Diseño de conexiones tipo perno en vigas compuestas de acero y hormigón en situación de incendio

Design of stud connections in steel – concrete composite structures in fire situation

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Resumen

En el trabajo se aborda el estudio de los factores que inciden en la resistencia, en situación de incendio, de las conexiones tipo perno en estructuras compuestas hormigón-acero con tipología de viga y losa maciza. Se realiza el diseño del experimento, la modelación térmica de los especímenes del ensayo push-out y el análisis de significación de diferentes parámetros en las relaciones de temperatura en secciones compuestas con vigas sin revestimiento y con revestimiento contra incendio. Por último, se proponen las temperaturas a considerar en el hormigón y el conector, expresadas como porcentajes de la temperatura en el ala del perfil, para determinar los factores de reducción de la resistencia de la conexión en situación de incendio. Los resultados demuestran que los porcentajes propuestos por EN 1994-1-2 (2005) para determinar la temperatura en el hormigón y el conector a partir de la temperatura en el ala no son válidos para todas las situaciones de diseño dentro del alcance del código.

Palabras claves: Análisis térmico, estructuras compuestas, ensayo push-out, conexiones tipo perno, incendio

Abstract

This work studies the factors that impact on the fire resistance of stud connections in steel-concrete composite structures, considering beams with solid slab. The design of the experiment, the thermal modeling of the push-out specimens, with or without fire protection material, and the analysis of the significance of the different parameters in the temperature relationships are carried out. Finally, the temperatures that should be considered in the concrete and the connector, expressed as percentages of the steel flange temperature, are proposed in order to determine the reduction factors of the connection resistance in fire situation. The results demonstrate that the percentages proposed in EN 1994-1-2 (2005) to determine the temperature in the concrete and the connector, based on the temperature in the steel flange, are not valid for all design situations within the scope of the code.

Keywords: Thermal analysis, composite structures, push-out test, stud connections, fire

1. Introduction

In steel-concrete structures, both materials work jointly to resist external stresses. The stud is the most used connector in the international construction practice, due to its easy placing and fast operation.

The study of the behavior of steel-concrete beams in fire situations is complex because of the different materials that compose them. When a composite beam is subjected to fire, both the steel profile and the concrete slab are directly exposed; however, shear connectors are indirectly heated through the heat transferred by the steel flange. In order to guarantee the structural safety, the metallic structure often needs to be encased by materials that can delay the action of fire upon them.

Internationally, several connector tests have been performed, usually called push-out tests, to evaluate the strength and load-displacement behavior of the connections at room temperature, mainly related to stud connections.

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Compared with the large number of push-out tests performed at room temperature, a reduced number of similar tests have been carried out in fire situation. In 1992, the first high-temperature connection tests in the world were made at the Centre Technique Industriel de la Construction Métallique (CTICM), France (Kruppa and Zhao, 1995). The results of this relevant research served as a base for establishing design criteria for stud connections in fire situation, recommended in EN 1994-1-2 (2005).

Recently, new stud connection tests at high temperatures have been performed, among which two experimental programs carried out in the Asian region can be highlighted (Satoshi et al., 2008; Chen et al., 2012). In general, the experimental programs performed to date are limited by the fact of not covering all the design situations stated in the scope of EN 1994-1-1 (2004) and EN 1994-1-2 (2005).

Former researches (Larrúa & Silva, 2013a, 2013b) demonstrated that the percentages proposed in EN 1994-1-2 (2005) to determine the temperature in the concrete and the connector based on the steel flange temperature are not valid for all design situations within the scope of the code for beams without fire protection. Therefore, new percentages were proposed, which take into account the connector height, based on the average values of the ratios θ_c/θ_f (average concrete temperature to average steel flange temperature) and θ_s/θ_f (connector temperature to average steel flange temperature) at the fire exposure interval of 0-90 minutes. These authors include the determination of the concrete temperature in two levels; $0.5h_{sc}$, which is consistent with the level considered, from experimental data, in the determination of the current formulation of EN 1994-1-2 (2005); and $0.25h_{sc}$ based on former studies on failure mechanisms of stud connections at room temperature, and also the coincidence of higher temperatures in the area close to the lower part of the slab.

