire scenario. For the selection of a heating profile of a structural element with respect to time, either (i) a heat transfer analysis

can be performed or (ii) empirical equations for the determination of the temperature development in structural steel elements such as those provided in EN 1993-1-2 (2005) for the ISO 834-1 (2020) standard fire can be utilised. In this study, the former approach was adopted where heat transfer analyses were performed on structural steel members; in the heat transfer analyses, the ambient temperature was increased adopting the ISO 834-1 (2020) standard fire which have been used for the development of fire design methods of EN 1993-1-2 (2005). The thermal properties of carbon steel and stainless steel provided in prEN 1993-1-2 (2019) were utilized. The proposed fire design approach can be carried out using a finite element analysis software package which is able to take into consideration (i) the development and spread of plasticity throughout the volume of a steel member, (ii) the modifications in the material response and erosions in the material strength and stiffness at elevated temperatures, (iii) thermal expansions and (iv) geometric nonlinearities. Such software packages are available in practice such as Abaqus (2018), ANSYS (2018) and Safir (Franssen and Gernay, 2017). In this study, the proposed fire design approach was implemented through the finite element analysis software Abaqus (2018) using the two-noded Timoshenko beam finite elements designated as B31OS and B31 for I-section and hollow section members, respectively.

As shown in Fig. 4, in the implementation of the proposed method, the failure of a steel element designated by the limit temperature θ_{Rd} is determined by the (i) the strain limit temperature θ_{csm} at which the strain limit is attained within a cross-section of a steel member or (ii) critical temperature θ_{cr} where the member is no longer able to carry the applied loading at room temperature in fire, whichever occurs first. Moreover, if the limit time at which the structure fails according to the proposed design approach needs to be obtained, the time corresponding to the limit temperature θ_{Rd} can be taken as the failure (i.e. limit) time as the structural element is heated by adopting an appropriate temperature development scenario with respect to time. In the application of the proposed design approach, the total strains ε_t in the cross-sections of steel members are equal to

$$\varepsilon_t = \varepsilon_m + \varepsilon_{th} \quad (12)$$

where ε_m are the mechanical strains and ε_{th} are the thermal strains. In the implementation of the proposed fire design approach, the mechanical strains ε_m should be checked against the elevated temperature cross-section strain limits $\varepsilon_{csm,\theta}$ (i.e. $\varepsilon_m = \varepsilon_{Ed,\theta} \leq \varepsilon_{csm,\theta}$) as the mechanical strains govern the local buckling behaviour and the modified CSM base curve was verified in Murtaza and Kucukler (2024) against the fire experiments using the mechanical failure strains of a wide range of steel cross-sections at different elevated temperature levels. Finite element analysis software packages such as Abaqus (2018) provide the mechanical and thermal strains in structural steel elements individually, thereby readily enabling the application of the proposed fire design approach. It is worth noting that the critical temperatures θ_{cr} of steel elements at which they are no longer able to carry the applied loading can be determined using the deformation and deformation rate limits provided in ISO 834-1 (2020) for steel columns and beams. In Murtaza and Kucukler (2024a), further information regarding the procedures for the determination of the critical temperatures θ_{cr} of steel elements in fire is provided. In the application of the proposed fire design approach to structural steel systems subjected to moment gradients along their lengths, the strain averaging approach where the maximum strains within the cross-sections of steel members are averaged over the local buckling half-wavelengths can be utilized. In Murtaza and

Kucukler (2023, 2024a) and Quan and Kucukler (2024), detailed information about the strain averaging approach which consider the beneficial influence of strain gradients through the lengths of steel elements on the local buckling resistances is provided. Moreover, the influence of high shear forces should also be taken into consideration in the application of the proposed fire design approach to steel members subjected high shear forces through applying reductions on the strain limits. Note that shear forces may need to be considered in a relatively few number of cases where the applied shear forces exceed half of the shear force resistances of steel members at elevated temperatures. In Murtaza and Kucukler (2023, 2024a), detailed information on the consideration of high shear forces in the application of the proposed fire design approach is provided.

