New Guidance on fire resistance of galvanized steel sections

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Introduction

Galvanizing to EN ISO 1461[1] is commonly used to provide protection against corrosion for a wide variety of steel components, ranging in size from nuts and bolts to large structural sections. The process involves dipping steel components into molten zinc (which is usually around 450°C) for a few minutes. Unlike a paint coating, the metallurgical bond that is formed through galvanizing becomes part of the steel itself and is not merely a chemical or mechanical bond. As a result, galvanized steel not only provides corrosion protection but also has a high resistance to mechanical damage during handling, storage, transport and erection.

The zinc protective layer also provides a reduced surface emissivity of the steel component, which influences the rate at which the temperature of a steel section increases when exposed to a source of heat. Laboratory and full-scale testing[2,3], have demonstrated that below approximately 500°C, the galvanized coating remains stable, and its surface emissivity is around half of that for non-galvanized steel. A galvanized steel section will therefore heat up at a slower rate than an equivalent non-galvanized section which means an increased duration of fire resistance or increased load bearing resistance for a given fire exposure period.

Temperature increase of a steel member under fire conditions

Heat transfer to a steel member is predominantly by two mechanisms — radiation and convection. EN 1993-1-2[4], clause 4.2.5.1 gives a simple heat transfer model, which is used to determine the increase in temperature of a steel member $\Delta\theta_{a,t}$ over a small time interval Δt of no larger than 5 seconds. This simple heat transfer model is given by equation (1).

$$\Delta\theta_{a,t} = k_{sh}\frac{A_m/V}{c_a\rho_a}\dot{h}_{net}\Delta t \quad [K] \qquad \text{Eq. (1)}$$

where:

- $\dot{h}_{net}$ is the design value of net heat flux per unit area [W/m²]
- c_a is the specific heat of steel [J/kgK]
- ρ_a is the density of steel [kg/m³]
- $\frac{A_m}{V}$ is the section factor of the member, per unit length [m⁻¹]
- k_{sh} is a correction factor, commonly attributed to the shadow effect of flanges

Equation (1) has to be solved following an iterative procedure because the specific heat c_a and the net heat flux $\dot{h}_{net}$ are both temperature dependent. The temperature reached by a steel member at a given time in a fire can then be determined by summing the small increments in temperature $\Delta\theta_{a,t}$ over the total time of fire exposure.

The net heat flux $\dot{h}_{net}$ to the surface of a steel member is given in EN 1991-1-2, clause 3.1 as the sum of the heat transfers by convection $\dot{h}_{net,c}$ and by radiation $\dot{h}_{net,r}$, expressed as:

$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \quad [W/m^2] \qquad \text{Eq. (2)}$$

The convective heat flux is calculated as:

$$\dot{h}_{net,c} = \alpha_c\,(\theta_g + \theta_a) \quad [W/m^2] \qquad \text{Eq. (3)}$$

where:

Galvanized steel carpark at Sky Headquarters (London). Photo: Philip Durrant

- α_c is the coefficient of heat transfer by convection, taken as α_c = 25 [W/m²K] when the standard temperature-time curve is used
- θ_g is the gas temperature in the vicinity of the fire exposed member [°C]
- θ_a is the surface temperature of the member [°C]

The radiant heat flux is calculated as:

$$\dot{h}_{net,r} = \phi\,\varepsilon_m\varepsilon_f\,\sigma[(\theta_r+273)^4-(\theta_a+273)^4] \quad [W/m^2] \qquad \text{Eq. (4)}$$

where:

- ϕ is the configuration factor, conservatively taken as 1.0
- ε_m is the surface emissivity of the member
- σ is the Stephan Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ [W/m²K⁴]
- ε_f is the emissivity of the fire, which is generally taken as 1.0
- θ_r is the effective radiation temperature of the fire environment, which for fully fire engulfed members may be taken as $\theta_r = \theta_g$ [°C]
- θ_r is the surface temperature of the member [°C]

The density and specific heat of galvanized steel is the same as that of non-galvanized steel, and they can be determined in accordance with EN 1993-1-2, clauses 3.2.2 and 3.4.1.2, respectively. The surface emissivity of non-galvanized steel is given in EN 1993-1-2, clause 2.2 as ε_m = 0.70 for all temperatures. An emissivity value for galvanized steel has now been derived from studies by a number of European researchers, and an amendment to EN 1993-1-2 will be included in the next revision of the standard (due to be published in about 2023) in which the surface emissivity for galvanized steel will be given as:

ε_m = 0.35 for $\theta_a \leq 500$°C

ε_m = 0.70 for $\theta_a > 500$°C

Therefore, when calculating the increase in temperature of a galvanized steel member, all the required parameters (with the exception of the surface emissivity) are the same as those used to determine the increase in temperature of a geometrically equivalent (i.e. same section factor A_m/V and correction factor k_{sh}) non-galvanized steel member. The slower temperature increase in a galvanized steel member is therefore only due to the lower radiant heat flux introduced, as shown by equation (4).

