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A Simple Method to Predict Temperatures in Steel Joints with Partial Intumescent Coating Fire Protection

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Abstract. Based on temperatures measured in steel joints with different extents of fire protection, this paper proposes a simple method to calculate temperatures in steel joints with partial intumescent coating fire protection. The method combines the simple temperature calculation methods in EN 1993-1-2 (Committee of European Normalisation CEN, Eurocode 3: design of steel structures—part 1-2: general rules—structural fire design, 2005) for unprotected and protected steel structures through the introduction of an exposure factor, which is the ratio of the unprotected surface area of the joint region to the total surface area of the joint area. Using the measured temperatures for fully protected steel joints, this paper first extracts the effective thermal conductivity of the intumescent coating used in the fire tests. Afterwards, this paper presents validation results based on fire test results on joints with partial fire protection. Finally, this paper presents methods to calculate the exposure factor for different types of partially fire protected steel joints.

Keywords: steel joints, partial fire protection, intumescent coating, temperature prediction, exposure factor, fire resistance

1. Introduction

Joints are critical members in steel framed structures. Following the World Trade Center disaster, a number of authoritative organisations FEMA [1], ISE [2] have identified joint integrity as a key to maintain structural integrity in fire and have called for extensive research on joints under fire conditions. Yet, despite recent tremendous progresses in understanding how steel structures behave in fire, large gaps still exist in understanding joint behaviour in fire. Against this background, the authors have been engaged in an extensive study of behaviour of steel joints under fire conditions. This study includes experimental and analytical investigations of temperature developments in steel joints and steel beam to column assemblies using different types of joints. This paper is concerned with predicting temperatures in steel joints under fire conditions.

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Steel being a thermally high conductive material, the temperature rise in unprotected steel exposed to fire attack is quick, resulting in rapid loss in strength and stiffness of steel in fire. To ensure sufficient fire resistance of steel framed structures, fire protection is often required to limit temperature rises in steel, even though it is now possible to use steel structures without fire protection in many situations (Wang [3, 4]). As intumescent coating is becoming the dominant fire protection material to steel structures, this paper will focus on steel joints with intumescent coating fire protection. The application of intumescent coating to joints can be a time consuming process, therefore how to reduce the effort of applying intumescent fire protection without degrading the fire protection effectiveness is an important practical concern of fire protection professionals. A particular practical issue is whether or not to protect the bolts. On the one hand, leaving the bolts unprotected can lead to high temperatures in the bolts which may degrade the joint structural performance in fire. On the other hand, joint fire protection is applied on site and the process can be a time-consuming one. It would be ideal not having to protect the bolts and without incurring large loss of joint performance in fire. This research reported in this paper will help resolve this issue, by developing a method to calculate unprotected bolt temperatures in protected steel joints. The authors have conducted an extensive fire test programme on different types of joints with different fire protection schemes. The experimental results have been presented in detail in another publication (Dai et al. [5]). This present paper follows on the aforementioned publication and presents a calculation method.

2. A Brief Summary of the Main Experimental Observations

Although the authors have presented their experimental results in detail in another publication (Dai et al. [5]), a brief summary of these fire tests and the main experimental observations are provided here so as to help establish the basis of the calculation method to be developed in this paper.

A total of four tests on unprotected joints [6] and ten tests on joints with different fire protection schemes were carried out. These test specimens used the four different types of joints shown in Figure 1. Each test sample was made of one stub column, four short beams and a concrete slab supported on steel decking connected to the steel beams via shear connectors. The test specimens were unloaded. The different fire protection schemes included various combinations of the following: (1) full protection of all joint components, including the bolts; (2) full protection of the joint except the bolts; (3) full protection of the column in the joint region only; (4) partial protection of the beams to a length of 300 mm or 400 mm from the joint. Table 1 summarises the different fire protection schemes and also gives the applied average intumescent Dry Film Thickness (DFT) on each member of the joint assembly. In Table 1, **FP + B** refers to full protection including the associated bolts; **FP_B** refers to full protection but not including the bolts; **P300 + B** and **P400 + B** refer to partial protection of 300 or 400 mm length

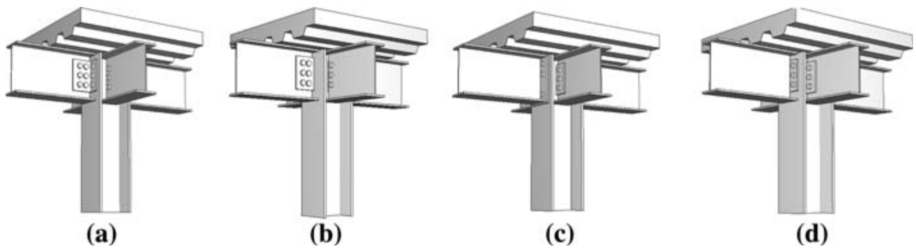


Figure 1. Joint types and configurations. (a) Web cleat joint. (b) Fin plate joint. (c) Flush endplate joint. (d) Flexible endplate joint.

