# EFFETTO DELLA ZINCATURA SU ELEMENTI IN ACCIAIO ESPOSTI ALL' INCENDIO

# GALVANIZATION EFFECT ON STEEL MEMBERS EXPOSED TO FIRE

Margherita Autiero,
Donatella de Silva
Antonio Bilotta
Emidio Nigro
University of Naples Federico II
Department of Structures for Engineering and Architecture, Di.St.,
Naples, Italy
margherita.autiero2@unina.it
donatella.desilva@unina.it
antonio.bilotta@unina.it
emidio.nigro@unina.it

Lello Pernice
AIZ - Associazione Italiana Zincatura,
Rome, Italy
lello.pernice@aiz.it

## ABSTRACT

Recent studies have shown that hot-dip galvanization, which is already efficient in protecting steel members from corrosion, can also benefit the temperature of steel members exposed to fire thanks to a reduction in surface emissivity. The current Eurocode provides a constant emissivity value equal to 0.70. Whereas background documents for the next generation of structural Eurocodes suggest considering this positive effect through a temperature dependent surface emissivity relationship. To investigate the effect of galvanization on the temperature of steel plates with variable section factors ($A_m/V$) an experimental campaign was carried out. The high-temperature small-scale tests were performed in an electrical furnace by exposing to heat only the upper face of plates and by inhibiting the heat exchange on the remaining surfaces thanks to protective materials, in order to obtain equivalent section factor by simply varying the thickness of the plates. For each section factor, ranging between 20 and 200$m^{-1}$, both galvanized and non-galvanized steel specimens were tested to directly compare their temperature. The test results show that the heating in hot-dip galvanized specimens was slower than the one recorded in non-galvanized specimens, confirming the beneficial effect of the galvanization. To quantify this effect and to calibrate the emissivity of the hot-galvanized steel, the analytical method of temperature calculation, suggested also by Eurocode, was applied using the temperatures recorded during the tests. The surface emissivity has been confirmed to be temperature dependent.

## SOMMARIO

Recenti studi hanno dimostrato che la zincatura a caldo, già efficace per proteggere gli elementi in acciaio dalla corrosione, è anche in grado di fornire un effetto benefico sulla temperatura dei componenti in acciaio esposti all'incendio grazie ad una riduzione dell'emissività superficiale. L'Eurocodice attuale fornisce un valore di emissività costante pari a 0,70, mentre i documenti di riferimento per la prossima generazione degli Eurocodici strutturali suggeriscono di considerare questo effetto positivo attraverso un valore di emissività dipendente dalla temperatura. Al fine di studiare l'effetto della zincatura sulla temperatura di piatti d'acciaio con fattori di sezione variabili ($A_m/V$) è stata condotta una campagna sperimentale. Le prove ad alta temperatura su piccola scala sono state eseguite in un forno elettrico esponendo solo la faccia superiore delle piastre e inibendo lo scambio termico sulle superfici rimanenti grazie all'utilizzo di materiali protettivi, al fine di ottenere un fattore di sezione equivalente semplicemente variando lo spessore delle lastre. Per ogni fattore di sezione, compreso tra 20 e $200m^{-1}$, sono stati testati campioni di acciaio zincato e non zincato così da poter confrontare la loro temperatura. I risultati mostrano che il riscaldamento nei campioni zincati è più lento di quello negli elementi non zincati, confermando l'effetto benefico della zincatura. Per quantificare questo effetto e calibrare l'emissività dell'acciaio zincato a caldo, è stato applicato il metodo analitico per calcolare la temperatura, suggerito anche dall' Eurocodice, utilizzando le temperature registrate durante le prove. I risultati confermano che l'emissività superficiale è funzione della temperatura.

