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# Composite joints under M-N at elevated temperatures

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ABSTRACT

The Eurocodes recognise robustness as a way to ensure the structural integrity of a building frame subjected to an unforeseen event and therefore to avoid a so-called "progressive failure" mode in extreme loading situations. However, few practical guidelines exist nowadays which would allow a designer to design a structure accordingly. Within the European RFCS ROBUSTFIRE project, the behaviour of steel and composite car parks subjected to localised fire leading to a column loss was investigated. Under such a scenario, the beam-to-column joints play a key role in the global structural response. Indeed, these joints, initially loaded in bending, may be subjected to elevated temperatures and to combined axial load "N", bending moment "M" and shear forces "V". In this paper, a methodology to predict the mechanical response of bolted composite beam-to-column joints at elevated temperatures under M-N is presented and validated through comparison with detailed numerical results and experimental tests. This methodology is based on an analytical method able to predict M-N resistance interaction curves for steel and composite joints and which is in full agreement with the component model recommended by the Eurocode.



## 1. Introduction

The growing number of cars in Europe during the last decades, as well as the number of large shopping centres, airports and railway stations, considerably increased the number of car park buildings [1]. Nowadays, part of these car parks are built above the ground ("open" car parks) because of a lower price per parking place, lower energy consumption, use of natural light and natural ventilation [2].

Consequently, an easy and low cost solution for the construction of open car park buildings is to use a composite steel-concrete structure. Steel and composite construction also presents the advantage of optimising the number of parking places of the car park and, consequently, to improve the return on investment by gaining floor area [3]. However, the increase of the market share for steel and composite car parks in Europe is somewhat limited by the lack of information on how these structures behave under fire. Fire loading due to burning cars allows for a very fast fire growth rate, but the large natural ventilation in this kind of buildings keeps the fire localised to the ignition zone. A localised fire which develops in an unprotected steel composite car park leads to the heating of some of the nearby structural elements (connections, beams and columns). This may result locally in a significant reduction of the carrying capacity of one column and subsequently to the loss of global stability of the car park. One way to prevent this type of failure consists, at the design stage, to check successively – according to the location of the fire in the structure – the stability of the structure in which one column would have been removed. Such a procedure is certainly safe but may be considered as time consuming and uneconomical. The use of active measures, such as sprinklers may obviously be considered; but such a solution increases the construction costs and requires constant maintenance. Moreover, a severe fire may affect the proper functioning of these active measures. An economical alternative consists in providing the structure with sufficient robustness. In this approach, the structure is designed in such a way that an unforeseen event does not lead to a disproportionate structural collapse. In other words, the structure is designed in a usual way, under classical loading situations, but should be able to undergo the complete or partial loss of a structural element (here a column) without losing its global stability. The development, locally in the structure, of large deformations or displacements is accepted, as long as progressive collapse is prevented [4].

During such an event, in addition to the large vertical deformations, the beam-to-column connections are subjected to particular load sequences involving bending moments, axial forces and shear forces (M-N-V interactions). In order to behave properly in such conditions,

*Abbreviations:* BFC, beam web and flange in compression; BT, bolt in tension; BWT, beam web in tension; C, compression; CFB, column flange in bending; CSC, concrete slab in compression; CWC, column web in compression; CWT, column web in tension; EPB, end-plate in bending; FE, finite element; FEM, finite element method; FM, *T*-stub Failure Mode (1, 2 or 3); $F_{Rd}^{-}$, ultimate resistance of the row, when the joint is subject to hogging bending moment; $F_{Rd}^{+}$, ultimate resistance of the row, when the joint is subject to sagging bending moment; $h_i$, distance between row i and the reference axis; $K_a$, beam axial restraint stiffness; M, bending moment; $M^{-}$, hogging bending moment; $M^{+}$, sagging bending moment; RT, longitudinal steel reinforcement in tension; T, tension; $\Phi_{j,u}$, ultimate joint rotation; θ, temperature.

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structural redundancy and local ductility at elevated temperatures are required from the various structural elements. Ductility of the joints is mainly required in order to avoid brittle damages and to dissipate energy by undergoing large deformations after initial yielding without any significant reduction in strength. Ductility in a system can be achieved by ensuring that the joints provide large rotations, so that membrane forces in the members can be activated, allowing a redistribution of internal forces to find a new equilibrium state in the deformed configuration. These joints, heated by localised fire, are subjected to varying bending moments (decrease or even inversion of bending moment), combined with axial tensile loads.

Within the European RFCS project ROBUSTFIRE [5], the behaviour of steel and composite car parks subjected to localised fire leading to a column loss was investigated, and a methodology to predict the mechanical response of bolted composite beam-to-column joints at elevated temperatures under M-N was developed. This methodology is based on an analytical method able to predict M-N resistance interaction curves for steel and composite joints [6,7], that is in full agreement with the Eurocode model recommended for the joint characterisation (the component method).

The validation of the proposed model through comparisons against detailed numerical results and experimental evidence, obtained from tests on a composite steel-concrete beam-to-column frame under localised fire, is presented in this paper.