Table 1
Summary of Fire Protection Schemes and Average Intumescent Coating Dry Film Thickness (DFT)

Test ID	Join type to column flange		Column	Beam 1	Beam 2	Beam 3	Beam 4
USP1	Flush endplate						
USP2	Flexible endplate						
USP3	Fin plate						
USP4	Web cleat				Unprotected		
SP1	Web cleat	Fire protection scheme	**FP + B**	**FP + B**	**P400 + B**	**P300 + B**	**P300 + B**
		DFT (mm)	0.67	1.02	1.18	1.12	1.15
SP2		Fire protection scheme	**FP_B**	**FP_B**	**P400_B**	**P300_B**	**P300_B**
		DFT (mm)	0.73	1.02	1.29	1.05	1.09
SP3		Fire protection scheme	FP_NB	–	–	–	–
		DFT (mm)	0.60	–	–	–	–
SP4	Fin plate	Fire protection scheme	**FP + B**	**FP + B**	**P400 + B**	**FP + B**	**FP + B**
		DFT (mm)	0.75	1.36	1.35	1.24	1.16
SP5		Fire protection scheme	**FP_B**	**FP_B**	**P400_B**	**FP_B**	**FP_B**
		DFT (mm)	0.77	1.08	1.16	1.3	1.19
SP6		Fire protection scheme	FP_NB	–	–	–	–
		DFT (mm)	0.62	–	–	–	–
SP7	Flush endplate	Fire protection scheme	**FP + B**	**FP + B**	**P400 + B**	**FP + B**	**P300 + B**
		DFT (mm)	0.95	1.29	1.25	1.19	1.15
SP8		Fire protection scheme	**FP_B**	**FP_B**	**FP_B**	**FP_B**	**FP_B**
		DFT (mm)	0.84	1.14	1.19	1.43	1.35
SP9	Flexible endplate	Fire protection scheme	**FP + B**	**FP + B**	**P400 + B**	**FP + B**	**P300 + B**
		DFT (mm)	0.78	1.21	1.19	1.25	1.33
SP10		Fire protection scheme	**FP_B**	**FP_B**	**P400_B**	**FP_B**	**P300_B**
		DFT (mm)	0.86	1.22	1.16	1.21	1.31

of beam from the corresponding connection ends including all the beam connectors and bolts. Specimens **P300_B** and **P400_B** differed from **P300 + B** and **P400 + B** in that the bolts in the former specimens were not protected.

The main observations from the fire tests are:

(1) if all the steel work (excluding the bolts) in the joint assembly was protected, whether or not protecting the bolts had very little effect on temperatures in

the protected steelwork other than the bolts. The bolt temperatures were higher if they were not protected than if they were protected, but the unprotected bolt temperatures in a joint with fire protection to other steelwork were much lower than bolt temperatures in a completely unprotected joint;

(2) as far as joint temperatures are concerned, protecting a segment of 400 mm of the beam was sufficient to achieve full protection;

(3) if only the column was protected, only the joint components that were in the immediate vicinity of the column (such as welds) developed noticeably lower temperatures than if the joint assembly was unprotected.

3. Development of a Calculation Method for Fire Protected Joints with Unprotected Bolts

The experimental observations indicate significant scope of using unprotected bolts in protected joints. The first step of realising this potential is to develop a method to calculate temperatures in the various joint components, including the unprotected bolts.

As has been mentioned above, if a joint is protected, whether or not protecting the bolts does not have any noticeable effect on temperatures in the connection components other than bolts. Therefore, these connection components can be considered to be fully protected. Calculation results will be presented in the Section 3.1 to validate this statement.

In a protected joint with unprotected bolts, the bolts may be partly protected and partly unprotected. Section 3.3 will propose and validate a calculation method to account for these effects, through the introduction of an exposure factor, which expresses the ratio of the unprotected surface area to the total surface area of the joint.

3.1. Temperatures in Protected Joint Components other than Bolts

For a fully protected steel section, the following equation, from EN 1993-1-2 [7], can be used to calculate the steel temperature:

$$\Delta\theta_{a,t} = \left[\frac{\lambda_{p,t}/d_p}{c_a\rho_a} \times \frac{A_p}{V} \times \left(\frac{1}{1+\phi/3}\right) \times (\theta_t - \theta_{a,t})\Delta t\right] - \left[\left(e^{\phi/10} - 1\right)\Delta\theta_t\right] \qquad (1)$$

But $\Delta\theta_{a,t} \geq 0$ where $\phi = \frac{c_p\rho_p}{c_a\rho_a} \times d_p \times \frac{A_p}{V}$, in which $\theta_{a,t}$, temperature of the steel at time t; θ_t, temperature of the gas at time t; A_p/V, section factor of the protected steel section; d_p, thickness of the fire protection material; c_a, ρ_a, specific heat and density of steel; c_p, ρ_p, specific heat and density of the fire protection material; $\lambda_{p,t}$, effective thermal conductivity of the fire protection material at time t.

Intumescent coating is a reactive material; therefore, its effective thermal conductivity does not have a fixed relationship with temperature, with the fire exposure being particularly influential. To obtain the effective thermal conductivity of the intumescent coating used in this research, it is assumed that in the same test, the intumescent coating behaviour was the same whether it was applied on the joint or on the beam section. This is reasonable as the fire exposure was the same.

Using the fire test results on the beam section, the inverse solution to Equation (1) can be used to extract the effective thermal conductivity of the intumescent coating. This is the approach in DD ENV13381-4:2002 [8]. The inverse equation to Equation (1) is:

$$\lambda_{p,t}(t) = \left[d_p \times \frac{V}{A_p} \times c_a \rho_a \times (1+\phi/3) \times \frac{1}{(\theta_t - \theta_{a,t})\Delta t} \right] \times \left[\Delta\theta_{a,t} + \left(e^{\phi/10} - 1 \right) \Delta\theta_t \right] \quad (2)$$

where $\Delta_t \leq 0.5$ min.

The following steps were followed in calculating the effective thermal conductivity of the intumescent coating used in this research:

Use the temperatures measured in the fully protected beam and column sections to calculate the effective thermal conductivity $\lambda_{p,t}$ of the intumescent coating according to Equation (2).

Assuming that the temperature of the fire protection material is $\theta_p = (\theta_t + \theta_a)/2$, transform the $\lambda_{p,t}$ (against time t) values to λ_p (against temperature θ_p) values.

Calculate the mean value λ_{pm} using different λ_p values obtained from various beam and column sections in the same test.

Use λ_{pm} and Equation (1) to calculate temperatures in the protected joint components.