## 1 INTRODUCTION

Galvanization is a surface coating process to protect steel members from corrosion, in which the steel is coated with zinc to prevent it from rusting. The most common galvanization method is hot-dip galvanizing, where the protective zinc coating is obtained by dipping the steel element into a bath of molten zinc usually at about 450°C. The zinc coating is formed by a metallurgic reaction during which several zinc-iron alloy layers are formed. Therefore, the coating is chemically bound to steel beneath, and it is not only laid on top of it. The formation of the zinc coating depends on several factors. On one hand, it depends on the galvanizing conditions such as melting temperature, dipping time and chemical composition of zinc bath. On the other hand, it is influenced by surface conditions and chemical composition of the steel (e.g. silicon and phosphorous content). Silicon concentration in quantities between 0.04% and 0.14% (Sandelin steel) or above 0.22% (hyper-Sandelin steels) can accelerate the iron-zinc reaction to form a thicker zinc coating with a different alloy layer structure [1]. Four steel categories (C_x), according to EN ISO 14713-2 [2] are defined based on the silicon concentration: C_A - Low silicon content steel ($Si \leq 0.04\%$), C_B: Non-Sandelin intermediate composition steels ($14\% < Si \leq 0.22\%$), C_C: Sandelin steel ($0.04\% < Si \leq 0.14\%$) and C_D: hyper-Sandelin steels ($Si > 0.22$ %).
The surface coating can modify the emissivity that is the ratio between the energy radiated from a surface of a material and the energy radiated from a black body, under same conditions, at same temperature and wavelength. The radiative component of the net heat flux depends on the emissivity of flame $\varepsilon_f$, and on the member surface $\varepsilon_m$ one [3]. The emissivity ranges between zero and one and lower is the emissivity of a surface, slower is the heating.
The radiation of metal surfaces depends on atomic and molecular level. Sala [4] states that the radiation behavior depends on the chemical composition in a layer with a thickness of few microns. The radiation behavior of galvanized surfaces should hence be provided exclusively by the

alloy layer (40 μm to 250 μm) or from the upper pure zinc layer alone, which is only a few micrometers thick .
Therefore, the emissivity of hot-dip galvanized steel elements is influenced by the alloy layer composition, by the oxidation of zinc, and by the melting of the outer zinc layer at a temperature of 419°C. As a result, the emissivity of the galvanized surface is variable with temperature [5].
The Eurocode EN1993-1-2 [3] suggests a simplified surface-independent constant emissivity, εm = 0,70 for carbon steel, whereas recent studies [5],[6],[7],[8] showed that galvanization can also reduce the surface emissivity with a beneficial effect on the temperature of steel members exposed to fire. Jirku and Wald (2013) [6] performed a fire test in a real scale building and two fire tests in furnace on steel members with IPE200 and hollow tube cross-sections, obtaining a constant value of emissivity for galvanized steel equal to 0.32. While Bihina et al.[7] carried out three standard fire tests on hot-rolled steel structural members, finding an equivalent emissivity for hot-dip galvanized specimens, that increases with temperature. Mensinger and Gaigl (2019) [5] assessed emissivity curves as a function of temperature for hot-dip galvanized steel elements by small-scale and full-scale tests. The temperature-dependent emissivity was determined for various hot-dip galvanized surfaces and steel categories C_A, C_B, and C_D were tested, combined with all possible surface conditions. The results showed an emissivity dependent not only on temperature, but also by the weathering, with the negative influence of outdoor storage. Moreover, the results highlighted that the zinc-iron alloy layers have a big influence on the emissivity value. In particular, only for steel of C_A and C_B, the emissivity value is lower than 0.7, for steel temperatures up to 530 °C. Due to chemical reactions, a new layer structure is formed with a higher roughness and a consequent increasing of surface emissivity. Therefore, while EN1993-1-2 [3] suggests a simplified surface independent constant emissivity for carbon steel $\varepsilon_m$ = 0,70, the experimental results showed a temperature-dependent emissivity for hot-dip galvanized steel, with values lower than 0.7 for steel temperatures up to 500 °C. Since the studies conducted in literature showed a positive effect of galvanization on the steel temperature due to the variation of the emissivity, Mensinger and Gaigl [5] suggested an emissivity ($\varepsilon_m$) equal to 0,35 for steel temperature ($\theta_{a,t}$) lower than 500 °C and εm equal to 0,70 for $\theta_{a,t}$ greater than 500 °C.
Starting from these considerations, this paper shows the results of high-temperature small-scale tests on square galvanized and ungalvanized steel plates, investigating and quantifying the effect of galvanization on the temperatures of steel elements, in order to calculate the emissivity of galvanized steel through small-scale tests in a common and economical electrical furnace.

