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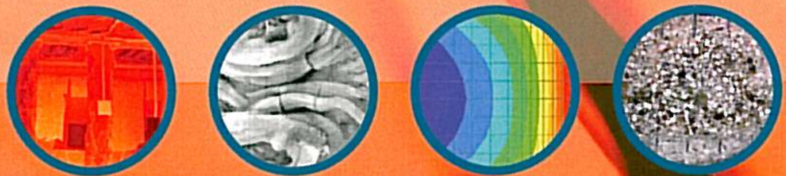
fire design of concrete structures

from materials modelling to structural performance



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"Fire Design of Concrete Structures – From Materials Modelling to Structural Performance"

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PUSH-OUT TESTS FOR PARTIALLY ENCASED BEAMS AT ELEVATED TEMPERATURE

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ABSTRACT

Partially encased beam is a steel-concrete composite element, made-up with a hot rolled profile and filled with concrete between flanges. Such structural element improves load-bearing capacity at elevated temperature. The mechanical and thermal interaction between steel and concrete is analysed for natural adherence at elevated temperature, using push-out tests to determine bond stress and thermal capacitance.

1. INTRODUCTION

Partially encased beam improves load-bearing capacity of steel profile at elevated temperature. Concrete between flanges reduces the heating rate through the steel profile under fire conditions. The condition for natural adherence is considered between steel and concrete. Bond stress should determine the strength limit state during splitting contact, being represented by the maximum shear stress at steel-concrete interface, which enables both materials to acquire composite action, see figure 1.

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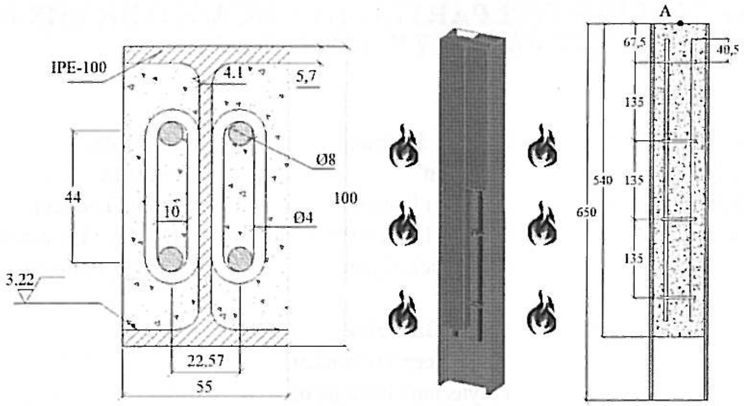


Figure 1 – Model for partially encased beam at elevated temperature.

When concrete is subjected to high temperatures, deterioration of mechanical properties arises and becomes an important factor to account for. Of particular importance is the loss in compressive strength and the collapse of bond between the cement paste and aggregates and the overall interface between steel and concrete. As the temperature approaches 250 [ºC] dehydration begins to take place and the compressive strength begins to reduce. At 300 [ºC] strength reduction would be in the range of 15-40 % and at 550 [ºC] reduction in compressive strength would typically range from 55% to 70% of its original value, [1], being this process almost irreversible.

Steel also presents mechanical properties degradation, in a different temperature scale. Temperature between 550 and 650 [ºC] is responsible for residual stress cutback, reducing its elastic modulus and yield stress to 60 % and 78%, respectively at 500 [ºC]. Between 500 [ºC] and 700 [ºC] these values fall very much and after 700-800 [ºC] steel becomes with a new austenitic phase, responsible for changing thermal and mechanical properties.

This work presents an experimental method for testing mechanical and thermal characteristics for the interface of partially encased beams at elevated temperature (400 [ºC]), which will be valuable for the interface numerical modelling. Interface may be represented by non linear finite spring element, introducing contact stiffness and conductance.

Push-out test is based on axially load concrete blocks by means of a hydraulic jack, at high temperature level, measuring the relative displacement of concrete, determining the load histogram. Load is stepped incremented up to the ultimate state conditions (slipping of concrete or local concrete failure). A set of three tests were carried out.