## 2. Review of experimental tests

### 2.1. Testing setup and experimental program

A sub-frame extracted from a braced open car park building with eight floors of 3 m height, with real cross-section dimensions: beams IPE 550, columns HEB 300, and bolts M30, cl. 10.9, was tested at the University of Coimbra [8]. The steel beam was fully connected to the composite slab (Fig. 1a). The main objective of the tests was to observe the combined bending moment (M) and axial loads (N) in the composite joint throughout the entire M-N resistance curve. In order to reach this goal, the effect of the axial restraint to the beam provided by the cold part of the building was simulated. When no restraint was applied (tests 1, 2 and 3), the beams were free to deform axially. For the beam restraint (tests 4 and 5), a steel beam with profile HEB 300, connected from the end of the tested beams to rigid walls was used (Fig. 1a). The real axial restraint to the beams (spring restraints in test 6) provided by the part of the building not directly subjected to the fire was simulated using hydraulic jacks. In order to simulate the effect of the localised fire that led to the column loss, the composite joint (Fig. 1b) was subjected to elevated temperatures: five tests at 500 °C or 700 °C and one test at ambient temperature (Table 1).

**Table 1**
Objectives of the seven experimental tests of sub-frames subjected to the loss of a column.

| Test | Objectives |
|---|---|
| 1 | Derivation of the joint properties at 20 °C \| *No axial restraint* |
| 2 | Derivation of the joint properties at 500 °C \| *No axial restraint* |
| 3 | Derivation of the joint properties at 700 °C \| *No axial restraint* |
| 4 | Derivation of the joint M-N curve at 500 °C \| *Total axial restraint* |
| 5 | Derivation of the joint M-N curve at 700 °C \| *Total axial restraint* |
| 6 | Derivation of the joint M-N curve at 700 °C \| *Realistic axial restraint* |
| 7 | Demonstration of the real joint behaviour of a sub-frame subjected to the loss of a column due to a localised fire \| *Realistic axial restraint* |

### 2.2. Description of the loading sequence

The testing procedure included three main phases (Fig. 2): phase A - an initial hogging bending moment was applied to the joint before the localised fire; phase B - the joint zone was heated in order to reproduce the effect of the localised fire (except for ambient temperature test), and

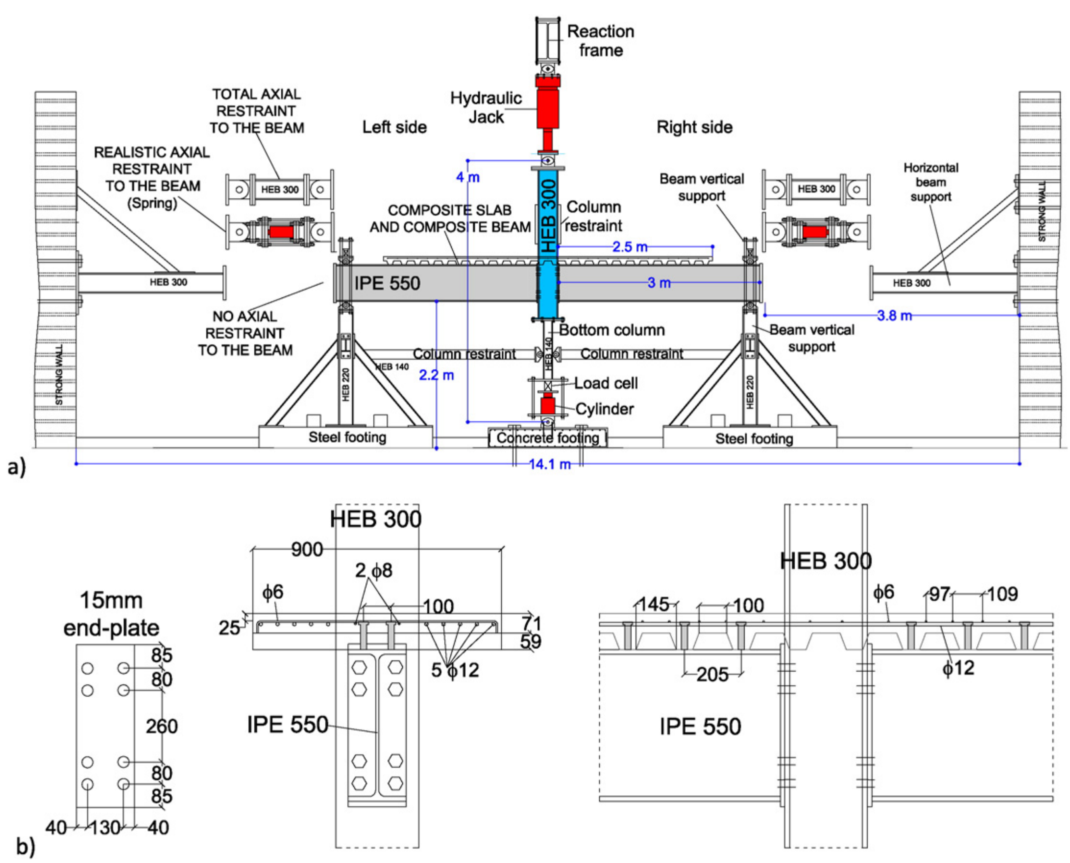


**Fig. 1.** a) General layout, longitudinal view; b) Composite beam-to-column joint.