## 2 EXPERIMENTAL PROGRAMME

The experimental tests were performed in an electrical furnace by exposing to heat only the upper surface of specimens, while the remaining parts were protected with an insulating material in order to reduce heat exchange. Therefore, the steel samples consisted of 44 plates, placed inside a box composed by a sequence of five calcium silicate boards 12.7 mm thick, in order to approximately obtain laterally adiabatic conditions (see Fig. 1a). The box was placed on a rockwool layer and finally on refractory bricks. Inside the box, a variable layer of rockwool was placed, to ensure that the sample and the box upper surfaces were aligned to each other (see Fig. 1b). The square samples had dimensions of 50x50mm, with a variable thickness, in order to obtain different section factors $A_m/V$ (ratio between the surface area exposed to fire and the volume of the element) ranging between 20 and 200m$^{-1}$. For each section factor, one non-galvanized (NG) and three galvanized (G) specimens were tested to have a direct comparison between their temperatures.
The test samples were galvanized using a galvanizing bath according to UNI EN 1461:09. As a result, the galvanized specimens have a mean galvanizing thickness of about 120μm. The ID of the specimen is X-Y-Z: where X is the section factor of the specimen, Y indicates if the sample is

galvanized (G) or not galvanized (NG) and Z indicates the number of the tested specimen. The thickness of the specimens and their section factors are listed in Table 1.

**Table 1** Test matrix

| Not galvanized (NG) | Galvanized (G) | | | $A_m/V$ [$m^{-1}$] | s [mm] |
|---|---|---|---|---|---|
| 20_NG_1 | 20_G_1 | 20_G_2 | 20_G_3 | 20 | 50 |
| 30_NG_1 | 30_G_1 | 30_G_2 | 30_G_3 | 30 | 35 |
| 40_NG_1 | 40_G_1 | 40_G_2 | 40_G_3 | 40 | 25 |
| 50_NG_1 | 50_G_1 | 50_G_2 | 50_G_3 | 50 | 20 |
| 60_NG_1 | 60_G_1 | 60_G_2 | 60_G_3 | 60 | 17 |
| 70_NG_1 | 70_G_1 | 70_G_2 | 70_G_3 | 70 | 14 |
| 80_NG_1 | 80_G_1 | 80_G_2 | 80_G_3 | 80 | 12.5 |
| 90_NG_1 | 90_G_1 | 90_G_2 | 90_G_3 | 90 | 11 |
| 100_NG_1 | 100_G_1 | 100_G_2 | 100_G_3 | 100 | 10 |
| 125_NG_1 | 125_G_1 | 125_G_2 | 125_G_3 | 125 | 8 |
| 200_NG_1 | 200_G_1 | 200_G_2 | 200_G_3 | 200 | 5 |

To measure the temperature in the steel samples three Chromel/Alumel K thermocouples were inserted from the furnace inspection hole while the fourth one was assembled in the furnace (see Figure 1b).