It should be considered that a beam without fire protection subjected to high temperatures presents failure due to reasons other than the specific failure of the stud connection, in a maximum work environment of approximately 30 minutes. However, considering that the push-out specimen is a simplified model of the real behavior of the composite beam, the factors that limit the failure of the unencased composite beam are not evidenced, and the connection failure is produced at fire exposure times far above 30 minutes (Kruppa and Zhao, 1995).

Therefore, the present study gives continuity to the results of Larrúa and Silva (2013a, 2013b) mentioned earlier, and proposes the temperatures to be considered in the concrete and the connector, expressed as percentages of the temperature in the steel flange, for two alternatives: steel beams without fire protection, which incorporated the analysis of its usual work range (0-30 minutes), and steel beams with fire protection, which have not been dealt with until now.

2. Thermal analysis

The numerical modeling is a widely used tool for solving structural engineering problems in fire situations. In turn, several previous studies demonstrate the efficacy of the software SuperTempcalc (Temperature Calculation and Design v.5) developed by FSD (Fire Safety Design, Sweden) when modeling heat transfer problems in structural engineering (Anderberg, 1991; Silva, 2005; Correia et al., 2011). This software belongs to the family of bidimensional modeling applications based on the finite element method. The present section aims at describing the criteria followed in the thermal analysis of the push-out test for stud connections in steel-concrete composite beams, with the mentioned calculation software, for steel sections with and without fire protection.

2.1 Thermal actions

The net heat flux is given by the sum of the convective net flux controlled by the convection coefficient (α_c), and the radiation net flux, controlled by the resulting emissivity (ϵ_r). The development of the specimen temperatures in the furnace depends on the material's emissivity (ϵ_m) and the fire emissivity (ϵ_f). The resulting emissivity is usually approximated to the product of ϵ_m and ϵ_f . In EN 1994-1-2 (2005) and EN 1991-1-2 (2002) the fire emissivity is usually taken as 1. EN 1994-1-2 (2005) considers that the emissivity of steel and concrete related to the surfaces of the members is 0.7.

In the understanding of the developed modeling, the exposed parts of the section are considered under the ISO 834 (1990) fire standard, with the convection coefficient (α_c) of 25 W/m²K and the resulting emissivity of 0.7, according to the definitions in EN 1991-1-2 (2002) for standard fire curve. In the non-exposed parts, the action of the 20°C room temperature is considered with a convection coefficient of 9 W/m²K.

2.2 Materials thermal properties

The followed approach considers the materials' thermal properties recommended in EN 1994-1-2 (2005), with the intention of developing more universal models based on standardized properties that can be used creatively in the study of different similar design situations.

The steel thermal conductivity and specific heat are assumed as properties depending on temperature, according to EN 1994-1-2 (2005). Based on the code, a density value independent from temperature of 7850 kg/m³ is adopted.

The thermal conductivity of normal weight concrete, according to EN 1994-1-2 (2005) is also a property depending on temperature and must be assessed between the upper and lower limit defined in that code (EN 1994-1-2, 2005; Schleich, 2005; Anderberg 2001). On the other hand, the specific heat of normal weight concrete was included as a property dependent on temperature, inasmuch as the density of this material is taken as a value independent from temperature in the interval between 2300-2400 kg/m³.

2.3 Geometric modeling

The domain is consistent with the push-out specimen's cross section of Kruppa and Zhao (1995). When it is appropriate, the fire resistant encasement material is included. Figure 1 illustrates two examples of the alternatives considered: beams without fire protection and encased beams.

Figura 1. Modelación de la geometría. a) Viga sin revestimiento contra incendio. b) Viga con revestimiento contra incendio (espesor de 25 mm)

Figure 1. Geometric modeling. a) Beam without fire protection. b) Beam with fire protection (thickness of 25 mm)

2.4 Modeling of the boundary conditions

The definition of boundary conditions, as indicated in Figure 2, includes boundary 1 upon which standard fire ISO 834 (1990) is acting, while boundary 2 represents the unexposed region, where room temperature prevails (20°C).