Using the measured temperatures in steel sections away from the joint region, temperature dependent effective thermal conductivity values of the intumescent coating were calculated according to the procedure above. The results are shown in Figure 2. There is significant variation in the effective thermal conductivity values of the intumescent coating when the temperature is less than about 350°C. This reflects that the intumescent coating had not fully expanded before this

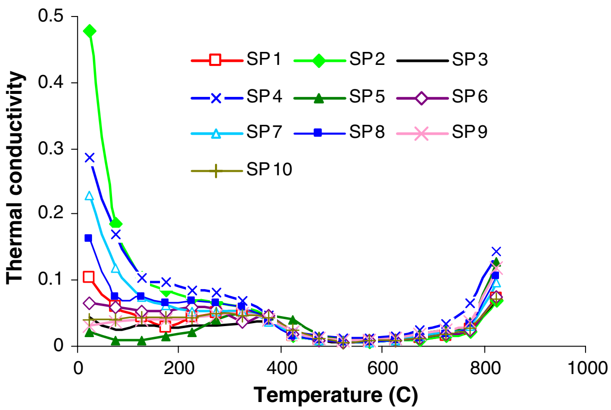


Figure 2. Effective thermal conductivity extracted from different tests using the procedure proposed in DD ENV13381-4:2002 [8].

temperature. However, the effect of this large variation in the effective thermal conductivity of the intumescent coating on the predicted steel temperature is small because the steel temperature rate during this stage behaves as if the steel is unprotected. To verify the values of the effective thermal conductivity of the intumescent coating, Figure 3 shows typical comparison between predicted and measured steel temperatures for the beam and column section of one test, which indicates very good correlation.

The thermal conductivity values are then used to calculate temperatures in protected connection components. First, Figure 4 shows how the section factor for each type of joint is calculated. The specific heat of intumescent coating is assumed to be 1000 J/kg K and the density is 1300 kg/m^3. Since the amount of

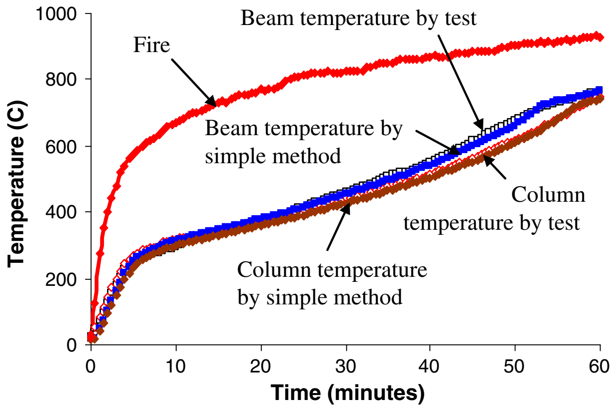
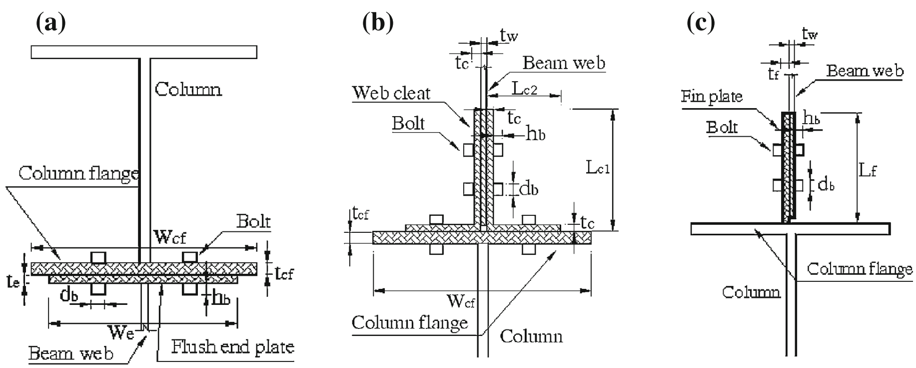


Figure 3. Comparison between temperatures measured in test and predicted using Equation (1) for the protected steel sections, test SP8.



$$A_p/V = \frac{2\times(W_{cf}+t_{cf}+t_e)}{W_{cf}\times t_{cf}+W_e\times t_e} \quad A_p/V = \frac{2\times(L_{c1}+t_{cf}+W_{cf})}{(L_{c1}-t_c)\times(2\times t_c+t_w)+2\times L_{c2}\times t_c+W_{cf}\times t_{cf}} \quad A_p/V = \frac{2\times(L_f+t_f+t_w)}{L_f\times(t_f+t_w)}$$

Figure 4. Calculation of section factors for different types of joint. (a) End plate joint. (b) Web cleat joint. (c) Fin plate joint.

intumescent coating used is very small, heat transfer in the intumescent coating is predominantly by heat conduction and there is no need to obtain very precise values of density and specific heat for intumescent coating. The steel properties are according to EN 1993-1-2 [7]. Figure 5 shows comparisons between calculated and