2. SPECIMEN PREPARATION

Partially encased beams were prepared in laboratory with S275JR IPE 100 steel profile and low strength reinforced concrete. Reinforcement was attained with 8 [mm] diameter B500s rib bars welded to 4 [mm] plain diameter steel bars for stirrups, spaced every 135 [mm]. The interface between steel and concrete is made without shear connectors, being natural adherence characterized by chemical and friction characteristics.

Minimum concrete cover shall be provided in order to ensure the safe transmission of bond forces, the protection of steel against corrosion (durability) and appropriate fire resistance. An external vibration and punching should guarantee the best consolidation and consequently the highest adherence between both materials, see figure 2. Cure was attained inside wet chamber at 23 ± 1,7°C and at least 95% of relative humidity, during 28 days.

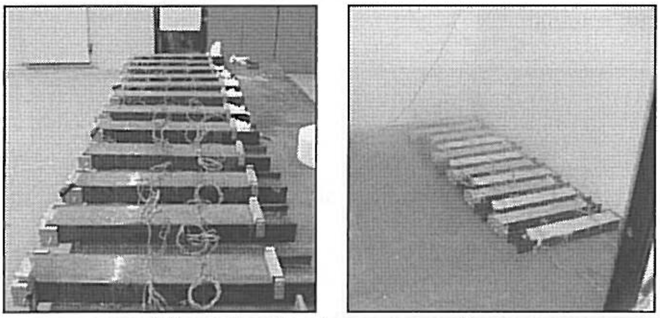


Figure 2 – Specimen preparation.

Every partially encased beam was set up with 650 [mm] long steel, filled with 540 [mm] long concrete block. Concrete should fill in between flanges and leave 110 [mm] air gap in the bottom flanged beam to allow measurement of concrete relative displacement.

Steel surface roughness was characterized according to ISO 4287 / 4288 standards, [2,3], along a specified evaluation length of 12.5 [mm], with 5 roughness sampling length of 2.5 [mm] each. Roughness was measured in every tested beam, each with 18 evaluation lengths. Arithmetic average roughness of 3.22 [μm] was determined which fall in-between expected values for this finished product (0,8 to 3,2 [μm]), [3]. This steel surface condition with concrete should produce a dry friction coefficient between 0.2 and 0.6, [4].

Specimens from steel profile were cut and normalized. Steel was received from manufacture with nominal yield stress equal to 490 [MPa], based on 6 tested specimens, with 11 [MPa] of standard deviation, [5].

Portland cement type II class CEM-II/B-L 32,5 N and siliceous aggregate were used in the concrete elaboration. Aggregate dimensions were restrained to web flange dimensions and also to volumetric concrete recover dimensions, using an average diameter equal to 4 [mm]. Specimens from concrete were produced and normalized for cubic compressive tests, according to EN 12390-2, [6]. Compressive strength for hardened concrete at 7 and at 28 days was determined. The average value of cube compressive strength allows concrete to be classified as C12/15. The residual humidity was determined equal to 6.75%.

Steel reinforcement was also classified according to standard procedures. From the 8 [mm] rebar B500s samples were prepared and tested according to standard [5], resulting yield stress equal to 500 [MPa]. Specimens from steel stirrups were produced and normalized for tensile tests, using same standards, resulting yield stress equal to 200 [MPa].

3. EXPERIMENTAL TESTS FOR PUSH-OUT

For testing partially encased beams under elevated temperature, an insulated chamber was created, using an electro-ceramic device to increase temperature, see figure 3. Low thermal conductivity materials were applied in insulated chamber, using vermiculite plate and special thermo-resistant glass material.

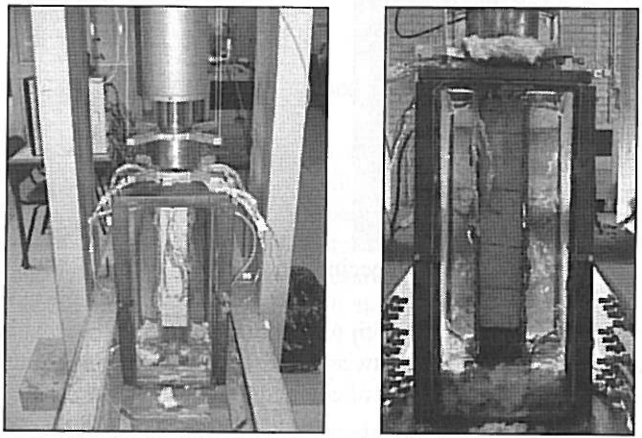


Figure 3 – Experimental set-up for push-out at elevated temperatures.

