

AN IMPROVED ANALYTICAL FORMULA FOR PREDICTING THE TEMPERATURE OF HEAVILY PROTECTED STEEL SECTIONS

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ABSTRACT

Fire verification might be particularly demanding for steel structures and insulation is a common option to slow down the temperature increase in the steel elements without modifying the original structural design. Simple analytical formulae, as provided for instance in EN1993-1-2 design standard, allow a quick estimate of the temperature of insulated steelwork, without determining the thermal field inside a steel cross-section by performing in-depth experimental or numerical analyses. However, the EN1993-1-2 formulation considers heat transfer with temperature boundary conditions, rather than more realistic conditions on the heat flux, and is inaccurate for heavily insulated steel sections, in which protective solutions with high heat capacity are adopted. In this paper a new analytical formula aimed at estimating the temperature of protected steel members is proposed. Its accuracy is assessed by comparing the predictions of the proposed and the EN1993-1-2 formulations with the results of a parametric analysis consisting of 1-D models. Several steel thicknesses, insulation materials and thicknesses and an exposure to the ISO 834 heating curve are considered in the analyses. It is shown that the EN1993-1-2 can be both conservative and unconservative depending on the ratio between the insulation and the steel heat capacities μ and is not suited for heavily insulated steel sections with high values of μ . On the contrary, the proposed formulation results in being always safe and particularly suited for heavily insulated steel sections.

Keywords: Fire protection; steel temperature; heat transfer; steel structures; Fire safety engineering

1 INTRODUCTION

Fire safety requirements may be particularly demanding for steel structures, due to the inherent vulnerability of steel to thermal attack and the small thickness of the cross-sections, and thus the fire design of unprotected steel members can govern the size of the profiles. Passive fire protection allows the temperature in the steel elements to be slowed down to meet the fire requirements and is one of the most popular solutions as it does not require modifications of the structural design. For this reason, fire protective measures were extensively studied aiming at accurately characterising existing measures and at developing new and optimised solutions [1-7]. For instance, several literature reviews describing the main features and strengths of protective measures were published. Among others, The National Institute of Standards and Technology (NIST) [1], Leborgne and Thomas [2] reviewed different types of fire protections as intumescent paints, sprayed-based protections and board systems, while Mariappan [3] focused on intumescent fire coating. Extensive experimental investigations are available in the literature for steel-concrete solutions as well, in which steel columns are encased in concrete, which provides fire protection

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to the inner steel core [4-7]. Moreover, in the last decades there have been continuous efforts to find new solutions, as fire-retardant products [8], spray-applied fire-resistive composites [9] or plug-and-play protections systems [10].

Despite the extensive research carried out so far and the improvement of computer capabilities that may allow to accurately characterise the behaviour of protected steel elements, easy-to-use hand-calculations are used for a quick assessment of the fire protection suitability to comply with the fire resistance requirements and are still preferred by designers owing to the flexibility required in the design process. Indeed, simple predictive equations support engineers and researchers in rapidly estimating the temperature of insulated steelwork, without performing extensive analyses, as experimental tests or numerical simulation. The predictive formula currently prescribed in the European standard for the fire design of steel structures EN1993-1-2 [11] was developed and calibrated in [12]. It was shown that this formula presents some limitations. In particular, starting from the formulation proposed in [12] and to ECCS recommendations [13], Melinek and Tomas [14] defined a more effective time delay term t_d , which accounts for the retardant effect of insulation on the steel temperature increase, to be substituted in the EN1993-1-2 formulation. Wang et al. [15] suggested the same time delay t_d for insulation materials with high heat capacity C , which typically consist in materials with high density as bricks or concrete. Moreover, it should be highlighted that a Dirichlet boundary condition was assumed in the derivation of the EN 1993-1-2 formulation by assigning the temperature of adjacent gas to the exposed surface $T_s(t, x = x_0) = T_g(t)$. Wong and Ghojel [16] highlighted that the total heat transfer coefficient h_{tot} , that accounts for convection and radiation, should be considered and thus, a more realistic condition on the total heat flux received by the surface $-k \cdot \frac{\partial T_s}{\partial x} \Big|_{x=x_0} = \dot{q}''_{tot}$ should be preferred.

This paper presents a simple predictive formula to estimate the temperature of insulated steel elements suited for insulation materials with relatively high insulation capacities and derived considering heat flux boundary conditions. The formula is based on a lumped approach and considers both radiative and convective components, while terms accounting for the time delay are neglected to keep the formulation simple. The proposed formulation was assessed against results of numerical simulation and compared with the EN1993-1-2 formula. For this purpose, a parametric study was conducted, performing 1-D finite element analyses covering different insulation materials and thicknesses as well as different steel thicknesses. Considerations are provided about the range of applicability of the two predictive formulae and the implications of their employment in the classification of protected steel elements in respect to the fire resistance.