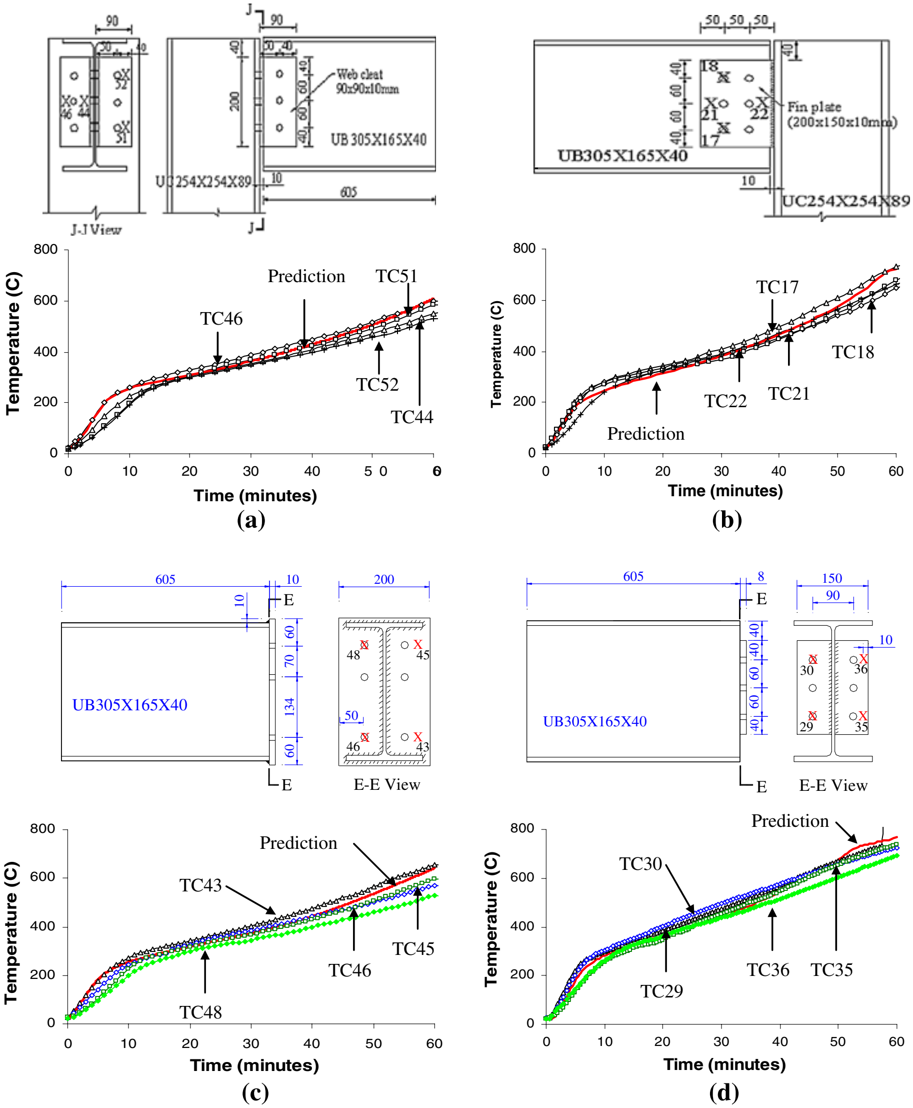


Figure 5. Comparison between predicted and measured temperatures in fully protected joint components of different types. (a) Temperatures in web cleat (test SP1). (b) Temperatures in fin plate (test SP4). (c) Temperatures in flush endplate (test SP7). (d) Temperatures in flexible endplate (test SP9).

measured temperatures in protected connection components in different types of joints. The good correlations between the two sets of results confirm the validity of using the effective thermal conductivity, extracted based on the steel section temperatures, to predict the protected joint temperatures.

3.2. Thermal Boundary Conditions for Unprotected Sections

When calculating bolt temperatures in protected joints with unprotected bolts, it is necessary to include heat contribution from the unprotected bolts. Accuracy of the calculation results depends on correct specification of the convective and radiant boundary conditions. For the joint region, there will also be shadow effect from the slab and reduced gas flow velocity near the joint region. Therefore, it is necessary to obtain appropriate values of the convective and radiant thermal boundary conditions.

3.2.1. Convective and Radiant Boundary Conditions. The steel temperature of an unprotected steel section may be calculated using the calculation method in EN 1993-1-2 [7], which is according to the following equation:

$$\Delta\theta_{a,t} = K_{sh}\frac{A_m/V}{C_a\rho_a}\dot{h}_{net}\Delta t \tag{3}$$

where additionally K_{sh}, correction factor for shadow factor, taken as 1 for the following two reasons: (1) for the joint region, the shadow effect will be explicitly considered by including radiation between the cooler slab surface and the joint as given in Equation (4); (2) for the steel beam and column sections away from the joint region, a resultant emissivity value of 0.5, instead of 0.7 as recommended in EN 1991-1-2:2002 [9], will be used. An examination of the background documents [10, 11] indicates that the principal reason for introducing the shadow factor is due to the different values of resultant emissivity recommended in the two different versions of Eurocode 3 Part 1.2, being 0.5 in ENV 1993-1-2 [12] and 0.7 in EN 1993-1-2 [9]; A_m/V, section factor for the unprotected steel member ($1/m$); $\dot{h}_{net}$, net heat flux per unit area (W/m^2).

The net heat flux per unit area can be calculated based on EN 1991-1-2 2002 (CEN 2002) [9] as:

$$\dot{h}_{net} = \dot{h}_{net.c} + \dot{h}_{net.r}$$

$$\dot{h}_{net.c} = \alpha_c(\theta_g - \theta_m)$$

$$\dot{h}_{net.r} = \Phi\varepsilon_m\varepsilon_f\sigma\left[(\theta_r + 273)^4 - (\theta_m + 273)^4\right]$$

where $\dot{h}_{net.c}$, net heat flux per unit area by convective heat exchange (W/m^2); $\dot{h}_{net.r}$, net heat flux per unit area by radiation heat exchange (W/m^2); α_c, convective coefficient

$(W/m^2K) = 25$; θ_g, gas temperature (°C); θ_m, member temperature (°C); Φ, configuration factor; ε_m, surface emissivity of member (0.5); ε_f, emissivity of fire (1.0); σ, Stephan Boltzmann constant $= 5.67 \times 10^{-8}$ (W/m^2K^4); θ_r, effective radiation temperature of the fire environment (°C); θ_m, surface temperature of the member (°C).

