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Deliverable III: Development of simplified behavioural models

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I. Introduction

The objectives of Work Package 2 (WP2) are to acquire the required knowledge on: A) the behavioural response of the individual frame structural elements directly affected by the localised fire, and B) on the resultant reduction of carrying capacity of: i) the heated column in compression and bending; ii) the heated beam subject to bending and axial force (membrane effects); and iii) the heated beam-to-column joints subject to bending and axial force (membrane effects). To reach this goal, experimental, numerical and analytical developments were carried out, with the aim, at the end, to derive behavioural models for elements at two different levels: a "sophisticated level" (FEM models) and a "simplified" level (models for designers).

As an outcome of WP2, the present deliverable (DIII) is about the development of simplified behavioural models: i) these models can be more easily used in practice, ii) they could possibly be, later, implemented in design guides or codes, and iii) they allow the designer to assess the behaviour of the structure in a rather easy and direct way, i.e. in agreement with his requirements in terms of efficiency and competitiveness.

The analytical method predicting the resistance of steel or composite joints submitted to both an axial force and a bending moment at elevated temperature is described in the following section, whereas the simplified models of beams and columns are used in WP3 when investigation the sub-structures and the structures at the simplified and sophisticated levels; they are detailed in the deliverables IV and V from WP3 (Fang et al., 2012a and 2012b).

The contractors involved in this WP2 were FCTUCOIMBRA, ULGG, ICST and ARECELORPROFIL.

II. M-N resistance of joints at elevated temperature

II.1. Introduction

This section presents an analytical method predicting the resistance of steel or composite joints submitted to both an axial force and a bending moment at elevated temperature. The model was developed in Cerfontaine (2004) (see also Cerfontaine et al., 2005) for steel joints at ambient temperature. It was extended to composite joints in Demonceau (2008) (see also Demonceau et al., 2010), in which a formula giving the resistance of the "new" component "concrete slab in compression" was introduced. It is extended here to elevated temperature.

First, the method is explained based on the particular case of the bolted joint linking the primary beams to the columns in the reference car park structure designed and investigated in the present project. Then, the model is validated by comparison to experimental tests performed on this joint at elevated temperature (using the temperature distributions measured during the tests). Finally, the analytical method is applied to an example based on temperature distributions determined through a thermal finite element simulation for the ISO fire curve to illustrate how the developed model can be applied in a situation of design.

II.2. Description of the considered joint

The studied joint links two IPE550 primary beams to a HEB300 column, as represented in Figure 1; it is the joint configuration tested in Coimbra as a contribution to the present project. It is a double-sided composite beam-to-column joint subjected to symmetrical loading. Only the solid part of the composite slab is taken into account for the joint computation (steel sheet and concrete in the ribs are neglected).