It should also be noted that the implementation procedure outlined in Fig. 4 can also be generalised for the application of the proposed approach to the fire design of structural systems made up of a number of individual steel elements. Moreover, even though it is necessary to check the strain limits within each cross-section of a steel member in the application of the proposed fire design approach, typically, it is sufficient to check the most heavily stressed cross-section of a steel member where the attainment of the strain limit is expected. It is also envisaged that the proposed fire design approach can be automated in a finite element analysis software, where the software can automatically calculate the strain limits, check the attainment of strain limits within the cross-section of steel members and provide the designer the failure temperatures and modes.

3. Shell finite element modelling

For the verification of the proposed fire design approach, the benchmark structural performance data from shell finite element modelling is utilised in this study. The shell finite element models of carbon steel and stainless steel members were created through the finite element analysis software Abaqus (2018), using the general purpose 4-noded reduced integration shell finite element referred to as S4R in the Abaqus finite element library which was also used in similar studies (Kucukler, 2020; Kucukler, 2021; Kucukler, 2023; Quan and Kucukler, 2023b; Quan and Kucukler, 2023c). To accurately capture the cross-section behaviour, sixteen elements were utilised to model each individual plates of steel cross-sections, while the total number of elements along the member lengths were selected such that the element aspect ratios were close to unity. In the shell finite element modelling, the elevated temperature material models recommended in prEN 1993-1-2 (2019) for carbon steel and stainless steel are utilised. The geometric imperfections were directly modelled in the shell finite element models. The member out-of-straightnesses were modelled as a half-sine wave in shape and 1/1000 of the member lengths in magnitude. For the case of local geometric imperfections, the local imperfection magnitudes were taken as 1/200 of the plate widths in accordance with the recommendations of EN 1993-1-5 (2006) for carbon steel cross-sections; on the other hand, the modified Dawson and Walker equation recommended in Gardner and Nethercot (2004) were utilised for the definition of local geometric imperfection magnitudes in stainless steel members. In Murtaza and Kucukler (2023, 2024a) and Quan and Kucukler (2024), detailed information on the modelling of global and local geometric imperfections in the shell finite element models of steel members is provided. The anisothermal analysis technique was adopted in the shell finite element simulations where the models were initially loaded at room temperature and then the temperatures of the models were increased up to the failure. The temperatures of the shell finite element models of steel members were increased using the temperature development versus time relationships obtained from separate heat transfer analyses. The heat transfer analyses were performed using separate shell finite element models of steel members created using the four-noded DS4 heat transfer shell element of Abaqus (2018),

where the ambient temperature was increased by adopting the ISO 834-1 standard fire. The thermal properties for carbon steel and stainless steel provided in prEN 1993-1-2 (2018) were utilised in the heat transfer analyses. Appropriate boundary conditions were established at the end sections of the members where the nodes within the end sections were kinematically constrained to the nodes at the centroids where the boundary conditions were defined and loading was applied, thereby avoiding the localised yielding at the load application points. In both shell finite element simulations and beam element simulations (the latter is necessary for the application of the proposed method), the presence of axial and rotational end restraints was modelled by using elastic translational and rotational springs. It should also be noted that since this study does not consider the application of the proposed fire design approach to steel members susceptible to flexural-torsional buckling effects, the I-section steel members were fully laterally restrained in the shell and beam finite element models. Extensive validation of the adopted shell finite element modelling approach for replicating the structural response of carbon steel and stainless steel members in fire against a broad range of fire experiments from the literature is provided in Murtaza and Kucukler (2023, 2024a) and Quan and Kucukler (2024), where it is shown that the developed shell finite element models are able to mimic the behaviour of steel members in fire.

4. Accuracy of the proposed GMNIA with strain based fire design approach for carbon steel and stainless steel structural members

In this section, the accuracy of the proposed GMNIA with strain limits based fire design approach is shown for a number of carbon steel and stainless steel members. It should be noted that in Murtaza and Kucukler (2023, 2024a) and Quan and Kucukler (2024), comprehensive studies were performed for the verification of the accuracy, safety and reliability of the proposed fire design approach for carbon steel and stainless steel members in fire. Herein, a number of cases from these comprehensive studies are set out.