Figure 6 compares the test results and predicted values using a configuration value of 1.0 and the above mentioned convective and radiant thermal transfer coefficients, for the unprotected beam and column sections of test USP4. The close agreement between the two sets of results indicates that the adopted values are appropriate.

3.2.2. Heat Flux to the Joint Region. In steel-concrete composite joints, the composite slab will be cooler than the steel section. The effect of this on the steel member section may be taken into account by assuming the slab/steel section interface to be protected so that the steel section has a reduced section factor. However, to the joint region, the joint/slab interface is a line which has no effect on the calculation of the joint section factor. Therefore, it may be necessary to explicitly consider the slab shadow effect on temperatures attained in the joint region. Also due to obstacles, gas flow in the joint region would be slower than around the steel beam and column cross-sections remote from the joint region. Therefore, it is expected that the convective heat transfer coefficient in the joint region would be lower than in regions remote from the joint. These two effects should be considered. To account for the slab shadow effect on radiation heat exchange, the heat flux to a location in the joint is given as:

$$\dot{h}_{net.r} = (1-\phi)\varepsilon_r\sigma\left[(\theta_r+273)^4-(\theta_m+273)^4\right]+\phi\varepsilon_r\sigma\left[(\theta_c+273)^4-(\theta_m+273)^4\right] \quad (4)$$

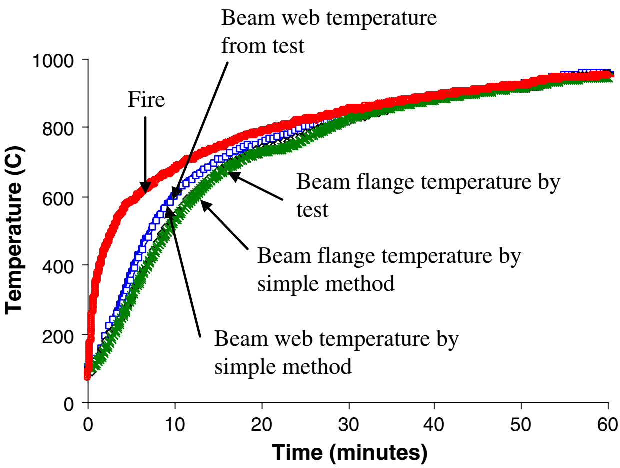
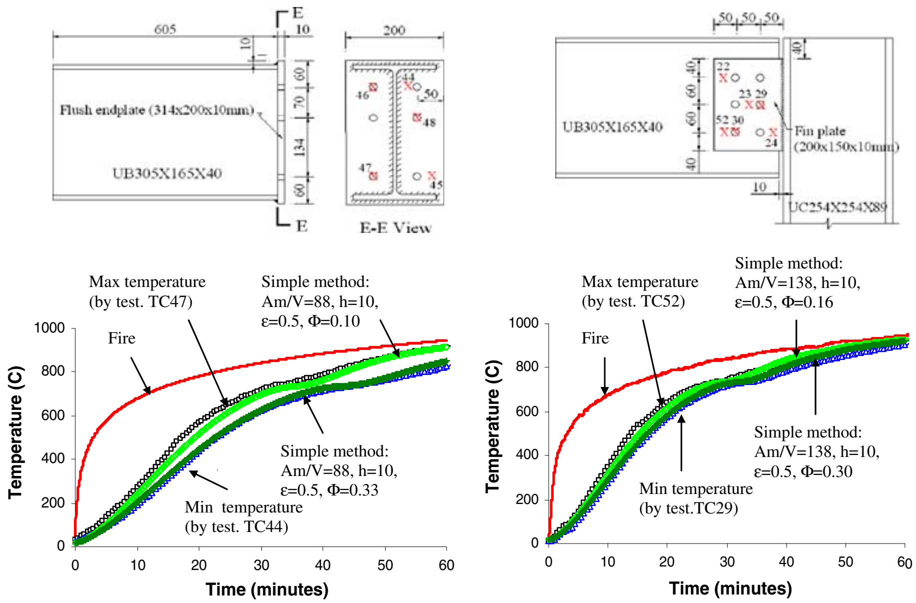


Figure 6. Assessment of thermal boundary conditions for unprotected steel joint (Test USP4).



(a) (b)

Figure 7. Comparisons between temperatures in unprotected joints obtained from tests and predicted by the simple calculation method incorporating slab shadow effect. (a) Temperatures in end plate (test USP1). (b) Temperatures in fin plate (test USP3).

where additionally, ϕ the configuration factor between the slab and the joint, ε_r ($=\varepsilon_m\varepsilon_f$) is the resultant emissivity (0.5 as used previously), and θ_c the temperature of the fire exposed concrete surface (°C).

To allow for the slower gas movement around the joint region, a convective heat transfer coefficient of 10 W/m^2K, rather than 25 W/m^2K will be used.

To verify the above approach, Figure 7 compares measured temperatures with predicted temperatures for the unprotected joint specimens using endplate and fin plate connections, representing connection components to the column flange and beam web. Two values of configuration factor are used: the minimum value (corresponding to the maximum temperature) for the thermocouple furthest away from the slab and the maximum value (corresponding to the minimum temperature) for the thermocouple nearest to the slab. It can be seen that by using different configuration factors relevant to the different joint temperature monitoring locations, the differences in the recorded temperatures in these monitoring locations may be reproduced.

3.3. Temperatures in Unprotected Bolts when other Connection Components are Protected

3.3.1. A Proposed New Calculation Method. Figure 8 shows that in a protected joint with unprotected bolts, the bolt heads/nuts were not covered by the expanded

Figure 8. Unprotected bolts in protected web cleat before and after 60 min fire exposure (test SP2).

intumescent coating (char) after heating. Therefore, there was direct heat transfer from the fire to the unprotected bolt/nuts. This resulted in the unprotected bolt temperatures to be higher than the fully protected component temperature. If fire design assumes the same temperature for the unprotected bolts and the protected connection components, the bolt temperature will be underestimated and the design will be on the unsafe side. On the other hand, if the bolt temperature is assumed to be the same as the bolt temperature in a completely unprotected joint, the bolt temperature will be too high and the results will be unduly conservative.

