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Protected steel columns vs partially encased columns: Fire resistance and economic considerations

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ABSTRACT

As is commonly known, resistant properties of steel columns decrease quickly with an increase in temperature. Thus, steel columns are usually surrounded with low thermal conductivity materials that protect them at high temperatures. Another interesting alternative is the use of partially encased columns, a sort of steel-concrete composite column. Focused on fire performance and economic cost of a standard column, this paper presents a comparison study between partially encased composite columns and I-shaped steel columns with and without protection. A range of geometric cross-sections and material properties have been tested and the Pareto frontier has been used to show the cheapest columns with the best performance. The study is carried out assuming geometrical and material restrictions accepted by the European codes and imposing a constant axial load. Results show that most of studied protected columns resist around 120 min before collapsing in fire conditions. The structural response of partially encased composite (PEC) columns under simulated fire conditions is good and it can be seen from this study that significant savings can be obtained with a good design of PEC column, savings around 50%. The relative costs of the three design options studied are quantified. Considerations about the geometry and materials criteria are provided. All steel sections described in this study are commercial ones, which includes European, British, American, Japanese and Russian standard steel sections.

1. Introduction

The history of structural design may be explained in terms of a continuous progress toward optimal constructional systems, with respect to aesthetic, engineering and economical parameters, which better fulfill engineering requirements (load carrying and fire resistance). Structures have changed according to new materials, improvements have been made to the form of resistance elements and the synergic combinations of known materials.

In modern buildings and throughout the last century, steel and concrete are the most utilized materials in construction. Steel has many valuable benefits such as low weight, high strength, ductility, fast construction, adaptability to different shapes and energy absorption in case of earthquake. The main disadvantages of steel are durability and fire resistance capacity. In case of fire, steel elements need to be protected in order to ensure safety for occupants and firefighters, and reduce material loss. These fire protection materials are rockwood, brick, gypsum, perlite-vermiculite, calcium silicate and concrete.

Until the 1950s, a normal practice was to use a wet mix with low strength properties and neglect the contribution of concrete to the strength and stability of the column. Later, investigations [1–2] showed that savings could be made using better quality concrete and designing the column as a composite element. Concrete protects steel against fire action and reduces its effective slenderness, therefore increasing its resistance to axial load. Besides, concrete holds within an extra compressive resistance capacity.

In current international practice, composite construction is gaining importance in industrial buildings, structural frames and supports, spatial construction and in particular in high-rise buildings and bridge piers. A composite structural section has a number of distinct advantages over an equivalent steel, reinforced concrete or steel reinforced concrete section. Reinforced concrete provides high rigidity, is economical, durable and in partially encased concrete steel columns, the concrete provides fire protection and buckling resistance for the steel section [3–4].

The number of combinations and utilities of these two materials are very high [5]. This article is focused in the study of partially encased composite (PEC) columns of an I-shaped steel section with concrete cast between its flanges. PEC columns are constructed using standard size rolled steel sections with additional longitudinal steel reinforcing bars in an attempt to improve their behavior.

This article carries out a comparison between PEC, non-protected and protected steel columns, evaluating the cost of different solutions for the same problem considering fire resistance of the column.

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Nomenclature

A. General definitions

PEC columns	partially encased composite columns
EC3	Eurocode 3
EC4	Eurocode 4
N_{Ed}	applied axial load
L	column length

B. Geometry of steel cross-section

b, h, t_w, t_f	width, height, web and flanges thickness
A_a, I_{ay}, I_{az}	area and moments of inertia

C. Geometry of concrete in composite steel-concrete cross-section

A_c, I_{cy}, I_{cz}	area and moments of inertia

D. Geometry of reinforcing bars in composite steel-concrete cross-section

ϕ, $n_{\phi y}$, $n_{\phi z}$	diameter and number of reinforcing bars
S_y, S_z	distance between reinforcing bars in Y and Z direction
ρ_s	reinforcement ratio

E. Geometry of additional fire protection material for steel cross-section

d_p	thickness

F. Material properties

f_{ck}	characteristic cylinder strength of concrete (150 × 300 mm cylinder test)
f_{ya}	yield stress of steel cross-section
f_{ys}	yield stress of reinforcing bars
ρ_p, λ_p, c_p	density, thermal conductivity and specific heat, respectively, of fire protection material
E_a, E_c, E_s	elasticity modulus of steel, concrete and reinforcement

Calculations are made for a specific non-eccentric applied load and a column length for a wide combination of geometrical and material range and the optimal configuration based on the Pareto frontier is indicated in each case. This paper provides geometrical and material criteria for an economically optimal design of partially encased composite columns and I-shaped steel columns, taking into account fire resistance requirements.