Figura 2. Condiciones de frontera

Figure 2. Boundary conditions

2.5 Selection of the finite element type and the grid density

Due to the fact that the cross section of the specimens is formed by rectangular geometries, the grid was generated with rectangular elements of four nodes. The size of the larger side of the elements was defined as $1 \leq 0.01$ m. For practical reasons concerning the measurement of temperature points, a localized refinement of 0.005 m was decided, which allows obtaining the temperature in those specific points, thus avoiding a global refinement. Figure 3 shows the example of the discretization for an unencased specimen.

Figura 3. Discretización del dominio

Figure 3. Discretization of the domain

2.6 Results recording

The software offers the possibility of obtaining results in different formats: graphs, Microsoft Excel tables and/or animations. Temperature fields are among the graphs, which allow appreciating, through the polychromatic shades associated to a color scale, the distribution of temperatures in the domain for a given fire exposure time.

Figure 4 shows the temperature fields at 30 minutes of fire exposure of the specimens corresponding to the two alternatives considered, without fire protection and with fire protection (25 mm thick). Marked differences in the thermal behavior of both cases can be observed.

Figura 4. Campos de temperatura a 30 minutos de exposición al fuego. a) Espécimen sin revestimiento contra incendio. b) Espécimen con revestimiento contra incendio

Figure 4. Temperature fields at 30 minutes of fire exposure. a) Specimen without fire protection. b) Specimen with fire protection

3. Beams without fire protection

3.1 Numerical experiment design

The purpose of the experiment design is to define the influence of the connector height, density, conductivity and moisture content of concrete on the behavior of the ratios θ_{sc}/θ_f and θ_c/θ_p for the interval of 0-30 minute of fire exposure time.

The experiment for beams without fire protection consists of a factorial design with two factors (with three levels each) and two factors (with two levels each). Table 1 shows the studied variables and their respective levels. The thermal conductivity of concrete is assessed for the lower (LL) and upper limits (UL) set out in EN 1994-1-2 (2005), because although this code suggests the upper limit (UL) for composite structures, the characteristics of the tests performed to establish that limit differ from the present work's case study.

Tabla 1. Diseño numérico experimental para vigas sin revestimiento contra incendio

Table 1. Numerical experiment design for beams without fire protection

Variables	Niveles/ Levels		
Densidad/ Density (kg/m ³)	2300	2350	2400
Altura/ Height (mm)	50	100	
Conductividad térmica/ Thermal Conductivity (W/mK)	LI	LS	
Humedad/Moisture Content (%)	1,5	4,25	7

3.2 Determination of the ratios θ_{sc}/θ_f and θ_c/θ_f

The temperature at the base of the connector (θ_{sc}), the average temperature of the upper steel flange (θ_f), and the average temperature of concrete near the connector (θ_c) were measured, based on temperature-time values measured at different points of the cross section of the push-out specimen. θ_f was considered as the average of the temperature measured at five points, θ_{sc} was measured at the edge of the connector at a height of 5 mm measured from the upper edge of the flange, θ_c was measured as the average of six points measured at the mid-height level of the connector ($0.50h_{sc}$) and as the average of six points measured at the one quarter-height level from the base of the connector ($0.25h_{sc}$). The ratios θ_{sc}/θ_f and θ_c/θ_f were calculated for each specimen, and their behavior curves were obtained based on fire exposure time.

3.3 Analysis of the significance of factors

Based on the result matrix, derived from the experiment's statistical design, several statistical analysis were carried out with the help of the software STATGRAPHICS Centurion XV Version 15.2.06.

The parametrical study determined that the connector height (h_{sc}) is the independent variable that has most influence on temperature relationships, and that it is possible to obtain a high level of adjustment when defining equations based on that variable to predict the studied relationships, with multiple coefficients of determination (R^2) between 92.62 and 95.28%.

Figure 5 illustrates the influence of the connector height on temperature relationships, for a 0-30 minute fire exposure time, of two unencased specimens, SR-A and SR-B, with connector height of 50 mm and 100 mm, respectively. Both have a density of 2400 kg/m^3 , moisture content of 1.5% and upper limit of thermal conductivity (UL). It can be observed that the connector height has a significant influence on the ratios θ_c/θ_f , for the two levels considered, and the same variable has an insignificant influence on the ratio θ_{sc}/θ_f .