2 LUMPED MASS APPROACHES FOR THE ESTIMATE OF THE EQUIVALENT TEMPERATURE OF INSULATED STEEL MEMBERS

In the described formulations, since steel has a very high thermal diffusivity, it is assumed that the temperature is uniform in sufficiently thin sections and all the heat of the section can be lumped into a zero-dimension point. Therefore, no temperature distributions in the solids are considered and temperatures are only time-dependent.

2.1 EN 1993-1-2 formulation

EN-1993-1-2 [11] provides a recursive equation for the estimate of a uniform temperature distribution in an insulated steel cross-section T_{st} . This formulation is derived assuming a Dirichlet boundary condition in the heat transfer equations, assigning to the exposed surface the temperature of adjacent gas. In detail, the temperature increase ΔT_{st}^{i+1} during the time interval $\Delta t = t_{i+1} - t_i$ is obtained as follows

$$\Delta T_{st}^{i+1} = \frac{\lambda_{in} A_{st} / V_{st}}{d_{in} c_{st} \rho_{st}} \frac{(T_g^i - T_{st}^i)}{\left(1 + \frac{\mu}{3}\right)} \Delta t - \left(e^{\frac{\mu}{10}} - 1\right) \Delta T_g^{i+1} \quad (1)$$

$$T_{st}^{i+1} = T_{st}^i + \Delta T_{st}^{i+1}$$

with $\Delta T_{st}^{i+1} \geq 0$ if $\Delta T_g^{i+1} = T_g^{i+1} - T_g^i > 0$

where T_g is the gas temperature and the parameter μ is calculated as

$$\mu = \frac{c_{in}\rho_{in}}{c_{st}\rho_{st}} d_{in} \frac{A_{st}}{V_{st}} \quad (2)$$

the exponential term of Eq.(1) account for a time delay t_d in the temperature increase of the steel member. As prescribed in EN1993-1-2, the value of Δt should not be greater than 30 seconds.

2.2 Proposed formulation

The derivation of the proposed recursive equations is based on thermal equilibrium. The total received heat flux \dot{q}''_{tot} by the exposed area A in a time dt should be equal to heat stored in the volume V , which is proportional to the temperature rise of the solid dT . Hence, can be defined as

$$\begin{aligned} \dot{q}''_{tot} \cdot A \cdot dt &= V \cdot \rho \cdot c \cdot dT \\ \frac{dT}{dt} &= \frac{A}{V \cdot \rho \cdot c} \dot{q}''_{tot} = \frac{\dot{q}''_{tot}}{C} \end{aligned} \quad (3)$$

where dT/dt is the temperature rise rate, and ρ , c and C are the density, the specific heat capacity and the heat capacity of the heated solid. Consistently with the assumption of lumping the system into a single temperature point, \dot{q}''_{tot} can be taken proportional to the difference between the gas and the steel temperature, as depicted in the electric circuit analogy in Figure 1a, and the rate of steel temperature increase can be expressed as follows

$$\dot{q}''_{tot} = \frac{(T_g - T_{st})}{R_{h+in}} = \frac{(T_g - T_{st})}{\frac{1}{h_{tot}} + \frac{d_{in}}{\lambda_{in}}} \quad (4)$$

where d_{in} is the insulation thickness, λ_{in} is the insulation conductivity and h_{tot} is the total heat transfer coefficient. For heavily insulated steel sections, the contribution of the insulation material to the total heat capacity is relevant and should be accounted as follows

$$\begin{aligned} C &= C_{st} + \chi C_{in} \\ \text{with } C_{st} &= \frac{V_{st}}{A_{st}} \cdot \rho_{st} \cdot c_{st} = d_{st} \cdot \rho_{st} \cdot c_{st} \text{ and } C_{in} = d_{in} \cdot \rho_{in} \cdot c_{in} \end{aligned} \quad (5)$$

d_{st} , ρ_{st} , c_{st} and d_{in} , ρ_{in} , c_{in} are the thickness, the density and the specific heat capacity of steel and insulation respectively. V_{st}/A_{st} is the ratio between the volume per unit length and the enveloping area of the steel section, equivalent to the effective steel thickness d_{st} in the one-dimensional case. The parameter χ quantifies the contribution of the insulation to the heat capacity of the system and is assumed constant for simplicity. In detail, based on preliminary analyses, it was found that considering half of the insulation heat capacity in the total heat capacity, i.e., $\chi=0.5$, allows for good and conservative predictions. Hence, assuming the time derivative of temperature with a differential $\frac{dT}{dt} \approx \frac{\Delta T}{\Delta t}$, and a constant time increment $\Delta t = t_{i+1} - t_i$ between two consecutive steps i and $i+1$, the following formulation is obtained from Eq. (3), Eq. (4) and Eq. (5)

$$T_{st}^{i+1} = T_{st}^i + \frac{1}{(C_{st} + \frac{d_{in}\rho_{in}c_{in}}{2})} \frac{1}{\left(\frac{1}{h_{tot}^i} + \frac{d_{in}}{\lambda_{in}}\right)} (T_g^i - T_{st}^i) \Delta t \quad (6)$$

$$\text{with } h_{tot}^i = h_r^i + h_c = \varepsilon_s \cdot \sigma (T_g^2 + T_s^2) \cdot (T_g + T_s) \approx 4\varepsilon_{in}\sigma (T_g^i)^3 + h_c$$