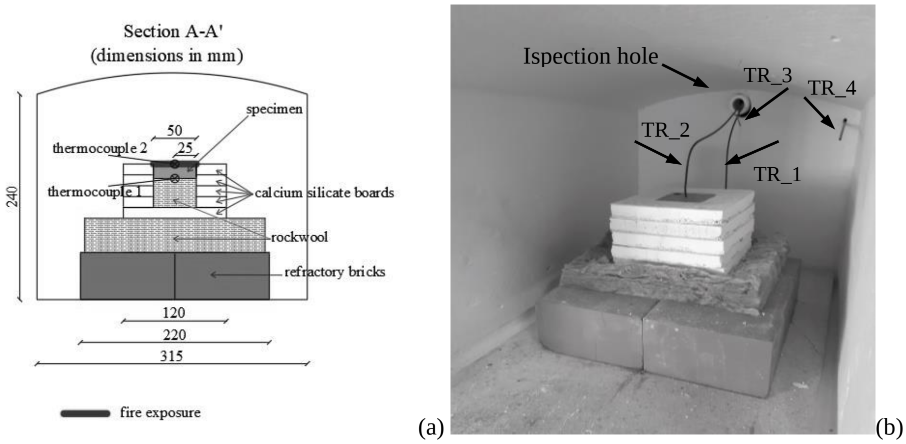



**Fig. 1** Test set up: (a) cross section, (b) setup in the furnace

In particular, the thermocouple (TR_1) was used to measure the steel temperature in the directly exposed face, while the (TR_2) measured the temperature in the non-exposed face. To insert these two thermocouples each steel sample was previously drilled with a hole diameter of 2.5mm and a depth of 4mm. The (TR_3) was used to monitor the furnace temperature, as also the furnace thermocouple (TR_4); the scheme of these devices is shown in Figure 3a. An acquisition system allows to record all the temperatures detected by each thermocouple. The tests were carried out by using an input fire curve with a development from 20°C to 800°C, and so slower than the standard fire curve, because of this particular type of furnace. The graphs of Fig. 2 contain the input fire curve obtained as the mean of each test with same $A_m/V$ (Mean_input_Am/V).

Fig. 2a shows the temperature recorded by TR_1 for each galvanized sample and their mean value (black curve) for the three selected section factors. For sake of brevity, in this paper the results obtained for only the section factor $A_m/V$ equal to 80 $m^{-1}$ and 200 $m^{-1}$ are discussed below, where for the section factors $A_m/V$= 80 $m^{-1}$, all the test results were available While, for the $A_m/V$= 200 $m^{-1}$ only the results obtained for two galvanized and one ungalvanized specimens are available, because one thermocouple didn't work during the test .