4.1 Carbon steel columns

Fig. 5 shows the accuracy of the proposed GMNIA with strain limits based fire design approach for carbon steel columns without axial end restraints as well as those with axial end restraints and axial and rotational end restraints. Grade S355 carbon steel with the yield strength of 355 MPa was used for all the columns. Note that in Fig. 5, α_N is the applied axial load intensity equal to the applied axial compression N_{Ed} divided by the the room temperature flexural buckling resistance of the column $N_{b,Rd}$ determined according to the European room temperature structural steel design standard EN 1993-1-1 (i.e. $\alpha_N = N_{Ed} / N_{b,Rd}$), $\bar{\lambda}$ is the room temperature non-dimensional column slenderness equal to the square root of the axial yield load Af_y divided by the elastic critical flexural buckling load about the corresponding axis N_{cr} (i.e. $\bar{\lambda} = \sqrt{Af_y / N_{cr}}$) and $\bar{\lambda}_p$ is the room temperature cross-section slenderness. Moreover, k_Δ and k_ϕ are the axial and rotational end restraint stiffnesses, E is the room temperature Young's modulus, A_c is the cross-section area of the column, I_c is the second moment of area with respect to the buckling axis, L is the column length and α_Δ and α_ϕ are the axial and rotational end restraint degrees determined considering the geometric properties of the column as shown in Fig. 5. As indicated in Section 3, the proposed design approach is applied through the anisothermal analysis technique where the columns were first subjected to loading at room temperature and then heated up to failure. It should be noted that to consider the most critical local buckling scenarios for the columns, the web and flange plate slenderness were specified such that they were equal for I-section columns (i.e. $\bar{\lambda}_{p,f} = \bar{\lambda}_{p,w}$); for the case of the square hollow section columns, of course, the plate slenderness of the cross-section

elements are equal, thus leading to the most critical local buckling scenario where the cross-section elements buckle with minimum interactions. In Fig. 5, the failure modes of the columns according to the proposed fire design approach are also indicated which are due to the attainment of (i) the cross-section strain limits or (ii) critical temperatures where the columns are no longer able to carry the applied loading and show excessive deformations and deformation rates which are specified according to ISO 834-1. Fig. 5 shows that a broad range of cross-section slendernesses $\bar{\lambda}_p$ and axial load intensities α_N are considered for the verification of the proposed fire design approach where the results from the shell finite element (FE) models were taken as the benchmark data.