A heating rate of 400 [ºC/h] was applied up to the specified test temperature level (400 [ºC]). After temperature stabilization, both concrete blocks were mechanically loaded using an incremental force system up to the maximum force level (maximum bond strength). After that, an incremental displacement method was applied to find out the post bond behaviour and the friction adherence.

3.1 Instrumentation

Tests were carried out using an axial loading system, especially designed for the push-out experiences. The hydraulic jack was connected to a load cell and will push-out concrete along the flanges and web of steel profile. At the other extremity another load cell was positioned for reaction force measurement. Concrete displacement was measured with a wire potentiometer position sensor (displacement transducer with an accuracy of +/- 0,1 [mm]), connected to an acquisition data centre.

To control the heating process and to measure temperature inside concrete and over the steel beam, type K thermocouples were positioned in specific places according to figure 4. An extra thermocouple was installed over the external concrete surface to track the heating temperature delivered by the heating power unit (bulk temperature).

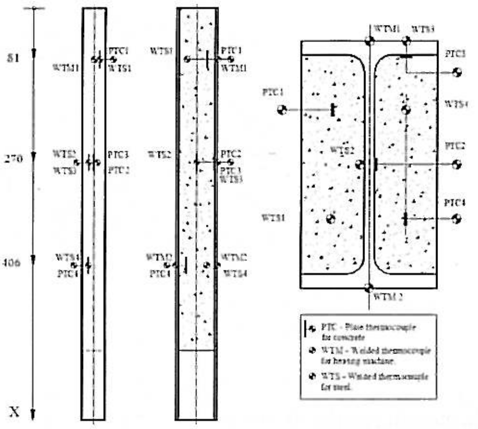


Figure 4 - Thermocouples position for temperature measurement.

3.2 Experimental results

Temperature was incremented inside insulated chamber, using an heating system with 70 [kVA], with electro-ceramic resistances applied to beam flanges. Temperature in steel and concrete follows the prescribed heating curve, as represented in figure 5.

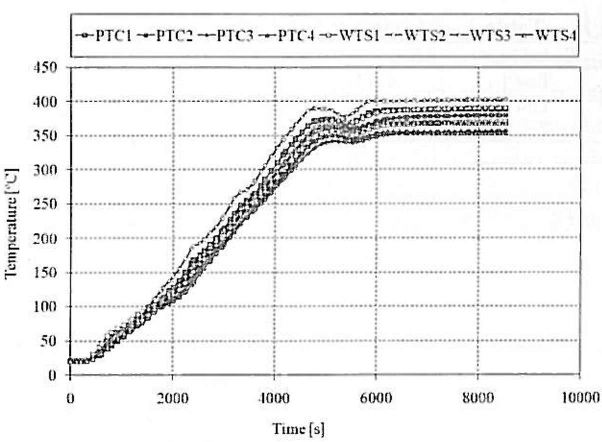


Figure 5 - Measured temperatures during heating process, for natural adherence.

After temperature stabilization, the mechanical loading process began. Concrete did not present any visible crack or crushing failure under axial load. Push-out experiments were conducted with breaking of natural adherence, as represented in figure 6. When adhesion bond breaks, a negative pending appears in load-displacement curve. The final curve behaviour corresponds to friction at interface level between concrete and steel surface.

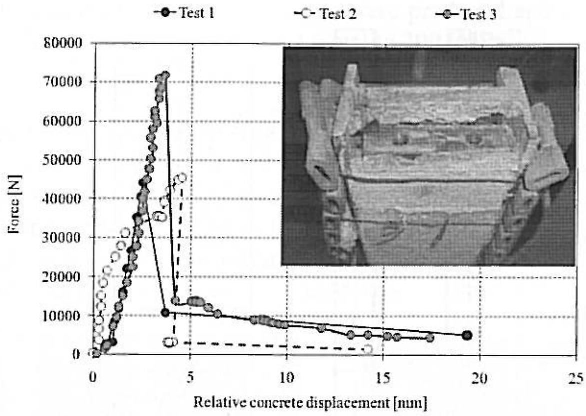


Figure 6 - Load-displacement results at elevated temperature with natural adherence.