The structure of this paper is as follows. First, a presentation of the problem to be minimized is offered, defining variables, variable ranges and the considered constraints. Then, the model established to consider the cost of each solution is introduced. Afterwards, a presentation is made for the models that verify resistance and stability of steel columns with or without fire protection and PEC columns at ambient temperature, and the model for predicting fire resistance. Then, the results obtained are presented and analyzed. The paper concludes with a summary of the main results and conclusions. In addition, interesting considerations are provided in order to obtain the most economical configuration of feasible PEC columns.

2. Problem statement

In this study the main aim is to obtain the optimal column configuration among all combinations of commercial geometries and materials that constitute feasible columns. All possible columns configurations are analyzed with the restrictions of European rules and the geometric restrictions. The resulting amount of feasible solutions is very wide. The optimal column subjected to an applied load is the one that, while fulfilling mechanical and geometrical constraints, has the minimal cost. In the process the resistance time of the column under fire conditions is considered. The Pareto frontier is chosen for showing the cheapest columns with the best performance in this study. Pareto frontier is used in multicriteria decision-making, and it is a subset of the set of feasible solution points with at least one objective optimized. In other words, the Pareto frontier is a subset of the design space with "the best" values of it. Then, they are the cheapest columns that support the constraints imposed in acceptable conditions.

In an optimization problem it is necessary to establish the boundary conditions, define the variables with their ranges and the objective functions of the problem. In the following section all the details are presented.

2.1. Objective function

The objective function to be minimized is the total cost of the column that fulfills all requirements and constraints. The algorithm applied can be written mathematically in the form of:

Find $x = [\text{Section}, f_{ya}, f_{ys}, f_{ck}, n_{\varnothing y}, n_{\varnothing z}, \text{protection material}, \text{thickness of protection}]$.such that

$$c(x) \to min \tag{1}$$

Subjected to $g_i(x) \le 0$.

Where $c(x)$ is the cost function and $g_i(x)$ are the different constraints.

In this problem, the cost calculation of each solution is based on material and fabrication costs, but transportation, associated labor cost and complementary materials and the required ancillary items are also considered. Other costs as general expenses of the company, industrial surcharge or taxes as VAT are not considered here.

Among several feasible solutions, the optimal one, in economic terms, is the cheapest one. In order to compare the different feasible solutions for each axial load and a specific column length, a cost function has been defined. For this purpose, the data cost base of BEDEC [6] has been employed. The data cost base utilized is specific for Spain at the present time. It is therefore assumed that in other countries or periods of time it will be different. However, the objective is to draw general conclusions that can be useful for any place or time. Other design criteria could be considered, e.g. durability, ease and speed of construction, future maintenance fee, etc. But the economic cost criteria based on Spanish official costs allows obtaining general results and extrapolating them to other countries.

2.2. Type of columns analyzed, variables and ranges

A large number of possibilities are analyzed in this study. Steel profiles available in the standard market are tested in this study. Depending on the type of the column (see Fig. 1), the number of variables is different. In this section the problem variables according to column types are exposed: I-shaped steel columns, protected steel columns and PEC columns.

The standard applied in the calculation of this study is Eurocode 3 and 4 [7–10]. The standard limits the application to a range of materials.

2.2.1. Steel columns

This type of column has the lowest number of variables: the I-shaped steel profile and the yield limit of its steel. With the aim of making a complete analysis the whole range of standard steel columns is studied. The European, British, American, Japanese and Russian standard sections have been considered. The studied series are: H, HD, HL, HE, HG, HP, W, S, J, UB, UC, UBP, IPE and IPN. The geometry standards and properties were consulted in Constructalia (in Arcelor Mittal web page [11]). The steel sections, including their range of dimensions, amount to 747 different steel section profiles. The values of yield stress of steel cross-sections considered in MPa are those accepted by Eurocode 235, 275, 355, 420 and 460.