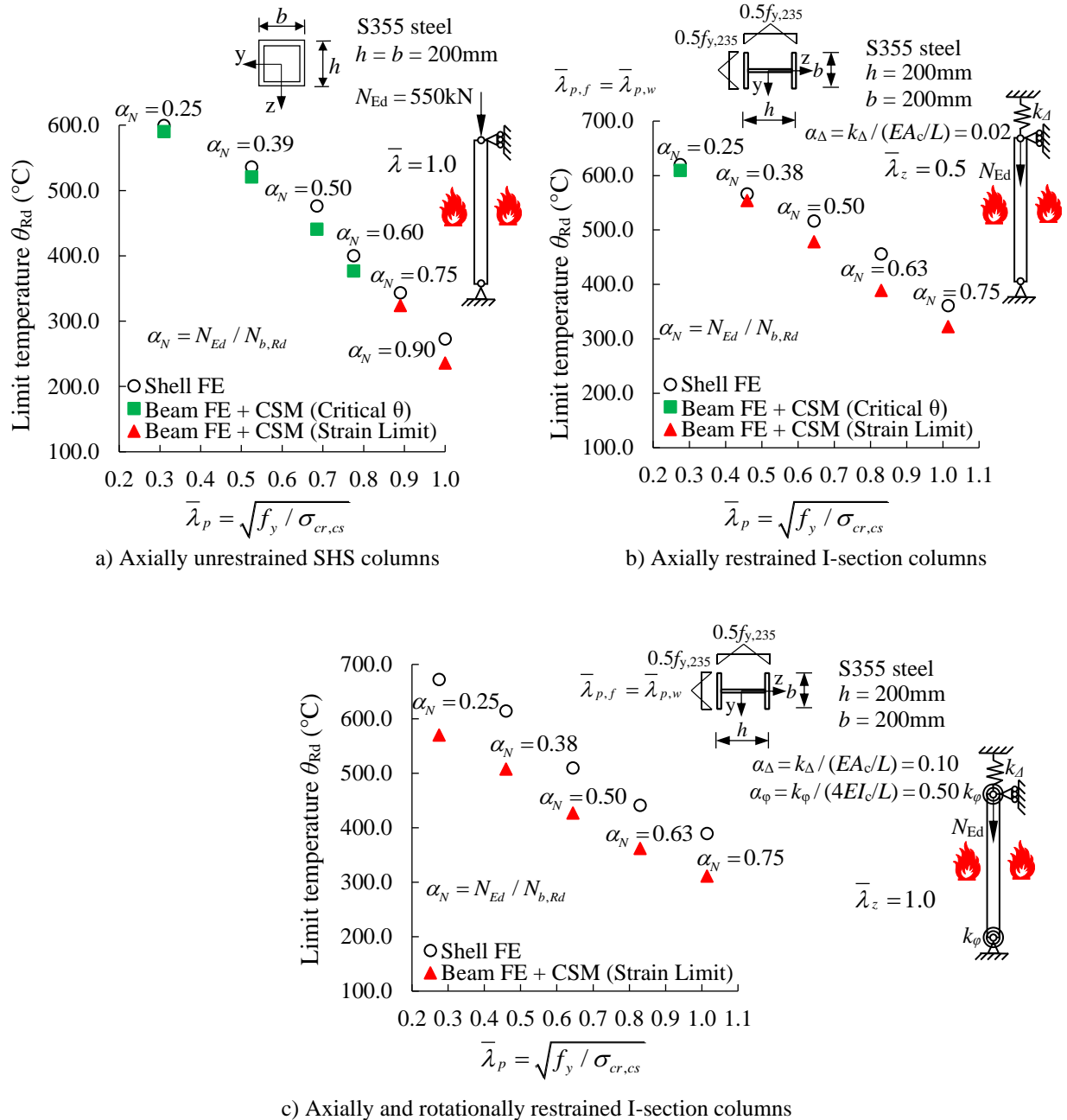


Figure 5: Accuracy assessment of the proposed GMNIA with strain limits based fire design approach for axially unrestrained, axially restrained and axially and rotationally restrained carbon steel columns in fire