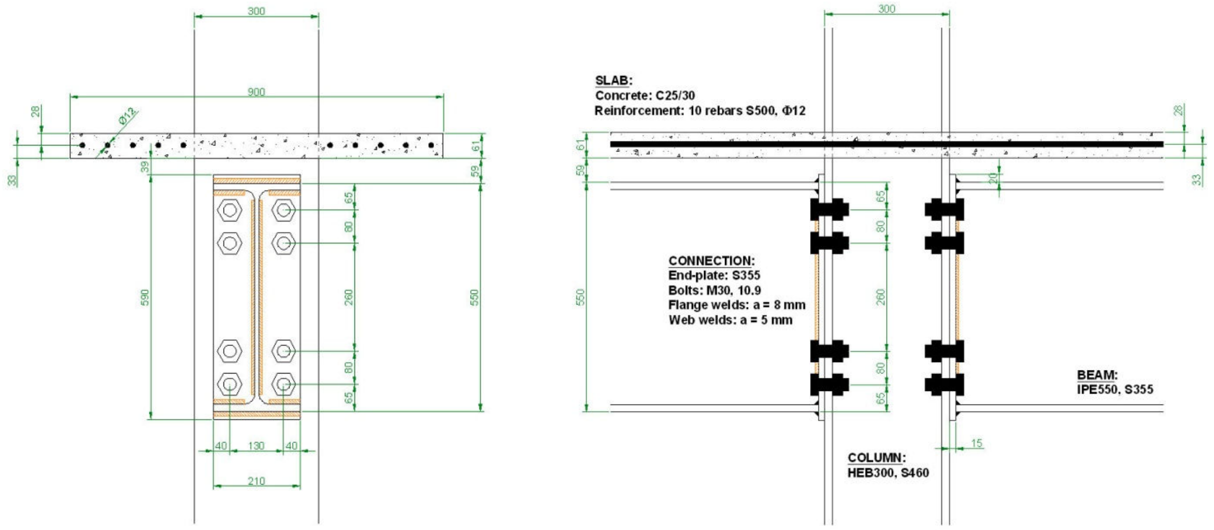


Figure 1. Considered joint

II.3. M-N interaction curve for joint resistance

When a joint is subjected to both bending moment and axial load, its resistance is represented by an interaction curve that can be evaluated following the procedure presented herein. The proposed analytical model is based on the component method (method recommended in the Eurocodes for the design of steel and composite joints) and on the assumption that all components activated at failure are fully ductile, meaning a plastic redistribution of the forces is considered within the joint without any displacement limitations.

The joint is divided into different rows (Figure 2) that can be activated or in tension (T) or in compression (C). The resistance of each row can be calculated using the component method (i.e. using the rules from Eurocode 3 Part 1-8 or from Demonceau (2008) for the component “concrete slab in compression”): it is given by the resistance of the weakest component involved in the row. These rows are listed below for the considered joint, with the corresponding components:

- <u>Row 1 (C)</u>: upper part of the slab in compression → *concrete slab + column web*
- <u>Row 2 (T)</u>: slab reinforcement in tension
- <u>Row 3 (C)</u>: lower part of the slab in compression → *concrete slab + column web*
- <u>Row 4 (C)</u>: top flange in compression → *beam flange and web + column web*
- <u>Row 5 (T)</u>: bolt row 1 in tension → *column flange + end-plate + bolts + beam web + column web*
- <u>Row 6 (T)</u>: bolt row 2 in tension → *column flange + end-plate + bolts + beam web + column web*
- <u>Row 7 (T)</u>: bolt row 3 in tension → *column flange + end-plate + bolts + beam web + column web*
- <u>Row 8 (T)</u>: bolt row 4 in tension → *column flange + end-plate + bolts + beam web + column web*
- <u>Row 9 (C)</u>: bottom flange in compression → *beam flange and web + column web*

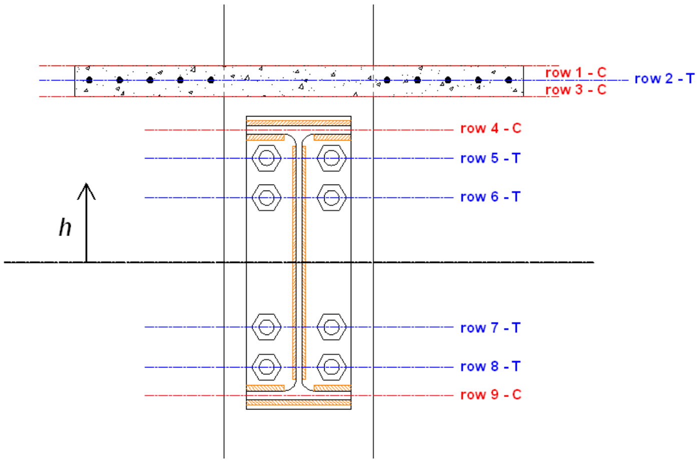


Figure 2. Rows and reference axis

For given bending moment and axial force, each row will be activated or not depending on the position of the neutral axis and whether the upper rows are in tension or in compression. In any case, the following equilibrium equations have to be fulfilled:

$$N = \sum_{activated\ rows\ i} F_i$$

$$M = \sum_{activated\ rows\ i} F_i \, . \, h_i$$

Where:

- F_i is the force sustained by row i; it is taken positive in tension.
- h_i is the distance from row i to the reference axis, positive for upper rows (the reference axis is arbitrary chosen at mid-height of the beam profile in Figure 2).