The maximum shear stress for natural bond adherence was determined for this temperature level for all tests. Differences between results may be justified by the fact that both concrete blocks travel at the same time for test 1, while test 2 presented local failure in one block, followed by large concrete displacement. The third test followed measured force displacement of the first test with higher maximum shear stress, but with the same characteristic behaviour. See table 1 for maximum bond strength.

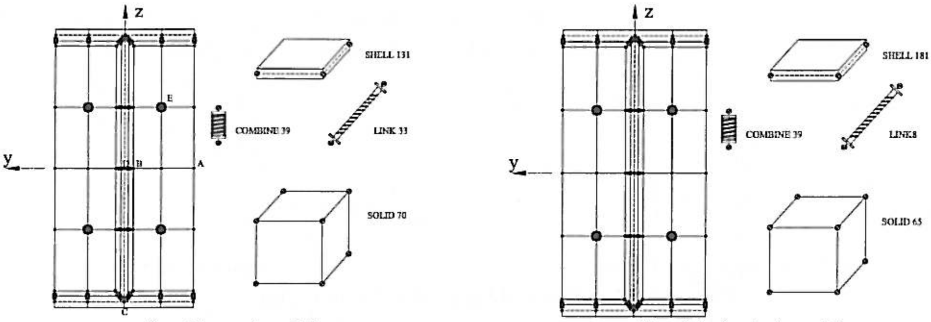
Table 1 – Maximum bond strength results.

Tested beam	Max. force [N]	Max. Bond stress [MPa]
Test 1	44142	0.293
Test 2	45487	0.302
Test 3	71689	0.476

4. NUMERICAL SIMULATION FOR PUSH-OUT

4.1 Numerical model

Thermal and mechanical non linear analyses were applied to simulate the experimental push-out tests for partially encased beams. Results are presented at elevated temperature, using the experimental bond behaviour between steel and concrete. A three dimensional finite element model was used to simulate thermal and mechanical analysis, base on Ansys finite element solutions, [7]. One part of the mesh was generated with finite shell elements to represent steel profile and the other mesh with solid and link elements to model reinforced concrete. These meshes were joined by non-linear finite spring elements used to simulate bond behaviour, see figure 7.



a) Thermal model. b) Mechanical model.

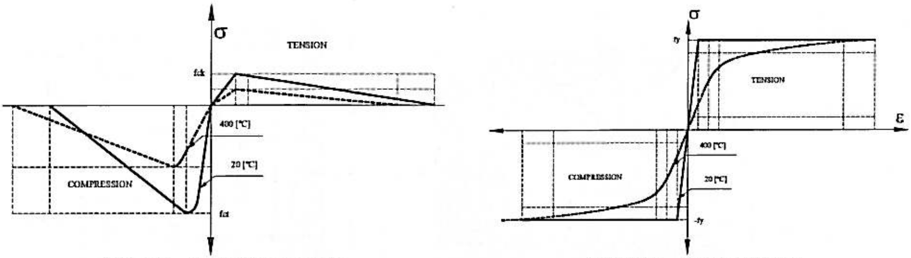
Figure 7 – Finite Element model for bond analysis.

Thermal model required non linear unsteady solutions for the experiments simulation at elevated temperatures, using appropriate thermal conductance for the interface between steel and reinforced concrete. An optimum design strategy was conducted to determine the best approach to this interface property, based on the minimization of the squared relative error between numerical temperature results and experimental measured temperature, see Eq. 1.

$$OBJ = Error = Min\left(\sum_{t=1}^{time}\left[\frac{\left(T_t^{num} - T_t^{\exp}\right)}{T_t^{\exp}}\right]^2\right) \tag{1}$$

This design variable (contact conductance) was estimated by numerical design optimization, using the first order method. The objective function, error, was considered to minimize differences between predicted and measured temperature values, in space and in time, according to the previous equation and the specific measured temperature values. The first order method uses gradients of the dependent variables with respect to the design variables. Gradient calculations are performed in order to determine a search direction. Each optimization iteration accounts for a number of sub-iterations that includes search direction, gradient computations and several thermal analyses loops. A conductance value of 100 [W/m^{2}K] was considered for the interface steel-concrete, being in accordance with reference [8].