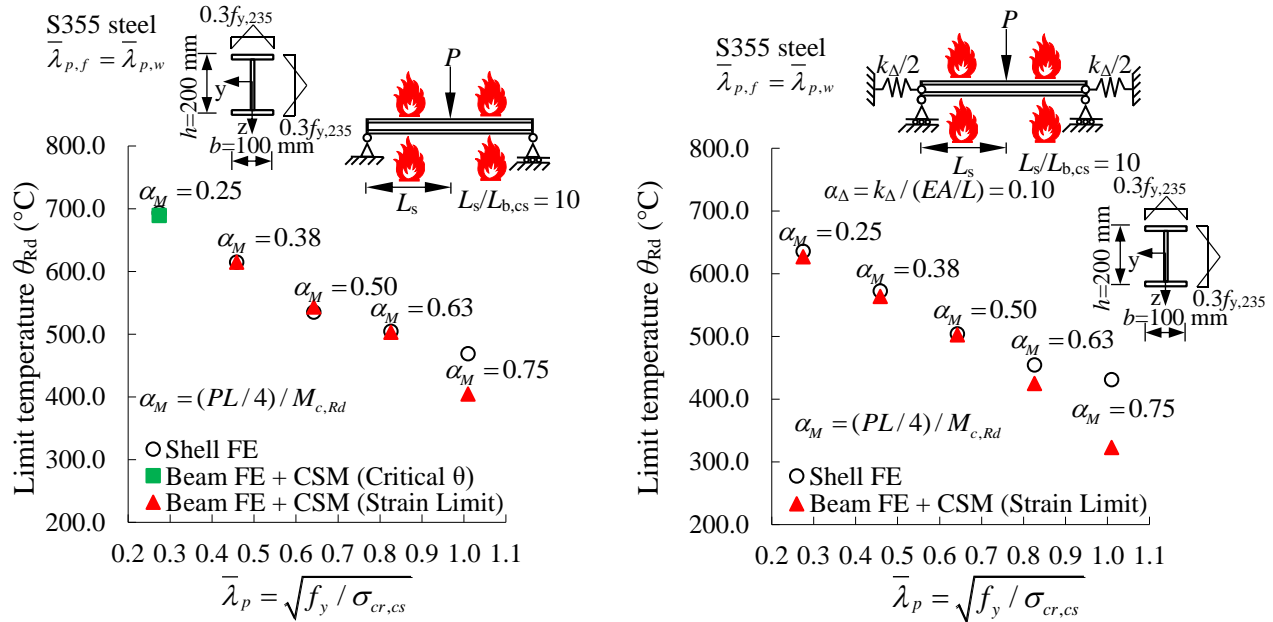
As can be seen from Fig. 5, the proposed GMNIA with strain limits based fire design approach provides accurate and safe limit temperature θ_{Rd} estimations for the considered wide range of carbon steel columns. Fig. 5 shows that the higher axial load intensities α_N and cross-section slendernesses $\bar{\lambda}_p$ lead to lower limit temperatures for steel columns as expected, which is accurately taken into account by the proposed GMNIA with strain limits based fire design approach. It is of interest to note that for axially unrestrained columns, generally, the attainment of the critical temperatures dominate the failure modes with the exception of the columns with very high cross-section slenderness $\bar{\lambda}_p$ where the columns show excessive overall deformations and deformation rates with the attainment of the critical temperatures. On the other hand, for axially restrained and axially and rotationally end restrained steel columns, the failure modes are dominated by the attainment of the cross-section strain limits which indicate the importance of the local buckling effects on the ultimate resistances; this is not surprising since significant additional compressive forces occur as indirect fire actions in axially and axially and rotationally restrained columns because the axial expansions of the columns in fire are restricted due to the presence of axial end restraints. As can be seen in Fig 5, in all of these cases, the proposed fire design approach accurately takes into account these indirect fire actions and provide accurate and safe limit temperature predictions. In Murtaza and Kucukler (2023), the accuracy of the proposed fire design approach is also compared against EN 1993-1-2 (2005) for a very broad range of cases where it is shown that the proposed GMNIA with strain limits based fire design approach leads to significantly more accurate, safe and reliable ultimate capacity predictions of carbon steel columns in fire relative to EN 1993-1-2 (2005).

4.2 Carbon steel beams

The accuracy of the proposed GMNIA with strain limits based fire design approach for axially unrestrained, axially restrained and axially and rotationally restrained carbon steel I-section beams subjected to three-point bending is shown in Fig. 6. In the figure, α_M is the bending moment loading ratio equal to the maximum bending moment within the beam determined considering simply-supported end conditions divided by the room temperature cross-section bending moment resistance $M_{c,Rd}$ determined according to EN 1993-1-1 (2005) (i.e. $\alpha_M = (PL/4) / M_{c,Rd}$), with P is the applied concentrated load at the mid-span and L is the beam length. The beam lengths L were selected such that the half of the beam lengths L_s were equal to 10 times of the local buckling half-wave lengths $L_{b,cs}$ of the cross-sections at the mid-spans (i.e. $L_s/L_{b,cs} = 10$). In Fig. 6, A and I are the cross-section area and second-moment of area with respect to the major axis respectively and k_Δ and $k_{\varphi,b}$ are the axial and rotational end restraint stiffnesses of the beams. Similar to the I-section columns considered in the previous subsection, to account for the most critical local buckling scenarios for the beams, the web and flange plate slendernesses were specified such that they were equal (i.e. $\bar{\lambda}_{p,f} = \bar{\lambda}_{p,w}$). The beams were fully laterally restrained and not susceptible to lateral-torsional buckling effects. Grade S355 carbon steel with the yield strength of 355 MPa was used for all the beams. Fig. 6 shows that a broad range of cross-section slendernesses $\bar{\lambda}_p$ and bending moment loading ratios α_M were taken into consideration for the assessment of the proposed fire design approach.