Based on the previous considerations, the whole resistance curve can be established as follows. Considering first that the upper rows are in tension, the activated rows can easily be determined for any chosen position of the neutral axis (at the very top of the joint, between two successive rows or at the very bottom). Knowing the activated rows, the corresponding loading (M,N) can be computed using the equilibrium equations. Indeed, all activated rows are supposed to sustain a force equal to their resistance (plastic distribution) while the other ones sustain a force equal to zero. One particular point of the resistance diagram can thus be determined for each position of the neutral axis. The same can be done for lower rows in tension. Finally, the whole interaction curve is established. Figure 3 shows the nominal M-N resistance curve of the considered joint at ambient temperature (reference axis is taken at mid-height of the steel profile – Figure 2) and Figure 4 gives the position of the neutral axis corresponding to each particular point of the interaction curve.

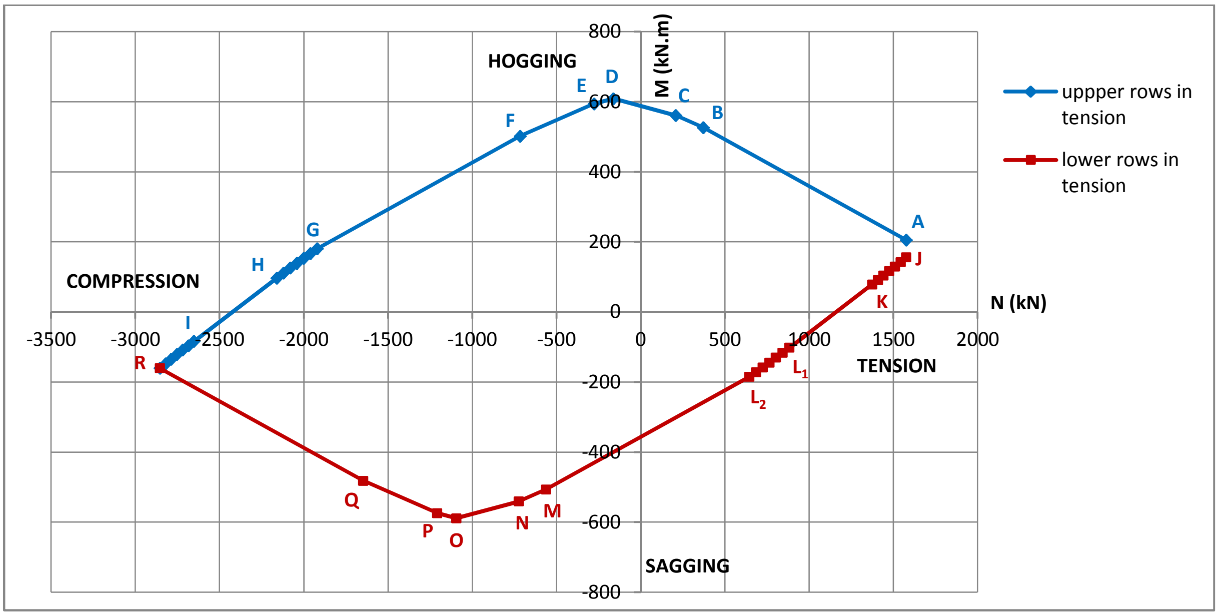


Figure 3. Nominal resistance curve at ambient temperature

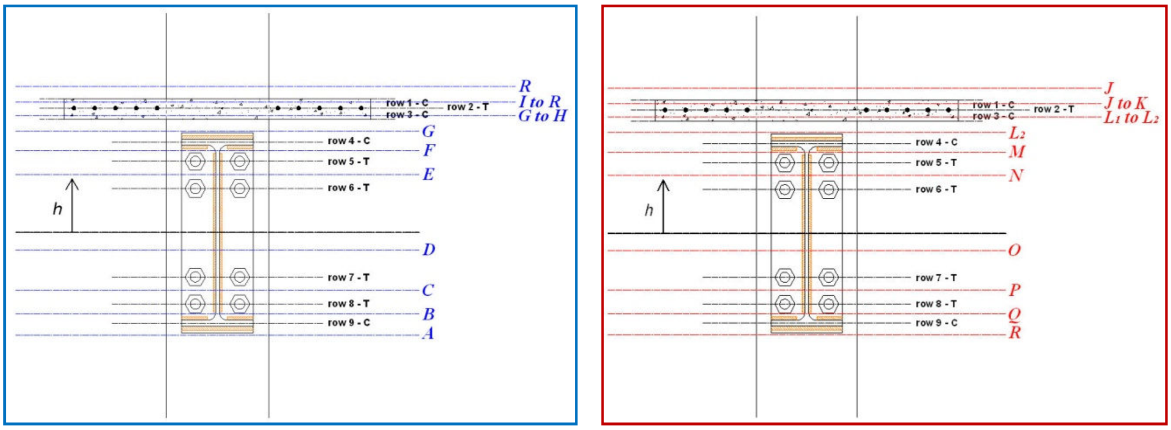


Figure 4. Position of the neutral axis for the particular points of the M-N resistance curve, for upper rows in tension (left) and for lower rows in tension (right)

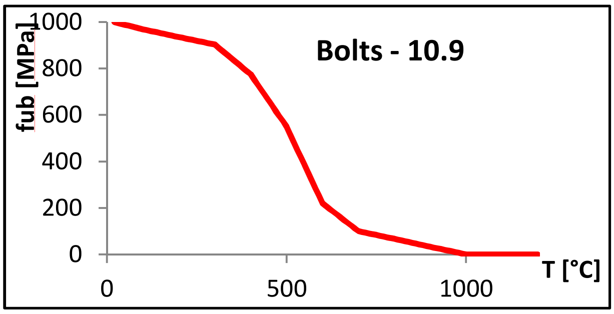
The same procedure can be applied at elevated temperature provided the temperature distribution in the joint is known. Each component resistance is then simply evaluated based on the material resistance at its given temperature.

II.4. Validation of the analytical model against experimental tests

II.4.1. Assumptions for the analytical predictions