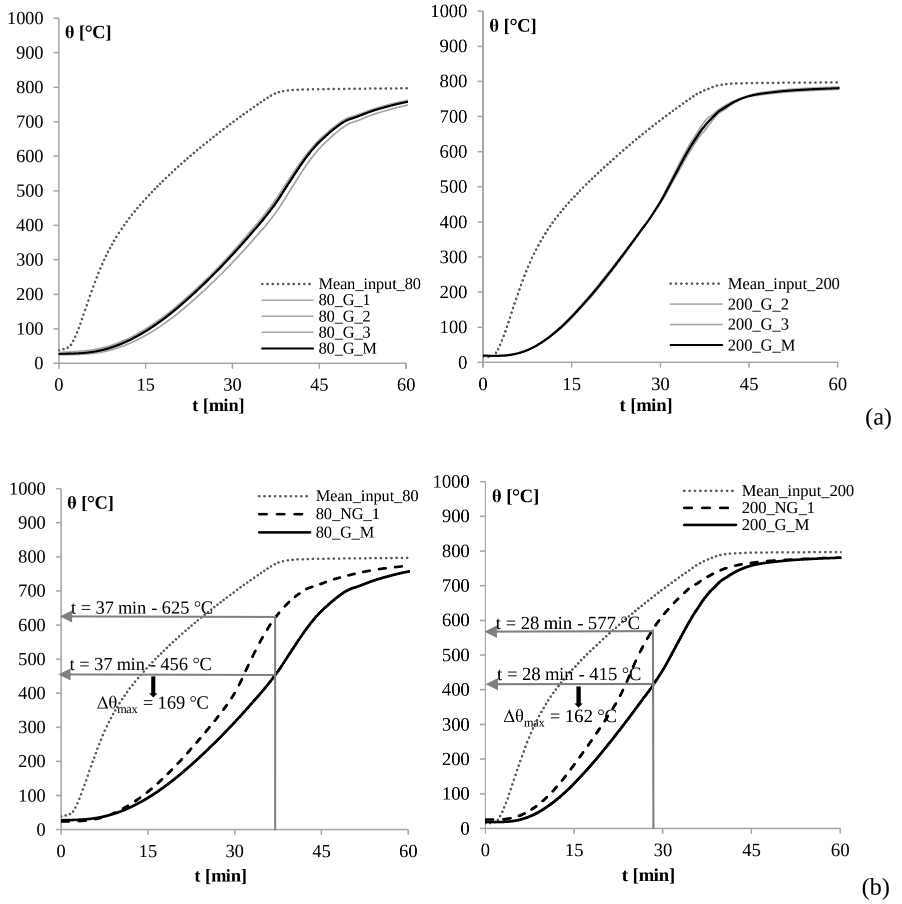



**Fig.2** Comparison between temperatures of three galvanized specimens with same $A_m/V$ and their mean value (G_M) (a); temperatures of the non-galvanized samples (NG_1) and the mean value of the galvanized ones (G_M) with same $A_m/V$ (b)

The graph in Fig.2a shows that, the steel temperatures recorded in the galvanized specimens, with the same section factor, during tests are very similar to each other, demonstrating not only the stability of the results but also the reliability of the test setup. For this reason, the mean temperature value ($A_m/V$_G_M) for each section factor is considered in the following comparison.

Fig. 2b shows the experimental results obtained for the non-galvanized (80_NG) and galvanized (80_G_M) specimens with dashed and continuous curves respectively. These results demonstrate the effect of galvanizing in terms of lower temperatures of the hot-dip galvanized specimens. For example, at 30 minutes of exposure time the temperature of blank specimen $\theta_{80\_NG}$ reached 400 °C while the same galvanized specimens have a temperature $\theta_{80\_G}$ of 315 °C. This difference of 86°C changes during the heating with a maximum value ($\Delta_{\theta max}$) of 169 °C at 37 minutes, when the temperatures are $\theta_{80\_NG}$ = 625 °C and $\theta_{80\_G}$ = 456 °C respectively. Passing from a section factor of 40 $m^{-1}$ to 200 $m^{-1}$ the specimens show faster heating and the maximum beneficial effect of galvanizing on the steel temperatures appears already at 28 minutes; at this time $\Delta_{\theta max}$ is equal to 162 °C with $\theta_{200\_NG}$ of 614 °C and $\theta_{200\_G}$ of 457 °C. With the increase of exposure time, the beneficial effect of galvanizing is reduced due to the rapid heating of the steel element characterised by a high value of $A_m/V$. Fig.3 plots a direct comparison between the experimental results of galvanized and non-galvanized specimens obtained for the three $A_m/V$ = 40, 80, 200 $m^{-1}$. Due to the different values of $A_m/V$, the steel temperature curves are clearly different, but for the same $A_m/V$, the maximum temperature difference between galvanized and blank samples is reached when the temperatures in galvanized specimens are about 450 °C at different heating times.

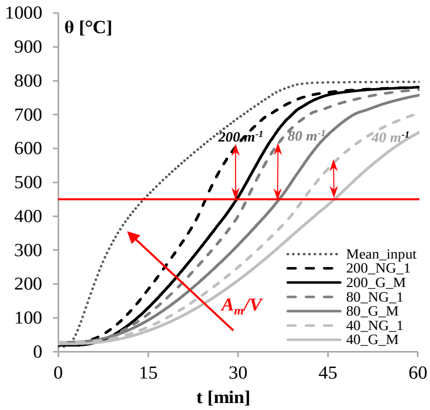



**Fig.3** Comparison between experimental results of different galvanized (G) and blank (NG) specimens with $A_m/V$ = 40, 80, 200 $m^{-1}$.