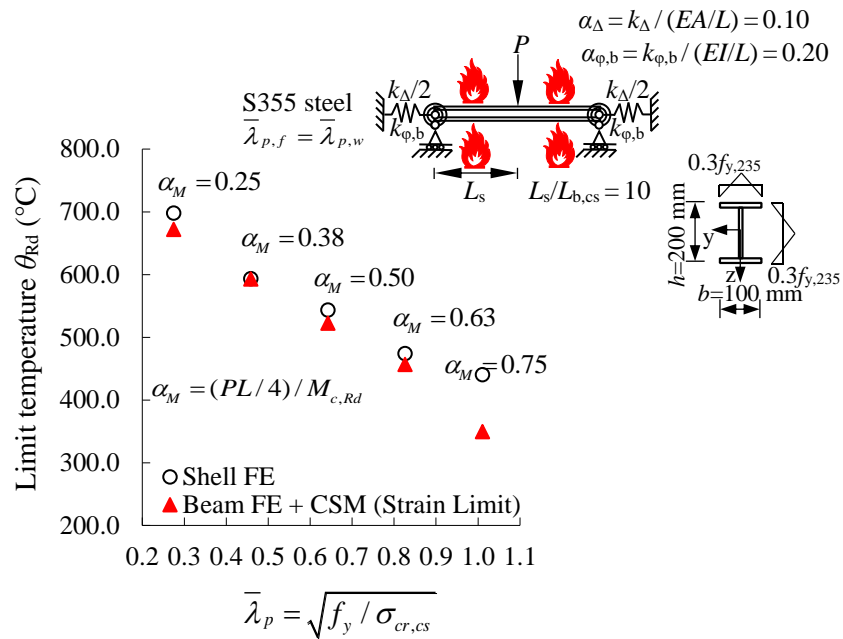
As can be seen in Fig. 6, the proposed GMNIA with strain limits based fire design approach leads to very accurate and safe limit temperature θ_{Rd} predictions for axially unrestrained, axially restrained and axially and rotationally restrained steel beams in fire. Similar to the columns

considered in the previous subsections, the beams were subjected to ISO 834-1 standard fire in the shell finite element simulations which were taken as benchmark data and in the application of the proposed fire design approach.



a) Axially unrestrained I-section beams

b) Axially restrained I-section beams



c) Axially and rotationally restrained I-section beams

Figure 6: Accuracy assessment of the proposed GMNIA with strain limits based fire design approach for axially unrestrained, axially restrained and axially and rotationally restrained carbon steel beams in fire

It is of interest to note that in almost all the cases, the failure is governed by the attainment of the strain limits which signify the failure due to local buckling or the attainment of the maximum

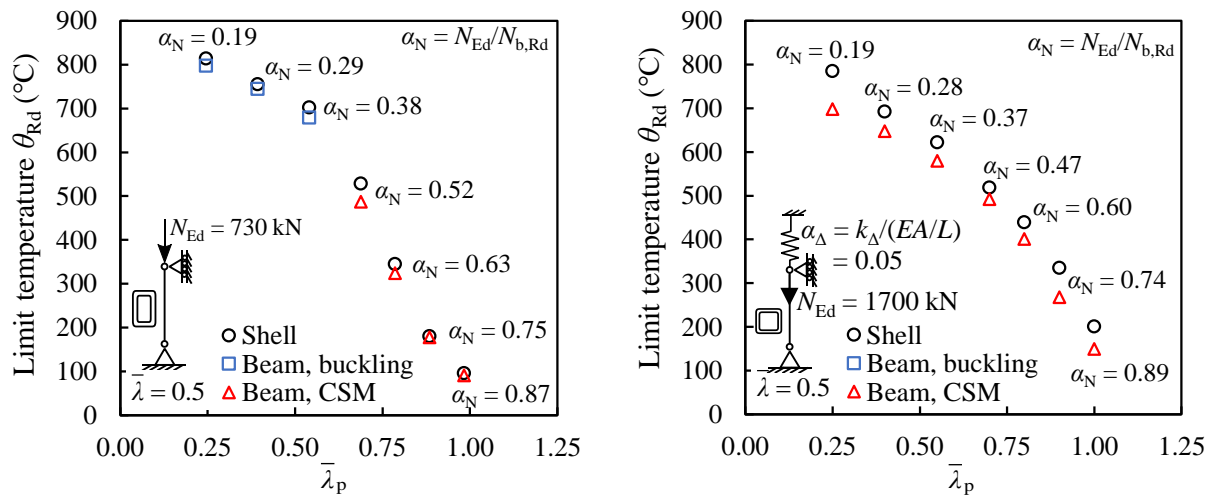
rotation capacity for the considered beams. As expected, the higher the cross-section slenderness $\bar{\lambda}_p$ and the bending moment loading ratio α_M , the lower the limit temperature θ_{Rd} of the beam which is accurately taken into account by the proposed fire design approach. Comparing Fig. 6 (a), Fig. 6 (b) and Fig. (c), it can be seen that the presence of axial restraints leads to reductions in the limit temperatures θ_{Rd} for the beams due to the development of additional axial compressive forces, while the presence of the rotational end restraints leads to increased limit temperatures θ_{Rd} . Both of these effects are very accurately taken into consideration by the proposed fire design approach as can be seen in Fig. 6. In Murtaza and Kucukler (2024a), the accuracy, safety and reliability of the proposed GMNIA with strain limits based fire design approach are extensively verified for steel beams and beam-columns where it is shown that it leads to considerably more accurate and reliable predictions relative to EN 1993-1-2 (2005) for steel beams and beam-columns for a very broad range of parameters. Murtaza and Kucukler (2023, 2024a) also include a number of worked examples which explicitly demonstrates all the steps that should be followed in the application of the proposed GMNIA with strain limits based fire design approach to steel columns, beams and beam-columns.