The aim of these analytical predictions is to be compared to the loading of the tested joints at failure. Consequently, the ultimate joint resistance should be predicted instead of the nominal resistance. That is why all safety factors γ were taken equal to 1.0 and the material ultimate resistances were considered instead of the yield resistances. The component temperatures were estimated based on the measurements made during the tests (they had to be extrapolated from the measure points which were not necessarily at the component locations).

The material resistances at elevated temperatures were evaluated based on the Eurocode rules and material tests when available. The slab reinforcement remained at relatively low temperature during the tests and the ambient-temperature nominal resistance was thus considered (anyway, it is not activated under sagging moment). Tests were performed on bolts; unfortunately, results were not yet available for the calibrations of the present analytical model, thus the nominal resistance was considered at 20°C as well as the Eurocode rule for the decrease with temperature (Figure 5). For concrete, the decrease in resistance with temperature was also given by the Eurocode but the ambient-temperature resistance was deduced from tests on concrete cubes at 20°C (Figure 6).



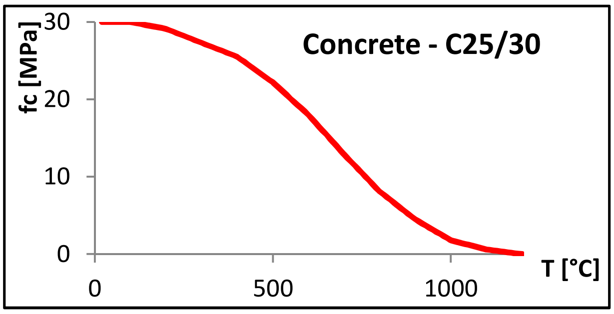


Figure 5. Bolts resistance versus temperature

Figure 6. Concrete resistance versus temperature

For steel profiles (beam and column), tension tests were performed on web and flange coupons at 20, 500 and 700°C. The graphs of Figure 7 give (versus temperature):

- in blue: the yield stress, based on the test results at 20°C and the Eurocode rule for the decrease with temperature;
- in orange: the ultimate stress, based on the test results at 20°C and the Eurocode rule for the decrease with temperature (this rule was modified for the initial plateau to be at the level of the measured ultimate resistance at ambient temperature);
- in green: the measured ultimate stress at 20, 500 and 700°C (from coupon tests);
- in red: the considered ultimate stress for the analytical predictions.