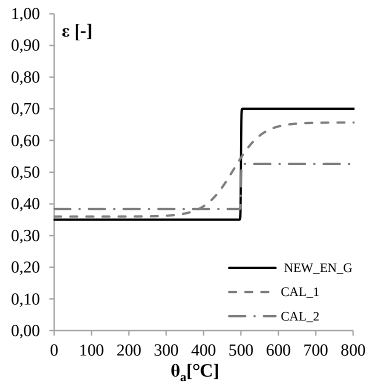
## 4 ANALYTICAL MODELLING OF GALVANIZED STEEL MEMBERS

Starting from the experimental results, a simulation of the tests on galvanized samples was carried out by implementing the analytical method for the steel temperature development, suggested also by Eurocode EN1993-1-2 [3], the effect of galvanizing was modelled according to the two-stages emissivity relationship suggested in [5] ($\varepsilon_m$ = 0,35 for $\theta_{a,t} \leq 500$ °C; $\varepsilon_m$ = 0,70 for $\theta_{a,t} > 500$ °C), later called NEW_EN_G. As thermal action the thermal input curves obtained from each test was considered, a convection coefficient, $\alpha_c$, lower than the one related to the standard fire curve was used to consider the convective thermal flux specific for these tests. This $\alpha_c$ value was calculated for non-galvanized specimens with three different section factors based on the mean of the temperatures recorded by the lower TC_1 and the upper TC_2 thermocouples and by considering the sample as a grey emitter and the furnace walls area bigger than the sample surface; in this way, a mean value $\alpha_c$ equal to 6.4 $W/m^2K$ was calculated.

Moreover, some calibrations were conducted to obtain the surface emissivity variation with the steel temperatures. Starting from all the data analyzed in the first part of the paper, the following analytical function was calibrated by comparing the experimental results obtained for the galvanized specimens with the analytical ones by varying the four parameters: $\varepsilon_{max}$, $\varepsilon_{min}$, β and γ:

$$\varepsilon_m = 0.5\cdot(\varepsilon_{m,\max}-\varepsilon_{m,\min})\cdot\tanh[(\frac{1}{\beta})\cdot\left(\theta_{a,t}-\gamma\right)]+0.5\cdot(\varepsilon_{m,\max}+\varepsilon_{m,\min}) \tag{1}$$

In particular, two different calibrations were carried out: CAL_1, which refers to each $A_m/V$, and CAL_2, which refers to all the $A_m/V$.




| | $\varepsilon_{m,min}$ [-] | $\varepsilon_{m,max}$ [-] | β [-] | γ [-] |
|---|---|---|---|---|
| **NEW_EN_G** | 0.35 | 0.7 | - | - |
| **CAL_1** | 0.36 | 0.66 | 77 | 480 |
| **CAL_2** | 0.38 | 0.53 | 1 | 500 |

**Fig. 4** Comparison between emissivity curves obtained for the two different calibrations, (CAL_1, CAL_2) and the NEW_EN_G.

Fig.4 shows the development of the two curves obtained from equation (1) for CAL_1 and CAL_2 and a comparison with the two-stages emissivity relationship (NEW_EN_G). Even though these two curves are based on results of small-scale tests performed in a common and cheap electrical furnace, they confirmed that the development of galvanized steel emissivity depends on the steel temperature.