Where h_r^i is the radiation heat transfer coefficient at step i , h_c is the convection heat transfer coefficient and T_s is the temperature of the exposed insulation surface. It should be observed that the simplification $T_s = T_g$ was employed only in the h_r^i term, differently from the EN 1993-1-2 in which $T_s = T_g$ was assumed as boundary condition. This simplification was introduced since the equation becomes easier to use and, as confirmed by preliminary numerical analyses, no significant variation in the steel temperatures predictions

T_{st} is obtained. Similarly, in order to keep the formulation simple, an explicit term to account for a time delay t_d was not considered. As for the EN 1993-1-2 formulation, if temperature-dependant material properties are used, e.g., $c_{st} = c_{st}(T_{st})$, they should be updated at each step as $c_{st}^i = c_{st}(T_{st}^i)$.

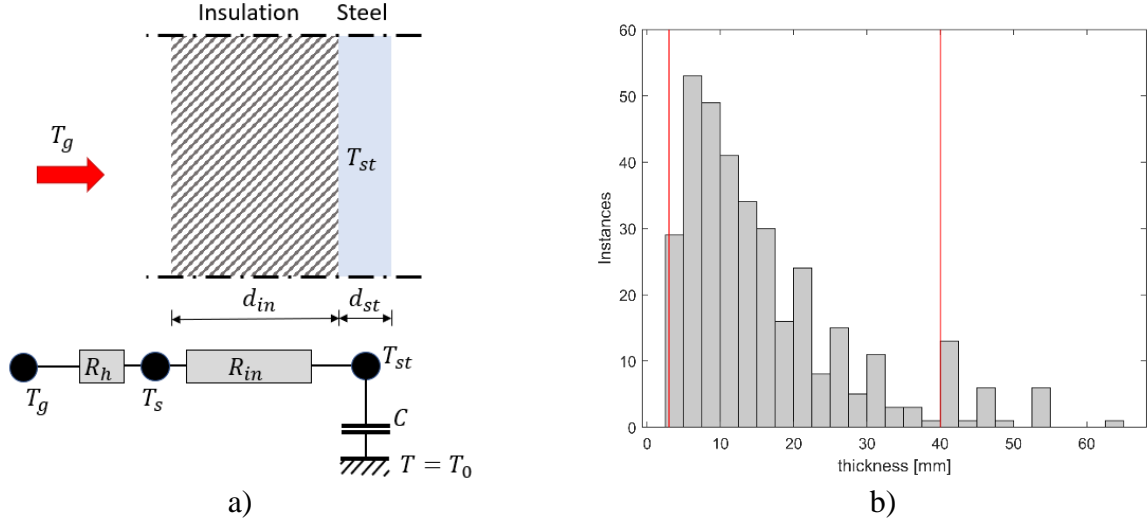


Figure 1. a) Protected steel sections: electric analogy of the thermal model; b) Thickness of plates composing H and I steel profiles

3 NUMERICAL SIMULATION

3.1 Parametric analysis

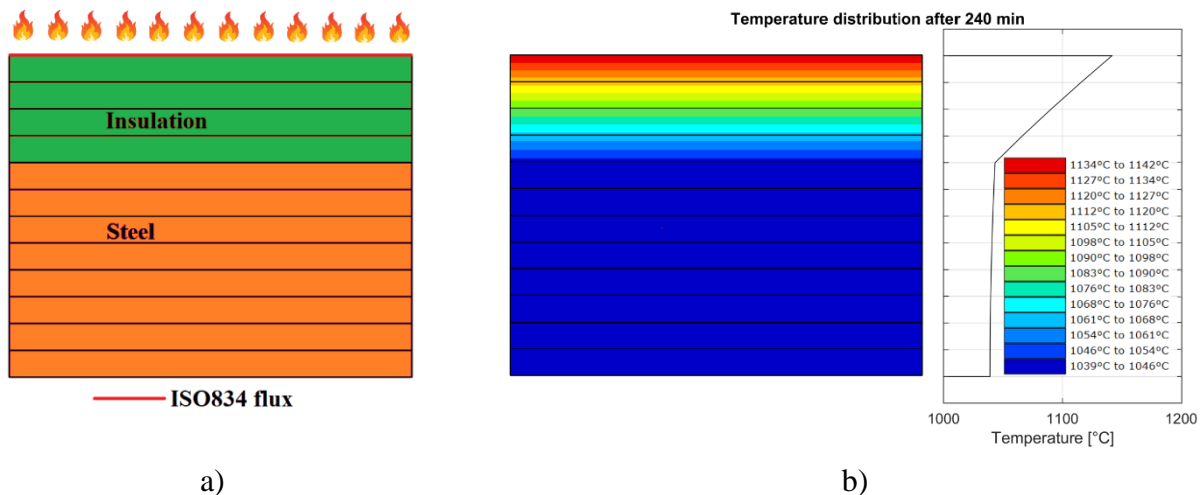
Predictions obtained with the EN1993-1-2 and the proposed formulations were compared against the results of a parametric study, consisting of 1-D thermal analyses. 1-D analyses are employed since the heat transfer through the thickness of the steel components composing typical steel sections, e.g. H and I profiles, is relevant and corner effects are usually neglected in the applications to which the investigated formulations apply. In order to investigate different steel-insulation configurations, 10 insulation materials, 9 insulation thicknesses d_{in} and 15 steel thicknesses d_{st} were considered, as reported in Table 1. The insulation thickness was varied in a range relevant to each of the insulation materials, i.e., 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, 50 mm for all the materials except bricks, for which thicknesses of 100 mm, 125 mm, 150 mm, 175 mm, 200 mm, 225 mm, 250 mm, 275 mm, 300 mm were studied. The values of steel thickness d_{st} were selected inside a range relevant for plates composing steel sections, as confirmed by Figure 1b in which the distribution of the thickness of plates composing H and I steel sections and the limits of the thicknesses considered in the parametric analysis are shown. In detail, the values of d_{st} employed were 3 mm, 5 mm, 8 mm, 10 mm, 13 mm, 16 mm, 18 mm, 21 mm, 24 mm, 26 mm, 29 mm, 32 mm, 34 mm, 37 mm, 40 mm.