4.3 Stainless steel columns

Fig. 7 shows the accuracy of the proposed GMNIA with strain limits based fire design approach for axially unrestrained, axially restrained and axially and rotationally restrained stainless steel columns in fire. In the figure, the results for the austenitic, duplex and ferritic stainless steel columns with rectangular hollow sections (RHS) and square hollow sections (SHS) are shown. In all the cases, the columns were subjected to minor axis flexural buckling effects and the room temperature non-dimensional column slendernesses $\bar{\lambda}$ of the columns with respect to minor axis flexural buckling were equal to 0.5 (i.e. $\bar{\lambda} = 0.5$). Similar to the previous cases considered for the carbon steel columns and beams in this study, the stainless steel columns considered in this subsection were subjected to the ISO 834-1 standard fire where the columns were first loaded at room temperature considering their loading ratios α_N and then they are heated up to failure. Fig.7 shows that a wide range of cross-section slendernesses $\bar{\lambda}_p$ and axial load intensities α_N are considered for the verification of the proposed fire design approach for stainless steel columns without axial end restraints, with axial end restraints and with axial and rotational end restraints, where the results from the shell finite element (FE) modes were taken as the benchmark data.

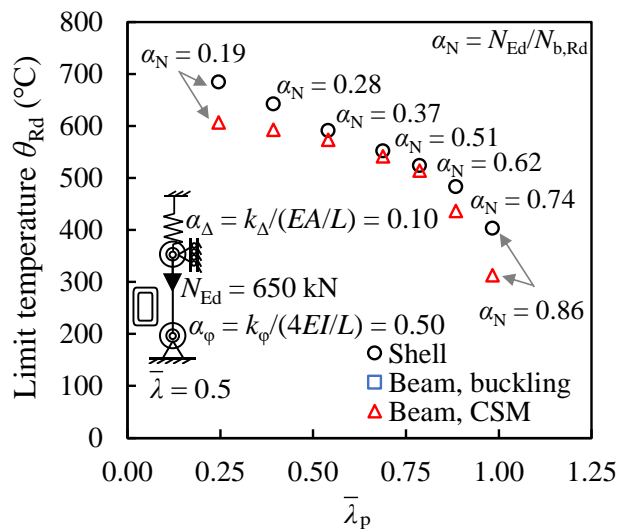
As can be seen from Fig. 7, similar to carbon steel columns and beams, the proposed GMNIA with strain limits based fire design approach provides very accurate as well as safe limit temperature θ_{Rd} predictions for stainless steel columns without axial end restraints and those with axial end restraints and axial and rotational end restraints. The higher the cross-section slenderness $\bar{\lambda}_p$ and the axial loading intensity α_N , the lower the limit temperatures θ_{Rd} for the stainless steel columns, which is accurately accounted for by the proposed fire design approach as can be seen from Fig. 7. The presence of axial restraints leads to additional axial compressive forces as indirect fire actions within stainless steel columns in fire due to the restricted axial expansions. Relative to those for carbon steel columns, the indirect fire actions are expected to be more substantial for stainless steel columns and lead to higher reductions in their limit temperatures as thermal expansion of stainless steel is greater than carbon steel (prEN 1993-1-2, 2005). As can be seen from Fig. 7, the proposed fire design approach accurately considers this increased indirect fire actions (i.e. additional compressive forces due to the restricted thermal expansion) in axially restrained and axially and rotationally restrained stainless steel columns, leading to accurate