In order to account for the effect of unprotected bolt surface in an otherwise protected joint, it is possible to use a coefficient named 'exposure factor' (F_e). This exposure factor expresses the unprotected surface area of the bolt heads/nuts as a proportion of the total surface area of the joint assembly. Thus, F_e ranges from 0 for a bolt assembly with full protection and 1 for a totally unprotected bolt assembly.

Consider a general steel section. Use Q_{up} and Q_p to denote the heat flux to per unit area of the unprotected surface and per unit area of the protected surface respectively. If the total surface area of the steel section is A, then the unprotected surface area is F_eA and the protected surface area is $(1 - F_e)A$, giving the total heat flux to the steel section as $Q_{up} \cdot F_e \cdot A + (1 - F_e) \cdot Q_p \cdot A$. If the steel section is completely unprotected (UP), the total heat flux to the steel section will be $Q_{up}A$. The steel temperature will be T_{up}, which can be calculated using Equation (3). If the steel section is fully protected (FP), the total heat flux to the steel section will be Q_pA and the steel temperature will be T_{fp}, which can be calculated using Equation (1). Therefore, for a protected joint with only the bolts unprotected, the temperature in the unprotected bolts may be calculated by the following formulation:

$$T_{pp} = T_{fp} + \left(T_{up} - T_{fp}\right) \cdot F_e \tag{5}$$

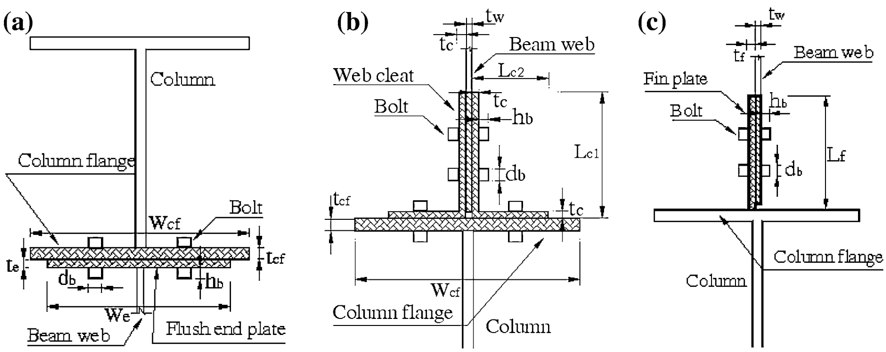
It should be pointed out that in a protected joint with unprotected bolts, the temperatures of the bolts and the protected connection components are different and the above equation only applies to the bolt temperature. The protected connection component temperature is calculated assuming full protection. This has been observed from the fire tests. Also when calculating the fully protected temperature (T_{fp}) and the completely unprotected temperature (T_{up}), the same section factor as illustrated in Figure 4 can be used.

3.3.2. Exposure Factor. To use Equation (5), it is necessary to calculate the exposure factor. Due to the 3-D nature of a joint, the exposure factor should ideally be calculated using the 3-D joint geometry. However, the calculations may become quite involved and there is advantage in developing a simplified 2-D calculation method.

One possibility of converting a 3-D joint assembly to a 2-D representation is to assume that the bolts occupy the entire width of the connected plates. Thus, for the joints tested in this research, the 2-D representations of the different types of joints are shown Figure 9, in which d_b is the equivalent diameter of the bolt head or the nut.

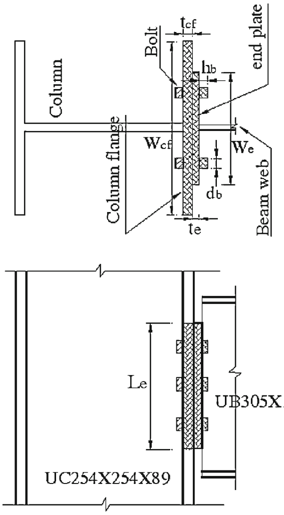
On the other hand, if the actual quantity and shape of the bolts and nuts in the joint assembly have to be considered, it is necessary to use 3-D representation of the joint. Figures 10–12 provide the approximate methods for calculations of the exposure factor and section factor for the different types of joints studied in this research. For the fin plate connections (Figure 12), the bolts are relatively far from the column flange so the column flange is not included. For the web cleat connections (Figure 11), if the column section connected is much bigger than the beam section and connectors, the column flange may not be included in the calculation otherwise the temperature in the connectors might be underestimated.

Based on the 2-D and 3-D calculation schemes, the section factor and exposure factor values have been calculated for the joints used in the tests. Table 2 lists a selection of the calculated results.



$F_e = 4\times d_b/(2\times W_{cf} + 2\times t_{cf} + 2\times t_e)$ $F_e = 8\times d_b/(2\times L_{c1} + 2\times t_{cf} + 2\times W_{cf})$ $F_e = 4\times d_b/(2\times L_f + 2\times t_f + 2\times t_w)$

Figure 9. Calculation of exposure factors for different types of joints, based on simplified 2-D representation of the joint assembly. (a) End plate connection. (b) Web cleat connection. (c) Fin plate connection.