Table 1. Investigated insulation materials

	ρ_{in} (kg/m ³)	λ_{in} (W/mK)	c_{in} (J/kgK)	d_{in} (mm) range
Calcareous concrete	2200	1.30	1200	10-50
Concrete with voids	600	0.30	1200	10-50
Lightweight concrete	1600	0.80	1200	10-50
Siliceous concrete	2400	1.70	1200	10-50
Mineral fibres	250	0.10	1100	10-50
Gypsum boards	800	0.20	1700	10-50
Rockwool	120	0.25	1100	10-50
Silicate boards	450	0.15	1100	10-50
Bricks	2000	1.00	1200	100-300
Vermiculite	300	0.15	1100	10-50

3.2 Numerical model

For each of the steel-insulation configurations of the parametric analysis, a numerical simulation was performed by means of the finite element software SAFIR [17]. In the numerical model, shown in Figure 2a, an insulation layer exposed on the upper surface, and a steel layer with an adiabatic condition at the bottom surface were defined. On the lateral surfaces adiabatic conditions were imposed. On the exposed surface a ISO834 flux boundary condition was applied. As 360 minutes is typically the highest requirement of fire resistance of civil structures, a fire exposure of 360 minutes was considered. The analyses were performed setting the timestep $\Delta t=10$ seconds. 4 quadrangular elements for the material with the smallest thickness and a variable number of elements for the material with the larger thickness, as shown in Figure 2a, were employed in the numerical models to have finite elements with comparable dimensions. The selected mesh discretization was sufficiently accurate since by increasing the number of elements in exploratory analyses the difference in the obtained steel temperatures was negligible.



According to EN 1993-1-2 [11], the specific heat c_{st} and the thermal conductivity λ_{st} of steel were considered to vary with the steel temperature T_{st} . These and further relevant model properties are reported in Table 2.

Figure 2. a) Numerical model; b) Typical temperature distribution at $t=240$ min

Table 2. Model properties

		Additional properties	
Heat transfer coefficient h_c (W/m ² K)	25	Specific heat of steel c_{st} (J/kgK)	$c_{st} = c_{st}(T_{st})$ [11]
Emissivity of steel ε_{st}	0.7	Thermal conductivity of steel λ_{st} (W/mK)	$\lambda_{st} = \lambda_{st}(T_{st})$ [11]
Emissivity of insulation ε_{in}	0.9	Unit mass of steel (kg/m ³)	7850

Though the temperature distribution was essentially uniform in the steel in most of the analyses, as shown in Figure 2b in which the typical temperature distribution inside a section is depicted, different temperatures were available at each finite element node. Hence, only the maximum steel temperature, found at the steel-insulation interface one temperature was conservatively chosen as the temperature $T_{st,FEM}$ to be compared with the predictions from the two investigated formulations.