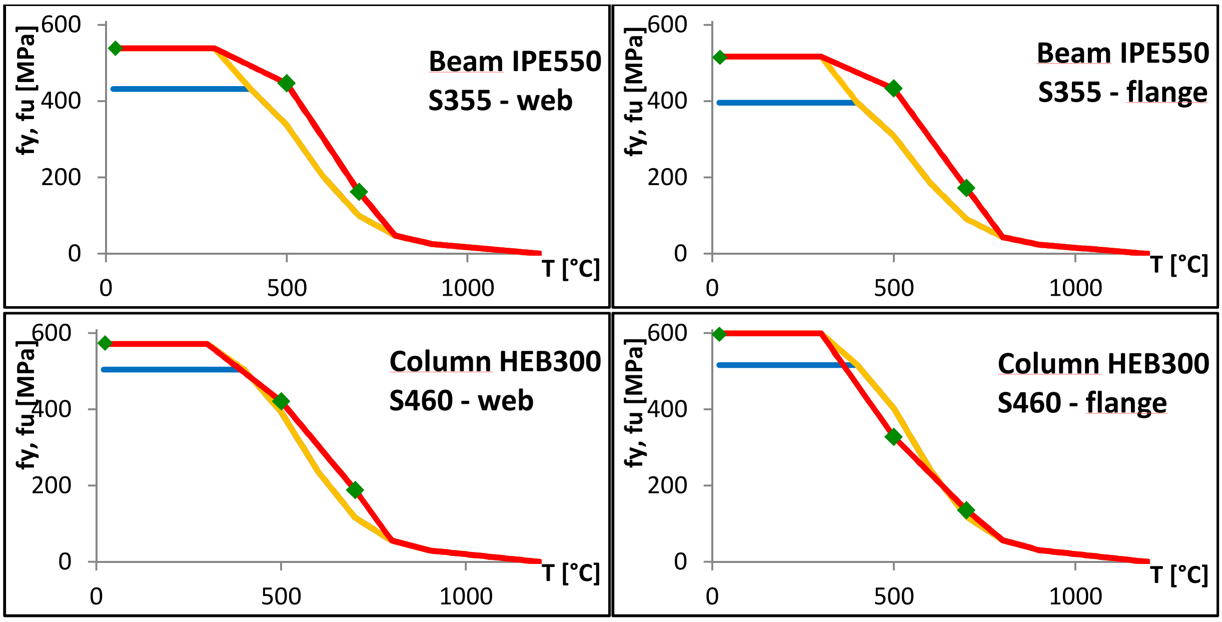


Figure 7. Steel profiles resistance versus temperature

No coupon tests were performed on the end-plate steel at elevated temperature. That is why the Eurocode rule was used for the decrease with temperature, in combination with the certificate values for the yield and ultimate stresses at 20°C, which were confirmed by coupon tests. Figure 8 shows the evolution of the yield and ultimate stresses with temperature (blue and orange curves as defined above). This “Eurocode” ultimate stress (orange curve) was admitted for the analytical predictions (as no coupon tests were performed at elevated temperature).

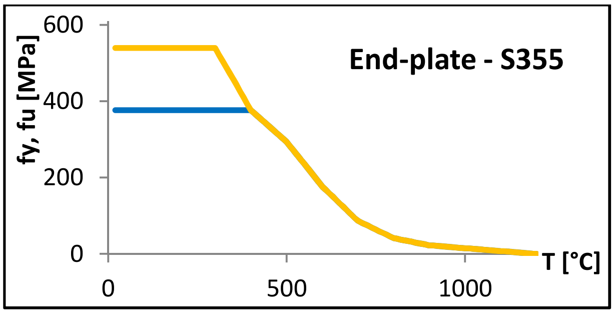


Figure 8. End-plate resistance versus temperature

II.4.2. Comparison of the analytical predictions to the test results

For each test, the loading M+N of the joint at failure could be identified. This loading corresponds to one particular point on a (M,N) diagram and can be compared to the analytically predicted M-N interaction resistance (based on the temperature distribution recorded at the moment the joint fails). As the temperature distribution during the tests was not exactly the same in the right and left connexions, one analytical resistance curve was computed for each side.