Thermal and mechanical properties were adopted from eurocode, [9,10], to simulate steel and concrete behaviour. An elasto–elliptic-plastic model was adopted for steel, using the appropriate experimental values. Concrete being quasi brittle material was simulated with different behaviour for tension and compression, as represented en figure 8. Concrete should be able to crack in tension and crush in compression, using appropriate failure criteria developed by Willam Warnke, [7].



a) Stress – Strain for concrete. b) Stress – Strain for steel.

Figure 8 – Mechanical behaviour for materials.

The mechanical model requires material and geometrical non-linear solutions to simulate large displacement and an incremental displacement method (maximum 0.12 [mm]). Force was simulated by means of step incremental displacement, in the concrete nodes of the loading section. This loading condition satisfies numerical convergence, using Newton-Raphson displacement criteria.

The numerical model for reinforcement considered no movement between steel and concrete. Bond behaviour was represented by non linear finite spring elements, used in normal and tangential directions. Higher stiffness was applied to finite spring elements in normal direction to restrain contact between concrete and steel surfaces. Experimental measured stiffness was applied in tangential direction to validate experimental tests. Bond stress behaviour was modelled by finite spring elements with experimental nonlinear generalized force-deflection ability.

4.2 Numerical results

Numerical simulation predicts nodal temperature values as represented in figure 9. Good agreement was achieved between experimental results and numerical simulation.

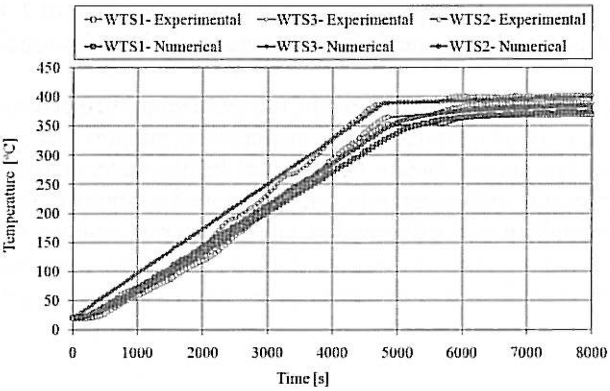


Figure 9 – Comparison between experimental and numerical results for temperature prediction.

Numerical results for the simulation of push-out tests are represented in figure 10. Collapse occurs between steel and concrete surface by adherence failure.

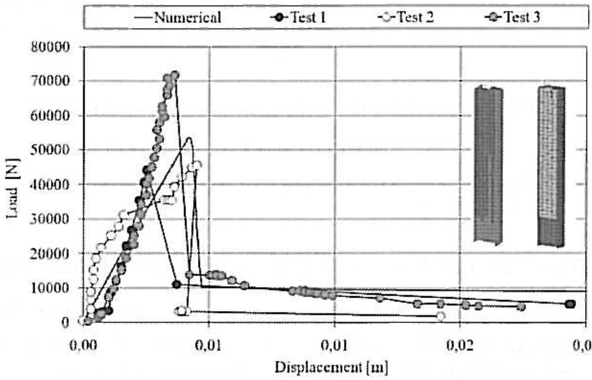


Figure 10 – Numerical results for push-out test simulation.

5. CONCLUSIONS

A new set-up was developed for push-out experiments at elevated temperature. More experiences were conducted at room temperature with natural adherence and with shear connectors welded to the web of steel profile.

Bond stress and bond behaviour were experimentally determined at elevated temperature for natural adherence. The results show that shear strength on web and flanges is higher than the expected value from eurocode (τ_{Rd}=0.2 [MPa]), [11].

The results at elevated temperature presented a decrease in bond strength relative to room temperature results.

Numerical validation was also presented for this adherence condition, considering the corresponding experimental value for bond behaviour at contact elements. Interface between steel and concrete was numerically modelled by means of non-linear finite spring element, considering appropriate conductance and stiffness as presented.

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