$$A_p/V = \frac{(2W_{cf} + t_{cf} + t_e)L_e + A_{bs}n_b}{W_{cf}t_{cf}L_e + W_e t_e L_e + V_{bo}n_b}$$

$$F_e = A_{be}n_b/[(2W_{cf} + t_{cf} + t_e)L_e + A_{bs}n_b]$$

n_b: Number of bolts in the analyzed joint

A_{bs}: Side surface area of a bolt excluding the part inside the connected member

$$A_{bs} = 2\times\pi d_b h_b$$

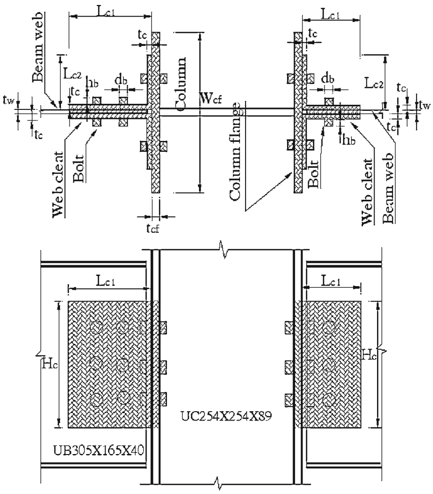
V_{bo}: Volume of a bolt and nut excluding the part inside the connected member

$$V_{bo} = 2\times\pi(\frac{d_b}{2})^2 h_b$$

A_{be}: Two end surface area of a bolt

$$A_{be} = 2\times\pi(\frac{d_b}{2})^2$$

Figure 10. Calculation of exposure and section factors for end plate connection, based on 3-D representation of the joint assembly.



$$A_p/V = \frac{(2L_{c1} + 2t_{cf} + 2W_{cf})H_c + A_{bs}n_b}{[(L_{c1} - t_c)(2t_c + t_w) + 2L_{c2}t_c + W_{cf}t_{cf}]H_c + V_{bo}n_b}$$

$$F_e = A_{be}n_b/[(2L_{c1} + 2t_{cf} + 2W_{cf})H_c + A_{bs}n_b]$$

n_b: Number of bolts in the analyzed joint

A_{bs}: Side surface area of a bolt excluding the part inside the connected member

$$A_{bs} = 2\times\pi d_b h_b$$

V_{bo}: Volume of a bolt and nut excluding the part inside the connected member

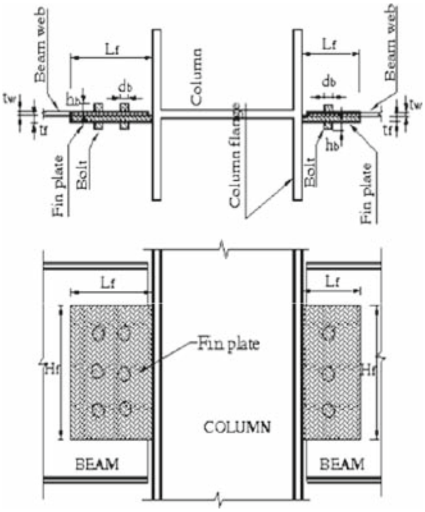
$$V_{bo} = 2\times\pi(\frac{d_b}{2})^2 h_b$$

A_{be}: Two end surface area of a bolt

$$A_{be} = 2\times\pi(\frac{d_b}{2})^2$$

Figure 11. Calculation of exposure and section factors for web cleat connection, based on 3-D representation of the joint assembly.

3.3.3. Validation of Temperatures in Unprotected Bolts in Partially Protected Joints. Using the method outlined above, temperatures of the unprotected bolts in otherwise protected joints have been calculated. Figure 13 compares predicted and measured temperatures in the unprotected bolts in a web cleat connection (test SP2). As expected, it can be seen that the predicted temperatures are lower than



$$A_p / V = \frac{(2L_f + t_f + t_w)H_f + A_{bs} n_b}{(t_f + t_w)L_f H_f + V_{bo} n_b}$$

$$F_e = A_{be} n_b / [(2L_f + t_f + t_w)H_f + A_{bs} n_b]$$

n_b : Number of bolts in the analyzed joint.

A_{bs} : Side surface area of a bolt excluding the part inside the connected members.

$$A_{bs} = 2 \times \pi d_b h_b$$

V_{bo} : Volume of a bolt and nut excluding the part inside the connected members.

$$V_{bo} = 2 \times \pi (\frac{d_b}{2})^2 h_b$$

A_{be} : Two end surface area of a bolt.

$$A_{be} = 2 \times \pi (\frac{d_b}{2})^2$$

Figure 12. Calculation of exposure and section factors for fin plate connection, based on 3-D representation of the joint assembly.

Table 2
Section Factors and Exposure Factors for a Selection of the Tested Joints

Connection types	Section factor (m^{-1})		Exposure factor	
	2-D model	3-D model	2-D model	3-D model
Web cleat (150 × 90 × 10), Figure 13	88	91	0.350	0.089
Fin plate (200 × 150 × 10), Figure 14	138	135	0.386	0.111
Flexible end plate (200 × 150 × 8), Figure 15	100	102	0.228	0.070

the measured temperatures in the unprotected bolts if no exposure effect is considered or F_e = 0. If the exposure factor is calculated by using the simplified 2-D representation of the joint (F_e = 0.37), the calculated exposure factor is higher and the calculated bolt temperatures are higher than the measured temperatures. If the more realistic 3-D representation of the joint is used to calculate the exposure factor (F_e = 0.089), the calculated and measured bolt temperatures are very close.

Figures 14 and 15 compare temperatures in the unprotected bolts in fin plate joint (test SP5) and flexible endplate joint (test SP10). The same behaviour as described above for the web cleat joint can be observed.