The following figures compare the experimental resistances to the analytical predictions for the different tests (tests 2 to 7). The temperature is supposed to remain constant during the loading simulating the column loss for tests 2 to 6 (500°C at the beam bottom flange, 20cm away from the column face, for tests 2 and 4 and 700°C at the same location for tests 3, 5 and 6). For test 7, the external force is maintained and the temperature is increased until joint failure. An axial restraint is provided to the beam for tests 4 to 7 inducing the development of an axial force in the beam (compression in the present cases) while the beam extremities are free for tests 2 and 3 (N=0).

For tests 4 and 5, two different analytical predictions are presented. The first one is the normal one, in which the resistance of the component "concrete slab in compression" is computed considering a given effective width where the compression stresses mainly develop close to the contact zone between slab and column flange. As the slab was observed to be crushed along its whole width at the end of the tests, a second analytical curve was determined considering the whole width of the tested specimen slab as effective.

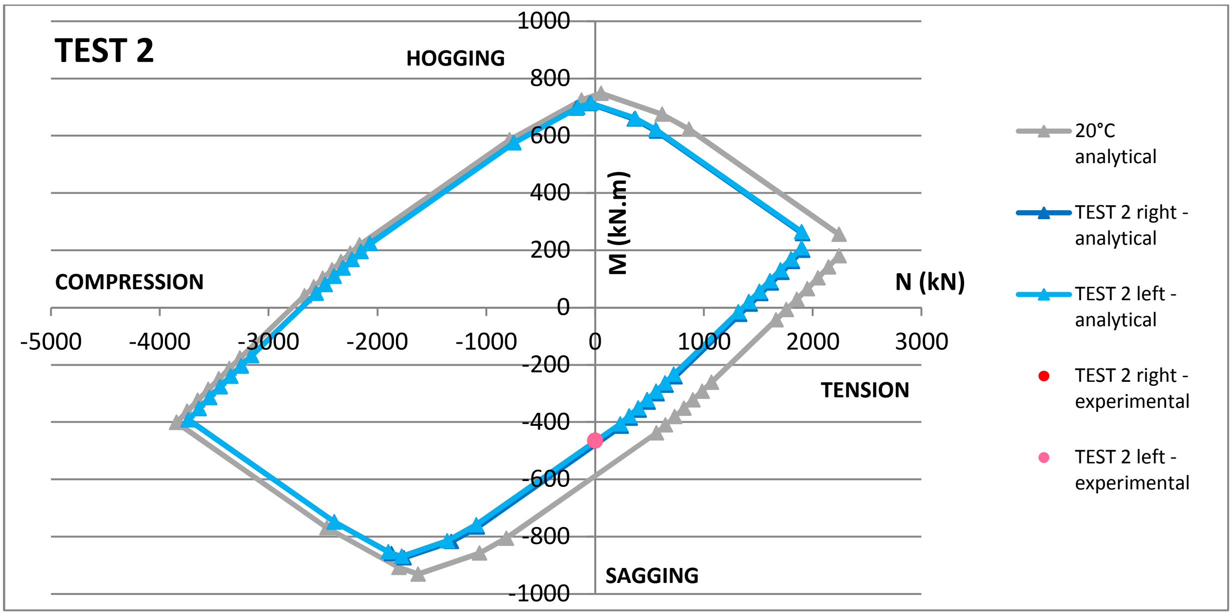


Figure 9. Comparison of the experimental resistances to the analytical curve for TEST 2