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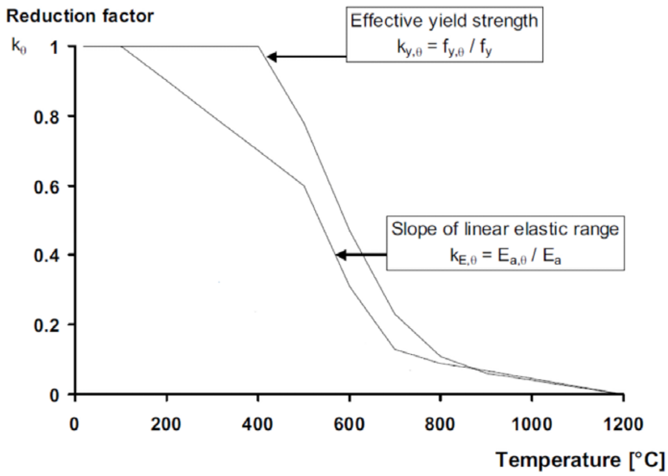

Figure 1: Strength and stiffness reduction factors of steel at elevated temperatures

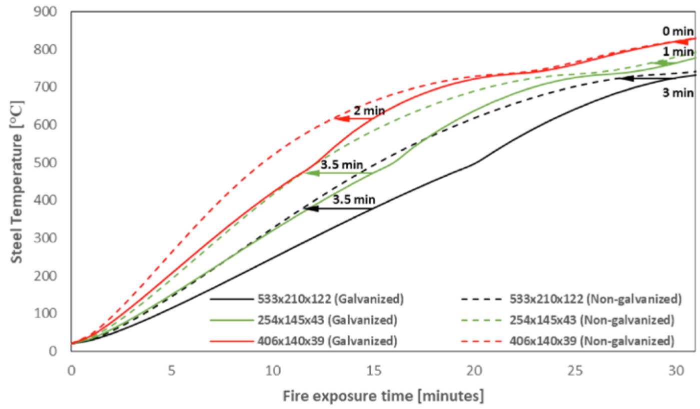

Figure 2: Temperature rise of galvanized and non-galvanized steel sections subject to the standard nominal fire curve

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Fire resistance

The design resistance of a steel member in fire is determined in a similar manner as the design resistance at room temperature, with an allowance made for the reduction in the relevant mechanical properties of the steel at elevated temperatures. When the resistance is not governed by member instabilities, such as the resistance of tension members, or the bending moment resistance of laterally restrained beams, the only material parameter affecting the resistance is the yield strength, and its reduction with temperature is accounted for through the reduction factor $k_{y,\theta} = f_{y,\theta}/f_y$, where $f_{y,\theta}$ is the yield strength at elevated temperature, and f_y is the yield strength at room temperature. When the resistance is governed by member instabilities, such as columns susceptible to flexural buckling, the resistance is also affected by the reduction in stiffness of the steel with temperature, which is accounted for through the reduction factor $k_{E,\theta} = E_{a,\theta}/E_a$, where $E_{a,\theta}$ is the slope of the linear elastic range at elevated temperature, and E_a is the modulus of elasticity at room temperature.

EN 1993-1-2, Table 3.1 gives values for $k_{y,\theta}$ and $k_{E,\theta}$ at discrete temperatures ranging from 20°C to 1200°C. These are shown in Figure 1, and are applicable to both galvanized and non-galvanized steel. Therefore, for a given fire exposure, the slower temperature increase in galvanized steel can be expected to lead to structural members with a higher fire resistance than an equivalent non-galvanized steel member. Or put in other words, when subject to the same loading conditions, a galvanized steel member can be expected to achieve a longer fire exposure than an equivalent non-galvanized steel member.