Figura 5. Influencia de la altura del conector (h_{sc}) en las relaciones de temperatura
Figure 5. Influence of the connector height (h_{sc}) on temperature relationships

A sensitivity analysis carried out by Larrúa and Silva (2013a, 2013b) shows that the temperature development is best predicted, in relation to the available experimental results (Kruppa and Zhao, 1995), when taking density of 2300 kg/m³, moisture content of 1.5 %, and when the upper limit is adopted in the assessment of the thermal conductivity of concrete, in accordance with the recommendation of EN 1994-1-2 (2005).

On the other hand, it should be noted that the experimental programs developed by Satoshi et al. (2008) and Chen et al. (2012) include substantial differences in relation to the tests carried out at the CTICM. Satoshi et al. (2008) tested specimens with a single concrete slab, with constant load, while Chen et al. (2009) tested specimen with two slabs that, unlike former cases, are brought to failure when predetermined temperature levels are reached. Both cases apply fire curves different from standard fire ISO 834, which generated a much slower heating of the specimens and their components.

The authors of the present paper performed numerical models considering the geometries and fire curves reported in the Asian experimental programs already mentioned, and they also took into account the thermal properties adopted for concrete by EN 1994-1-2 (2005). It was possible to verify that the adjustment between the numerical and experimental results is notably less than in the models of the CTICM program mentioned earlier. This is a consequence of the lack of correspondence between the fire curves considered by Satoshi et al. (2008) and Chen et al. (2012) and the thermal properties of concrete incorporated to the models, since they were derived from numerical extrapolations based on temperatures measured in structural member tests subjected to standard fire ISO 834 (1990).

Therefore, specimens of the CTICM program are modeled hereon with the final characteristics described above. Different connector heights are considered (50 mm, 60 mm, 75 mm, 90 mm, 100 mm and 125 mm) and the temperature relationships are calculated for the 0-30 minute range. Table 2 shows the results of the definite ratios proposed for the simplified calculation, expressed in percentages, for the studied work range.

Tabla 2. Relaciones de temperatura θ_{sc}/θ_i y θ_c/θ_i para un rango de trabajo de 0-30 minutos, en vigas sin revestimiento contra incendio
Table 2. Temperature ratios θ_{sc}/θ_i and θ_c/θ_i for a work range of 0-30 minutes, in beams without fire protection

Altura del conector/ Connector Height (mm)	θ_{sc}/θ_i (%)	θ_c/θ_i a/to 0.25 h_{sc} (%)	θ_c/θ_i a/to 0.5 h_{sc} (%)
50	75	60	45
60		55	40
75		50	35
90		45	30
100		45	30
125		40	25

For the 0-30 minute work range, it can be observed that the percentages to determine the concrete temperature vary based on the connector height. This confirms that the percentage of 40% proposed by EN 1994-1-2 (2005) to determine the concrete temperature is not valid for all design situations within the scope of the code, and it is consistent with the results obtained by Larrúa and Silva (2013b) for the work range of 0-90 minutes. In turn, it should be noted that the percentages adjusted by the 0-30 minute work range differ from those calculated earlier by these authors for the 0-90 minute work range. (Larrúa and Silva, 2013b).

In brief, for beams without fire protection, it is recommendable to use the values of the ratios corresponding to the 0-30 minute range, with the specification of using the values calculated at 0.25_{sc} for concrete (see Table 2), taking the aforementioned grounds into account.

4. Beams with fire protection

4.1 Numerical experiment design

The purpose of the numerical experiment design is to study the factors that have an influence on the temperature ratios θ_{sc}/θ_f and θ_c/θ_p in composite sections with beams with fire protection. The variable that had the biggest influence on the temperature relationships for the composite section with beams without fire protection, was the connector height; therefore, it is also considered as a study factor in the experiment, which includes representative conductivity and capacitance values of a wide range of protection materials that are usually employed in the international practice and the criteria followed by Wang (1998).

For the statistical design of the numerical experiment and the analysis of results, the software Statgraphics XV Centurion was also used. A multilevel factorial design was implemented to assess the effect of the selected factors, which generated a total of 54 combinations. Later on, the design optimization was performed, using the procedures included in the software, thereby defining 16 combinations. Table 3 shows the studied variables and their respective levels.