4 COMPARISON BETWEEN NUMERICAL RESULTS AND PREDICTIVE EQUATIONS

The maximum steel temperatures $T_{st,FEM}$ obtained in the parametric analyses were stored at each time of analysis t , or step of analysis i , where the uniform time increment between two consecutive steps was $\Delta t=10$ seconds. These temperatures compared with the predictions of the steel temperature T_{st} obtained with the EN1993-1-2 and the proposed formulations at the same step of the analysis and employing the same time increment, i.e., $\Delta t=10$ seconds. In this respect, Figure 3 provides a synthetic representation of the comparisons with the EN1993-1-2 and the proposed formulation. To identify over- and underestimated predictions in both relative and absolute terms, ranges from -10% to +10% and from -100°C and +100°C in respect to a perfect match between predicted and numerical temperatures (bisector line) are clearly

indicated in the figure. As shown in Figure 3a, EN1993-1-2 predictions (may be both safe (data above the bisector line) and unsafe (data below the bisector line), and significantly higher than +10% or lower than -10% of the FEM temperature. In particular, temperatures higher or lower than $T_{st,FEM}$ for more than 100°C were found until 900°C were not exceeded. Predictions obtained with the proposed formulation (Figure 3b) are much well distributed in the -10% to +10% range, especially for steel temperatures $T_{st,FEM}$ higher than 600°C, when the temperature overestimation becomes much lower than 100°C. Only at very low temperatures predictions are unsafe for more than 10%, but this is not particularly relevant as such predictions are never unsafe for more than 20°C. Indeed, in general an initial overestimation is found at low temperatures, but predictions gradually improve when the steel temperature increases. In addition, considering that failures of steel elements in fire, typically occur for steel temperatures $400^{\circ}\text{C} \leq T_{st} \leq 800^{\circ}\text{C}$ [18-20], a reference critical temperature $T_{crit}=550^{\circ}\text{C}$ within this range was indicated in Figure 3 with a dashed line. Though different temperatures could be assumed as critical for the stability of the steel elements, this temperature was selected as it entails a significant reduction of the yield strength at elevated temperature of 62.5% [11]. It can be observed that when $T_{st,FEM}$ attains T_{crit} , for the EN1993-1-2 (Figure 3a) a maximum and a minimum temperature of 706 °C and 20 °C are obtained (-96% to +28% of T_{crit}), whereas the proposal (Figure 3b) provides conservative predictions between 549°C and 626 °C (0% to +14% of T_{crit}).

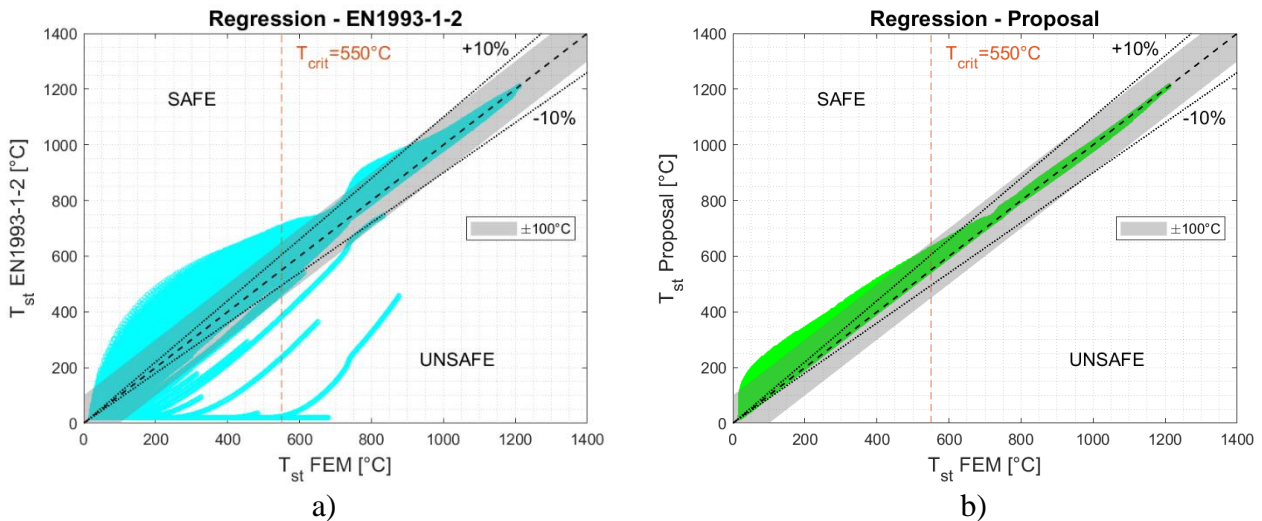


Figure 3. Predicted vs numerical steel temperatures: a) EN1993-1-2 b) Proposed formulation.

Figure 4 compares the results in terms of absolute error, evaluated as the difference between the numerical and the predicted steel temperatures, where each bin spans for an error range of 10°C. The dashed line indicates the zero-error line and unsafe and safe predictions can be found respectively on the left and right of this line. The higher the bins close to dashed line, the better the temperatures predictions. In this respect, the EN1993-1-2 formulation (Figure 4a) ensures fewer predictions in the -10 to 0°C error range compared with the proposed formulation, but in general more predictions are found in more unsafe ranges, i.e., errors <-10°C. Furthermore, higher percentage values are found for safe predictions in the 10 to 80°C range, while a lower percentage is attained for the 0 to 10°C range. Instead, the proposed formulation ensures higher percentages compared for the -10°C to 0°C and the 0°C to +10°C ranges, and no predictions are unsafe for more than 20°C (Figure 4b). Nevertheless, this formulation provides very conservative values for low steel temperatures and therefore, percentages higher than 1% are found until an error value of 150°C is attained. It is interesting to note that limiting the analysis to data for which $T_{st,FEM}$ is inside a relevant range, i.e., $0.9T_{crit} < T_{st} < 1.1T_{crit}$, the error distribution does not significantly differ from the one of the full dataset for the EN1993-1-2 (Figure 4a), while the error percentages become already negligible for an error less than +70°C and a higher percentage is reached in the 0 to +10°C error range for the proposed formulation(Figure 4b).