estimations of their limit temperatures θ_{Rd} . In Quan and Kucukler (2024), very extensive studies were performed for the verification of the proposed GMNIA with strain limits based fire design approach for stainless steel columns in fire, taking into account a very broad range of cross-section slendernesses, axial loading intensities, stainless steel grades, axial and rotational end restraint stiffness ratios. Stainless steel columns subjected to non-uniform heating was also considered. The accuracy of the proposed fire design approach was also compared against that of EN 1993-1-2 (2005). In Quan and Kucukler (2024), it was shown that the proposed GMNIA with strain limits based fire design approach leads to very accurate and safe capacity predictions for stainless steel columns, with a significantly higher level of consistency and reliability relative to EN 1993-1-2 (2005).



a) Axially unrestrained austenitic stainless steel RHS columns

b) Axially restrained duplex stainless steel SHS columns



c) Axially and rotationally restrained ferritic stainless steel RHS columns

Figure 7: Accuracy assessment of the proposed GMNIA with strain limits based fire design approach for axially unrestrained, axially restrained and axially and rotationally restrained stainless steel columns in fire

6. Conclusions

In this study, the fundamental principles and application of the new GMNIA with strain limits based fire design approach proposed in Murtaza and Kucukler (2023, 2024a) and Quan and Kucukler (2024) for carbon steel and stainless steel structures are described. The method is also applied to carbon steel and stainless steel members in fire. For the considered carbon steel and stainless steel members, a broad range of cross-section slendernesses and room temperature loading ratios were taken into account. The considered members were assessed by adopting the anisothermal analysis technique where the members were first loaded at room temperature and then heated up to failure. All the considered members were subjected to the ISO 834-1 standard fire. Both axially unrestrained as well as axially and axially and rotationally restrained carbon steel and stainless steel members were taken into account for the assessment of the accuracy of the proposed fire design approach; the latter cases are typically encountered in structures due to the presence of surrounding structural elements. For the axially restrained and axially and rotationally restrained carbon steel and stainless steel members, significant additional compressive forces may occur due to the restrictions to the thermal expansions, which are referred to as indirect fire actions and can result in significant reductions in the capacities of steel members. In all the considered broad range of cases, it is shown that the proposed GMNIA with strain limits based fire design approach provides consistent and safe capacity predictions for carbon steel and stainless steel structural elements in fire. The high accuracy of the proposed method for carbon steel and stainless steel members with axial end restraints and those with axial and rotational end restraints in fire was demonstrated, which typically exhibit complex structural response due to the development of significant indirect fire actions. The proposed GMNIA with strain limits based fire design approach provides a very direct and streamlined way of carrying out the fire design of carbon steel and stainless steel structures where all the factors that influence the structural response are taken into account by means of GMNIA performed by computationally efficient beam finite elements and strain limits. The overall structural response and failure modes in fire can be directly captured through the proposed GMNIA with strain limits based fire design approach, thereby providing a very valuable insight into the structural behaviour in fire to the designer and enabling the performance-based fire design where the weak areas of the structure in fire can be easily identified and mitigated. In Murtaza and Kucukler (2023, 2024a) and Quan and Kucukler (2024), the accuracy and reliability of the proposed GMNIA with strain limits based fire design approach are extensively verified for a very large number of carbon steel and stainless steel columns in fire; the fundamental principles and application procedure of the proposed fire design method are also extensively described in Murtaza and Kucukler (2023, 2024a) and Quan and Kucukler (2024). The extension of the proposed GMNIA with strain limits based fire design approach to carbon steel structural systems in fire is currently underway (Murtaza and Kucukler 2024b) and the future research will also focus on the application and verification of the proposed fire design approach to the fire design of stainless steel structural systems.

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