Tabla 3. Diseño estadístico del experimento para vigas con revestimiento contra incendio

Table 3. Statistical design of the experiment for beams with fire protection

Variables	Niveles/Levels		
Espesor del revestimiento contra incendio/ Thickness of fire protection (mm)	10	25	40
Conductividad térmica del revestimiento/ Thermal conductivity of fire protection (W/mK)	0.1	0.2	0.3
Altura del conector/ Connector height (mm)	50		100
Capacitancia del revestimiento/ Fire protection capacitance (J/m ³ K)	250000	625000	1000000

4.2 Graphical and numerical determination of the ratios

$$\theta_{sc}/\theta_f \text{ and } \theta_c/\theta_f$$

For the determination of the ratios, the same procedure described in paragraph 3.2 was followed, in relation to beams without fire protection. In the case of encased beams, temperature ratios for 4 fire exposure time ranges were determined: 0-30 minutes, 0-60 minutes, 0-90 minutes and 0-120 minutes.

4.3 Analysis of the significance of factors

A statistical analysis of results is made, for the work ranges mentioned above, with the help of the software STATGRAPHICS Centurion XV Version 15.2.06.

An analysis of significance of the independent variables for a 95% confidence was made. As in the composite section with beams without fire protection, the connector height is a significant factor in temperature relationships, and it is the one that has most influence on the ratio θ_c/θ_f . Another factor having a relevant influence is the thickness of the fire protection, and it is the most significant factor in the ratio θ_{sc}/θ_f . Conductivity has an influence on all three variables, but to a lesser extent. The lower the conductivity, the higher the ratio values.

In order to graphically illustrate the influence of the connector height on the ratios, Figure 6 shows the temperature ratios θ_{sc}/θ_f and θ_c/θ_f at $0.25 h_{sc}$, of the specimen with fire protection CR-A with connector height of 100 mm, and of the specimen CR-B with connector height of 50 mm, both with fire protection thickness of 10 mm, capacitance of $625000 \text{ J/m}^3\text{K}$ and conductivity of 0.3 W/mK .

Figura 6. Influencia de la altura del conector en las relaciones de temperatura θ_{sc}/θ_f y θ_c/θ_f a $0.25h_{sc}$
Figure 6. Influence of the connector height on the temperature ratios θ_{sc}/θ_f and θ_c/θ_f at $0.25 h_{sc}$

It can be clearly appreciated that the connector height has a significant influence on both ratios, although to a lesser extent on the ratio θ_{sc}/θ_f . Temperature ratios are higher as the connector height is reduced.

Figure 7 shows how the fire protection thickness has a significant influence on the temperature ratios of two specimens, the CR-C specimen with 40 mm thickness and the CR-C specimen with 10 mm thickness, both with h_{sc} of 100 mm, capacitance of the fire protection material of 625000 J/m³K, and conductivity of 0.1 W/mK.

It should be noted that in the first 30 minutes, the behavior of the ratios for the specimen with fire protection thickness of 40 mm is sharply different and the values of the ratios are significantly higher than those obtained with the thinner model.

Figura 7. Influencia del espesor del material de revestimiento contra incendio en las relaciones de temperatura θ_c/θ_f a $0.25h_{sc}$ y θ_c/θ_f a $0.5h_{sc}$
Figure 7. Influence of the thickness of the fire protection material on the temperature ratios θ_c/θ_f at $0.25 h_{sc}$ and θ_c/θ_f at $0.5 h_{sc}$.

Considering that the factors having most influence on temperature relationships are connector height, thickness of fire protection and its conductivity, modeling of specimens with the mean value of capacitance (625000 J/m³K) and conductivity of the fire protection material of 0.1 W/mK (which results in higher ratio values) was made, as well as different fire protection thickness of that material (10 mm, 25 mm and 40 mm), and connector heights of 50 mm, 60 mm, 75 mm, 90 mm, 100 mm and 125 mm, in order to determine the temperature relationships in the ranges of 0-30, 0-60, 0-90 and 0-120 minutes.

With the purpose of simplifying the results, a sensitivity analysis of the results' impact on the connection's resistance was additionally made, which led to the final proposal of temperature ratios shown in Table 4, where higher values corresponding to the range of 0-120 minutes were adopted, a result which remains on the safe side in relation to cases with higher conductivities of the fire protection material and lower fire exposure ranges.