Clearly, calculating the unprotected bolt temperature using Equation (5) can give very accurate results if the exposure factor is calculated based on 3-D representation of the joint. However, the 3-D calculations of the exposure factor can be quite involved as shown in Figures 10–12. Calculating the exposure factor using a

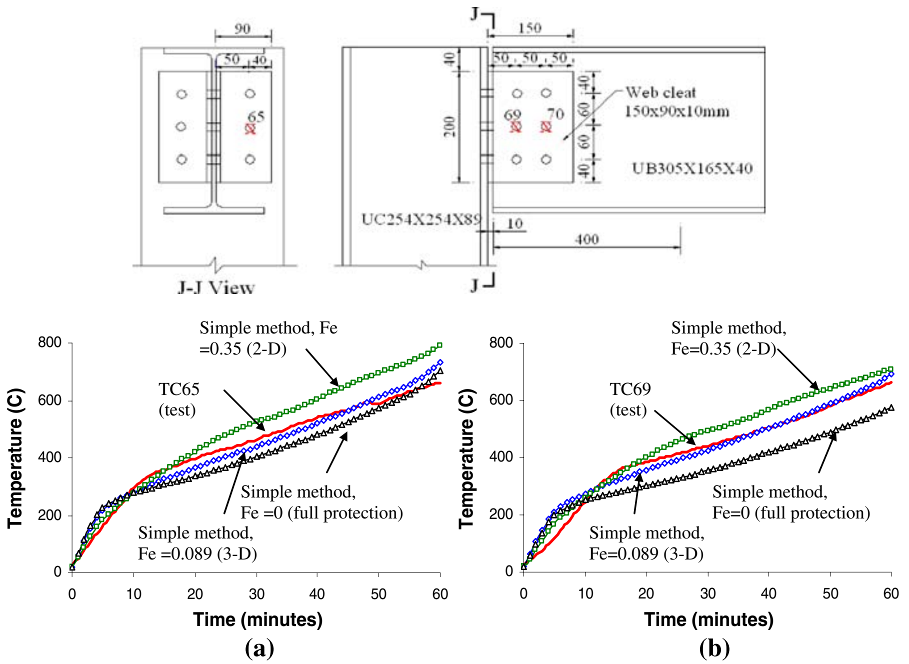


Figure 13. Comparisons of temperatures in unprotected bolts in a protected web cleat joint (test SP2). (a) Temperatures in unprotected bolts in a protected web cleat contacting column flange (SP2). (b) Temperatures in unprotected bolts in a protected web cleat contacting beam web (SP2).

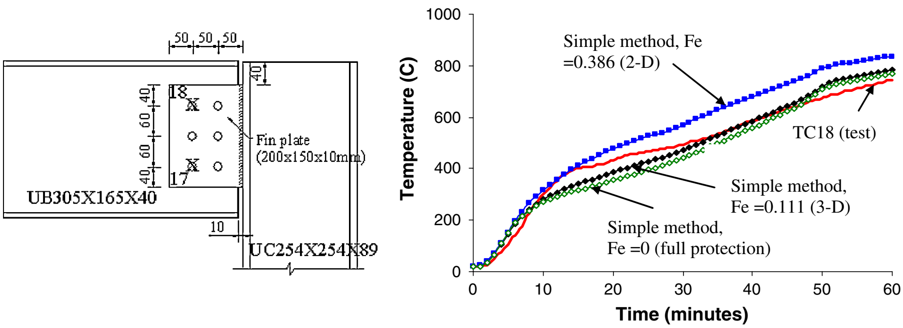


Figure 14. Comparisons of temperatures in unprotected bolts in a protected fin plate joint (test SP5).

2-D joint model is simpler, but this is at the expense of increased inaccuracy in the calculated temperature results. Nevertheless, the inaccuracy is on the safe side. Therefore, the simple 2-D calculation method may be acceptable as a first attempt.

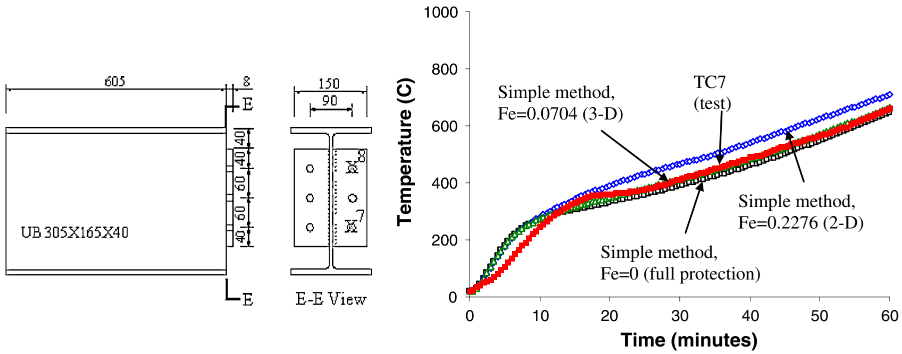


Figure 15. Comparisons of temperatures in unprotected bolts in a protected end plate joint (test SP10).

4. Conclusions

This paper has presented a simple method to calculate temperatures in intumescent coating protected composite joints with unprotected bolts. It has been demonstrated that the protected steel temperature calculation method in EN 1993-1-2: 2005(E) [7] can be used to calculate temperatures in the protected connection components other than the unprotected bolts. For this calculation, the effective thermal conductivity of the intumescent coating in the joint area may be assumed to be the same as that for the steel sections remote from the joint area, on the assumption that the fire exposure condition is the same. To calculate the temperatures in the unprotected bolts in a protected joint, an exposure factor should be introduced to account for the factor that the bolt heads or nuts will not be covered by the expanded intumescent char. This exposure factor is the ratio of the uncoated bolt head/nut surface area to the entire joint surface area. This exposure factor may be calculated using either a true 3-D representation of the joint assembly, or a simplified 2-D representation of the joint assembly. In the 2-D representation, the bolts are assumed to cover the entire width of the connected plate. Using the 3-D model is more involved in calculations, but the predicted bolt temperatures are very close to the measured values. Using the 2-D joint model gives a higher exposure factor than using the 3-D model, so the predicted bolt temperatures are higher than the measured values (being on the safe side).

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