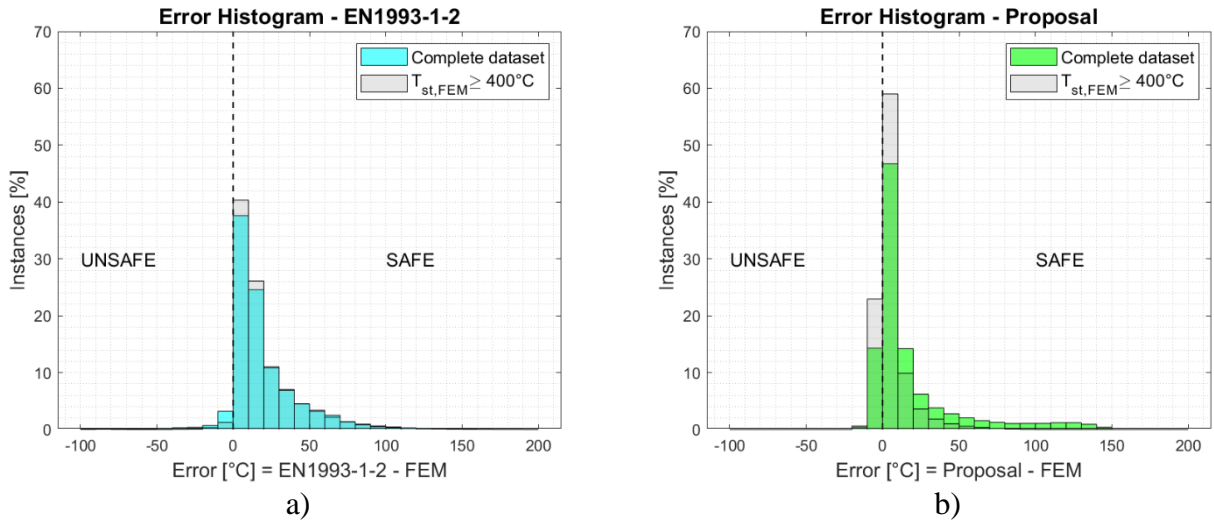


Figure 4. Error distribution: a) EN1993-1-2; b) Proposed formulation

In order to distinguish when the EN1993-1-2 provisions can still provide good predictions and when the proposed formulation should be preferred, results are compared in respect to the parameter μ in Figure 5. The parameter μ , defined as in Eq. (2) represents the ratio between the heat capacities of the insulation and the steel, and assumes higher values for heavy insulations, which typically ensure low temperature rise inside the steel sections. The parameter μ was selected since the EN1993-1-2 is particularly sensitive to this parameter, therefore allowing for the identification of a marked change in the ability to provide safe predictions. In Figure 5 the ratio between predictions and numerical results is reported for predictions associated with $T_{st,FEM}$ values that surpassed a relevant temperature threshold, i.e. $T_{crit}=550^{\circ}\text{C}$. This reference value was conventionally chosen since failure of steel structural elements is typically observed inside the 400°C to 800°C temperatures range owing to the degradation of mechanical properties of steel and in particular of the yield strength [18-20]. In order to provide a clearer representation, the constant value $c_{st}=460\text{ J/kgK}$ was used to calculate μ in Figure 5.