Benefit of using galvanized steel in fire

The benefit of utilizing galvanized steel members for fire resistance is apparent in structures that require short fire resistance periods, that is, 15 or 30 minutes of fire exposure, where the temperature reached by the galvanized steel members is around 500°C. Examples of structures that require such fire resistance periods include car parks and single-storey residential/office buildings[5]. There may also be benefit in using galvanized steel for other types of structures, such as single storey industrial buildings or some multi-storey office buildings, where the use of sprinklers may enable a reduction of the minimum fire period to 30 minutes.

Another important factor that affects the rate at which the temperature in a steel member increases is the section factor. In EN 1993-1-2, the section factor is defined as the surface area of the member exposed to a fire per unit length, A_m, divided by the volume per unit length, V. Therefore, a beam exposed to a fire on four sides has a higher section factor than an equivalent one exposed on three sides. This factor has the same effect irrespective of whether the section is galvanized or non-galvanized, as it only depends on the geometric proportions of the cross-section.

Figure 2 compares the rise in steel temperature of galvanized and non-galvanized steel beams for three different Universal Beam sections

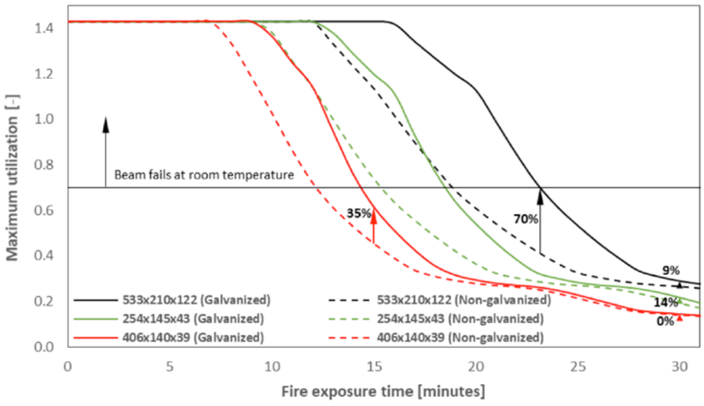

Figure 3: Fire resistance of galvanized and non-galvanized steel beams exposed to fire on three sides as a function of time

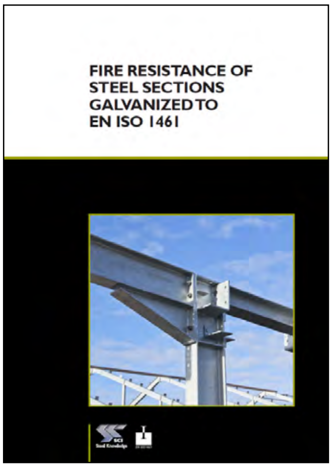

Figure 4: New SCI publication (P429) for the fire design of galvanized steel members

(533 × 210 × 122, 254 × 146 × 43, 406 × 140 × 39) exposed to fire from three sides with section factors k_{sh} $[A_m/V]_m$ of 75 m^{-1}, 109 m^{-1} and 170 m^{-1}, respectively. The figure shows that by using galvanized steel, the maximum fire exposure can be increased by up to 23 %. If the gains in fire exposure time using galvanized steel are translated into increased resistance, the advantages are more pronounced. Figure 3 shows that for the steel beams discussed, the resistance (or utilization) at 15 minutes fire exposure can be increased by up to 35 % as a result of galvanizing.

SCI publication for the design of galvanized steel members in fire

As shown here, the process of designing a steel member in fire is made complicated primarily due to the need to know the temperature of the member at the time of interest. This is in essence an iterative process which requires solving equation (1) hundreds of times. SCI has recently published a design guide which greatly simplifies the design of galvanized steel members in fire, avoiding any need for iteration[6] (Figure 4). The publication includes design tables to calculate fire resistances and maximum fire exposure periods for galvanized steel beams, composite beams, columns, and plates in tension, according to the Eurocodes[4,7], and the UK and Irish National Annexes. Design tables in accordance with BS 5950[8] are also provided. The design tables clearly show where the use of galvanized steel leads to an increase in fire resistance or fire exposure compared to non-galvanized steel. Worked examples are also provided to illustrate the use of the tables.

The publication is available as a free download from the SCI bookshop and Steelbiz (*https://portal.steel-sci.com/shop.html*) and Galvanizers Association website (*https://www.galvanizing.org.uk*)

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