Tabla 4. Relaciones de temperatura θ_{sc}/θ_f y θ_c/θ_f para vigas con revestimiento contra incendio
Table 4. Temperature ratios θ_{sc}/θ_f and θ_c/θ_f for beams with fire protection

Altura del conector/ Connector height (mm)	θ_{sc}/θ_f (%)	θ_c/θ_f a $0,25h_{sc}$ (%)		
		Espesor de 10/ Thickness of mm	Espesor de 25/ Thickness of mm	Espesor de 40/ Thickness of mm
50	85	80	85	90
60		80	85	90
75		75	80	85
90		75	80	85
100		70	75	85
125		70	75	80

It can be observed that the percentages proposed to determine the temperatures in the connector's steel and concrete for beams with fire protection are higher than those proposed in 3.3 for beams without fire protection (see Table 2). The reason for this is that heating occurs more slowly in the beams with fire protection, so that the temperatures of the connector and the slab concrete are closer to the steel flange temperature.

The above is especially clear in the percentages to determine the concrete temperature, which are considerably higher than the 40% adopted in EN 1994-1-2 (2005) and the percentages proposed in the present work for beams without fire protection. However, it should be taken into account that the impact of those high values on the design of the connection is mitigated, since they are applied as a multiplying factor at considerably lower average steel flange temperatures, derived from the presence of fire protection.

5. Impact of the above results on the determination of resistance

5.1 Design Methods for Stud Connections in Fire Situation

In the international standards, the only design method available is offered by EN 1994-1-2 (2005), where the stud connection resistance in fire situation is defined by the lowest of the following values:

$$P_{fi,Rd} = 0,8 \cdot k_{u,\theta} \cdot P_{Rd} \quad (1a)$$

or

$$P_{fi,Rd} = k_{c,\theta} \cdot P_{Rd} \quad (1b)$$

Where:

P_{Rd} = resistance at room temperature and it is obtained from EN 1994-1-1 (2004).

$K_{c,\theta}$ = reduction factor of the compressive strength of concrete at high temperatures, which is a function of the concrete temperature (θ_c) determined from the flange temperature (θ_f), according to the ratios θ_c/θ_f expressed in percentages.

$K_{u,\theta}$ = reduction factor of the steel resistance at high temperatures, which is a function of the connector temperature (θ_{sc}) determined from the flange temperature (θ_f), according to the ratios θ_{sc}/θ_f expressed in percentages.

EN 1994-1-2 (2005) adopts as temperatures of the connector's steel and the slab's concrete, 80% and 40% of the temperature of the upper flange of the beam, respectively.

Figure 6 illustrates the strength prediction differences when using the percentages indicated in EN 1994-1-2 (2005) and the percentages proposed in the present work, both for beams without fire protection (Figure 8a) and beams with fire protection (Figure 8b), for h_{sc} of 50 mm, connector diameter of 16 mm, f_c of 20 MPa and f_u of 415 MPa. In the examples, the prediction difference of the stud connection strength is significant and reaches 15%. This indicates that in some design situations within the scope of EN 1994-1-2 (2005) the resistance of the stud connection may be overestimated.

Figura 8. Predicción de la resistencia a elevadas temperaturas. (a) vigas sin revestimiento, (b) vigas revestidas con espesor de 25 mm

Figure 8. Prediction of the resistance of stud connections at high temperatures. a) Beams without fire protection, b) beams with 25 mm thick fire protection

6. Conclusion

1. Based on the results set forth, for beams without fire protection, it is suggested to adopt values associated to the 0-30 minute range and the determination level of the concrete temperature at one quarter of the connector height, differentiating the connector heights considered, as shown in Table 2.
2. As for the beams with fire protection, a strongly different thermal behavior is observed in relation to the case discussed above, which entails that the values of the ratios are visibly higher than those of EN 1994-1-2 (2005) and those proposed in the present work for beams without fire protection. This leads to the proposal of ratio values (presented in Table 4), which are valid in a wide range of thermal properties of the fire protection material and are dependent on the connector height and the thickness of the fire protection.
3. Finally, it has been demonstrated that for beams both with and without fire protection, the use of connector and concrete temperatures adopted by EN 1994-1-2 (2005) can lead to overestimate the resistance of the stud connection in fire situation, with regard to certain design situations within the scope of the code.

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