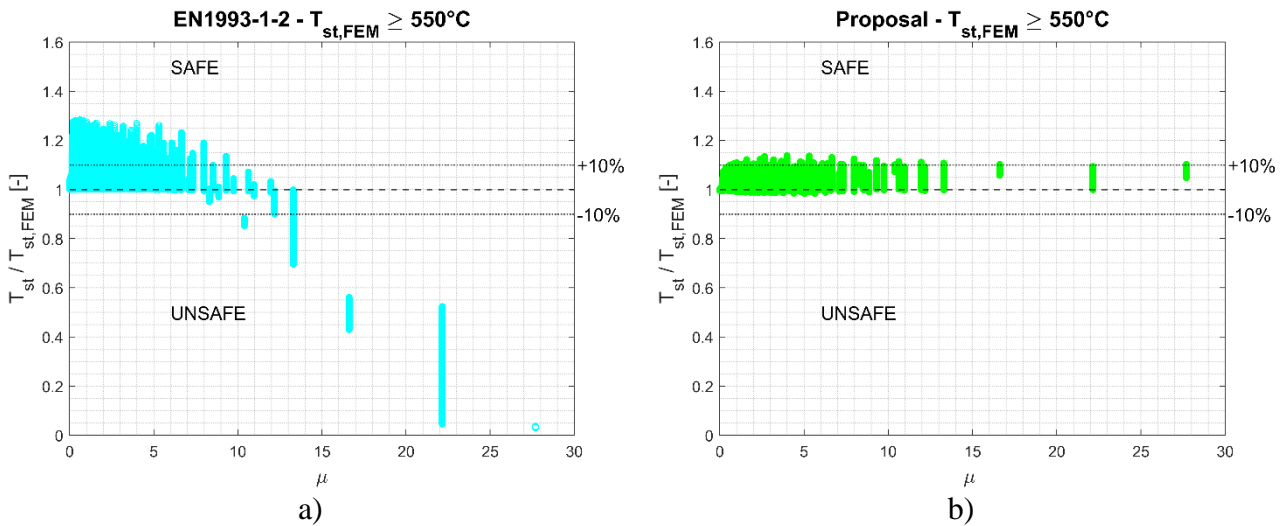


Figure 5. Predicted-numerical temperatures ratio depending on μ for $T_{st,FEM}>550^{\circ}\text{C}$: a) EN1993-1-2; b) Proposed formulation.

Figure 5a shows that the EN1993-1-2 formulation provides predictions of temperatures equal to or higher than T_{crit} that are always safe only for $\mu<7$ and always unsafe for $\mu>14$. Instead, the proposed formulation always provides safe or slightly unsafe predictions regardless of the value of μ (Figure 5b). However, differently from the EN1993-1-2 predictions, the predictions obtained with the proposed formulation are well disposed in the 0% to +10% range. It can be concluded that the proposed formulation should be preferred to the one of EN1993-1-2 for predicting relevant steel temperatures of heavily insulated steel member, and in particular for $\mu>14$. For $\mu<7$ the EN1993-1-2 formulation can be employed as it provides safe and not excessively overestimated prediction, though more accurate predictions of relevant

temperatures may be obtained with the proposal. For $7 < \mu < 14$ the EN1993-1-2 prediction may be better or worse than the proposal depending on the case, but the proposal seems more reliable for relevant temperatures. It should be observed that the proposed formulation gives higher overestimation of the steel temperature for low temperatures and therefore, a term accounting for a time delay t_a could be introduced in Eq.(6) to reduce the error. However, a more complex formulation would be obtained, and such a refinement is beyond the scope of this work, though the formulation could be improved in future developments.

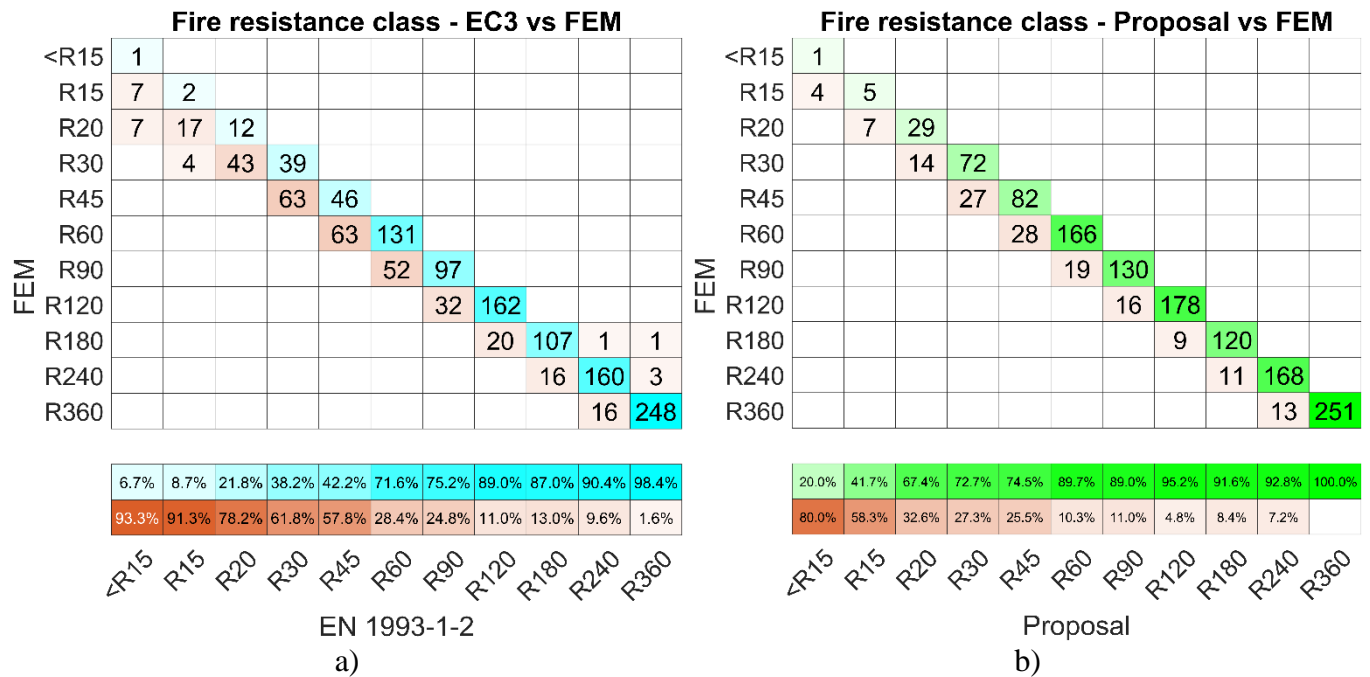


Figure 6. Fire resistance class misclassification for $T_{crit}=550^{\circ}\text{C}$: a) EN1993-1-2; b) Proposed formulation.