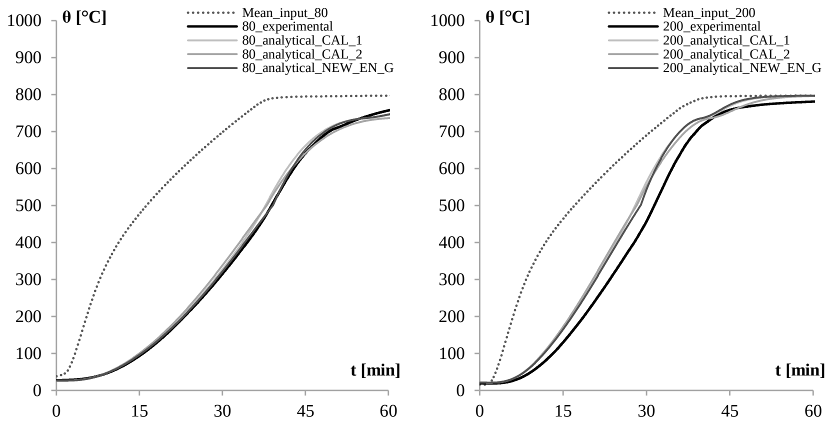



**Fig. 5** Comparison between experimental and analytical results

Fig. 5 compares the experimental temperatures and the analytical ones calculated using the emissivity values of CAL_1, CAL_2 and NEW_EN_G and obtained for the section factors $A_m/V$= 80 and 200 $m^{-1}$: a small difference is found with the experimental curves in the two cases. Furthermore, the analytical curves are very similar to each other using emissivity values according to CAL_1, CAL_2 and NEW_EN_G. an input curve slower than the standard ISO834 fire curve, the results of Fig. 5 show that several emissivity formulations may be used also for fire curves different from the standard one, as they are able to modelling the behaviour of galvanized steel elements with good accuracy.

## 8 CONCLUSIONS

This paper presents an experimental program aimed to investigate the behavior of galvanized steel members and the characterization of its surface emissivity starting from the temperatures measured during small-scale tests in a common and cheap electrical furnace. The experimental samples included both galvanized and blank steel plates with different section factors ($A_m/V$) between 20 and 200 $m^{-1}$, tested using an input curve slower than the standard ISO834 one. The experimental results showed that the temperatures in the hot-dip galvanized specimens were lower than the non-galvanized ones, confirming the beneficial effect of the galvanization. The analytical method suggested by the Eurocodes for the steel temperature development was implemented to calculate the emissivity starting from the measured temperatures and using a convection coefficient specific to this experimental setup. Confirming that the emissivity depends on steel temperature, two emissivity curves were calibrated and used to calculate the steel temperature according to the analytical method. The results were found to be in very good agreement with the ones calculated with the two-stages law, therefore these emissivity formulations may be used also for fire curves different from the standard one. Further developments of the research include some applications of temperature dependent emissivity law by considering natural fire curves.

## REFERENCES

[1] Pernice L. (2021). Zincatura a caldo. Mirapromotion Srl. (In Italian)
[2] ISO 14713-2:2009, Zinc coatings — Guidelines and recommendations for the protection against corrosion of iron and steel in structures — Part 2: Hot dip galvanizing
[3] EN 1993-1-2, Eurocode 3: Design of steel structures - Part 1-2: General rules -Structural fire design, 2005.
[4] Sala A. (1986) . Radiant properties of materials: Tables of radiant values for black bodies and real materials, Elsevier Science Ltd.
[5] Gaigl C., (2019). Fire resistance of hot-dip galvanized steel structures, PhD Thesis, Technical University of Munich.
[6] Jirku J., Wald F., (2013). Influence of zinc coating to a temperature of steel members in fire, in ASFE'13 - Application of Structural Fire Engineering, 19-20 April 2013, Prague, Czech Republic.
[7] Bihina G., Zhao B. (2021). Hot dip galvanizing of steel structural members: an alternative to passive fire insulation? Ce/papers 4, Proceedings of Eurosteel 2021: 1–3 September 2021, Sheffield, England.
[8] Autiero M., Bilotta A., de Silva D., Nigro E., Pernice L. (2021). Temperature of galvanized steel specimens heated in electrical furnace, in ASFE 2021 - Applications of Structural Fire Engineering, 10-11 June 2021, Lubiana, Slovenia. Paper Id. 62, 6 pp.

## KEYWORDS

Steel structures, steel elements, galvanization, fire resistance, experimental tests, surface emissivity, electrical furnace