Finally, the consequences of the use of the two proposals for the classification of fire resistance was investigated, assuming that the results of the numerical analysis provide the actual resistance class. For simplicity, it was considered that the resistance requirement is met until the temperature does not exceed $T_{crit}=550^{\circ}\text{C}$. Therefore, for each of the studied steel-insulation configurations the times t_{crit} for which the critical temperature T_{crit} was exceeded in the numerical analyses were identified and the associated resistance classes were determined for both formulations. Since the number in the class label, e.g. 15 in R15, represents the minutes for which the resistance of the steel element is guaranteed, the fire resistance class was determined as the highest class time exceeded by t_{crit} , e.g. an analysis with $t_{crit}=32$ minutes is classified as R30. The results of the classification are reported in two confusion matrices in Figure 6 comparing the classification of numerical analyses with the ones of the EN1993-1-2 and the proposal, respectively. The diagonal values correspond to the number of correct identifications for each resistance class, i.e. same classification as for the numerical analyses, while out-of-diagonal values represent the misclassified resistances, where over- and underestimated classes are found above and below the diagonal respectively. It can be observed that the proposal allows for a better classification as a higher number of analyses are found on the diagonal in respect to EN1993-1-2. The analyses misclassified with the proposal, see Figure 6b, are always below the diagonal and therefore on the safe side, and never for more than one class. As expected, more relevant misclassifications are found for lower classes, when the time between two classes is smaller than for higher classes. Instead, the misclassified analyses obtained with the EN1993-1-2 formulation (Figure 6a) sometimes differ from the classification of finite element analyses for more than one class and are not always on the safe side. In fact, a too conservative classification is obtained for the lowest classes, where some analyses cannot even be classified in the lowest resistance class (<R15), while some analyses are unsafe for the highest classes, where a variation of one class implies a difference in t_{crit} of 60 minutes or 120 minutes. The accuracy of the classifications can be evaluated with a synthetic indicator that spans from 0 (no class correctly identified) to 1 (all classes correctly identified), defined as

the ratio between the sum of the diagonal values and the sum of the diagonal and off-diagonal values. This indicator assumes the value of 0.74 and 0.89 for the EN1993-1-2 and the proposal respectively.

5 CONCLUSIONS

In this paper a new analytical formulation based on a mass lumped approach is proposed to predict the temperature of insulated steel elements. The proposed formulation is suited for heavily insulated steel, widening the applicability range of the current equation provided in EN1993-1-2, which was demonstrated to be inaccurate for insulation materials with relatively high heat capacity C . In particular, in contrast with the equation provided in EN1993-1-2, in which it is conservatively assumed that the temperature of the exposed surface equals the temperature of the surrounding gas, the new predictive equation is based on more realistic heat flux boundary conditions. In order to emphasise the improvement introduced, results of a parametric analysis consisting of 1-D heat-transfer finite element analyses were compared with the predictions of the proposed and the EN1993-1-2 formulations. Different steel-insulation configurations, obtained by varying the insulation properties and the steel and insulations thicknesses, were investigated for an exposure to an ISO834 fire for 360 minutes. The proposed formulation always ensured safe or just slightly unsafe predictions (unsafe for no more than 20°C), while the EN1993-1-2 formulation gave both safe and unsafe predictions and was significantly unsafe for high values of the ratio between the insulation and the steel heat capacities μ . In specific, considering only steel temperatures above a reference critical temperature above which it is assumed that a protected steel member has lost its bearing capacity, i.e. 550°C, the EN1993-1-2 gives predictions that are always safe for $\mu < 7$, always unsafe for $\mu > 14$, and can be both safe and unsafe otherwise. The proposed formulation instead, provides safe predictions that fit very well the safe 0 to +10% range. In addition, the consequences of the employment of the two different formulations were quantified in terms of fire resistance class, assuming 550°C as the reference critical temperature. It was observed that a more accurate classification is obtained with the new proposal, whereas a more relevant misclassification was found considering the EN1993-1-2 equation, for which too conservative and unconservative classifications were obtained for low and high fire resistance classes, respectively. In light of the presented analysis, the proposed formulation is suggested for heavily insulated steel sections, especially for $\mu > 14$, but it can also be employed regardless from the value of μ . More thorough numerical analyses, e.g. 2-D, and experimental results will be considered in future developments for further validations, as well as a more detailed evaluation of the consequences of the used of different predictive equations.

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