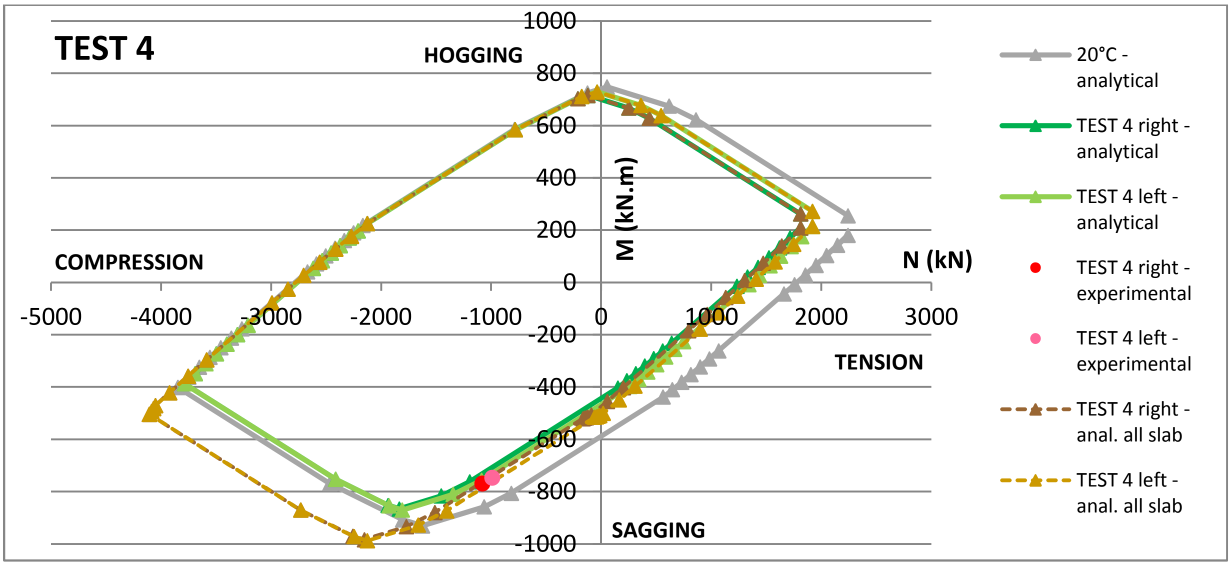


Figure 10. Comparison of the experimental resistances to the analytical curve for TEST 4

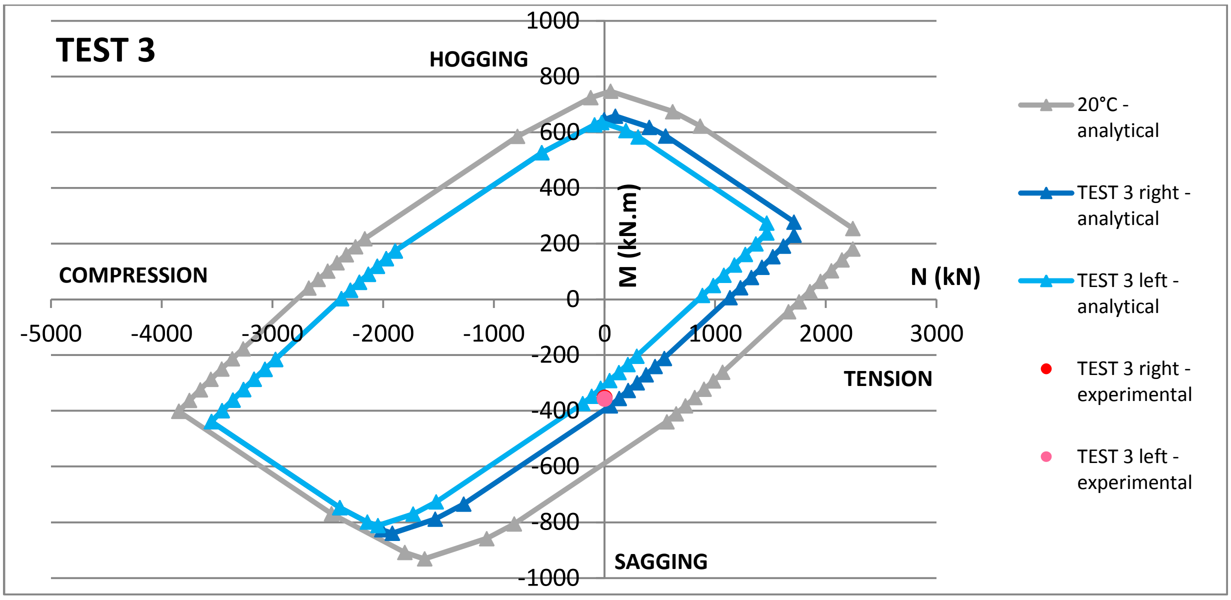


Figure 11. Comparison of the experimental resistances to the analytical curve for TEST 3

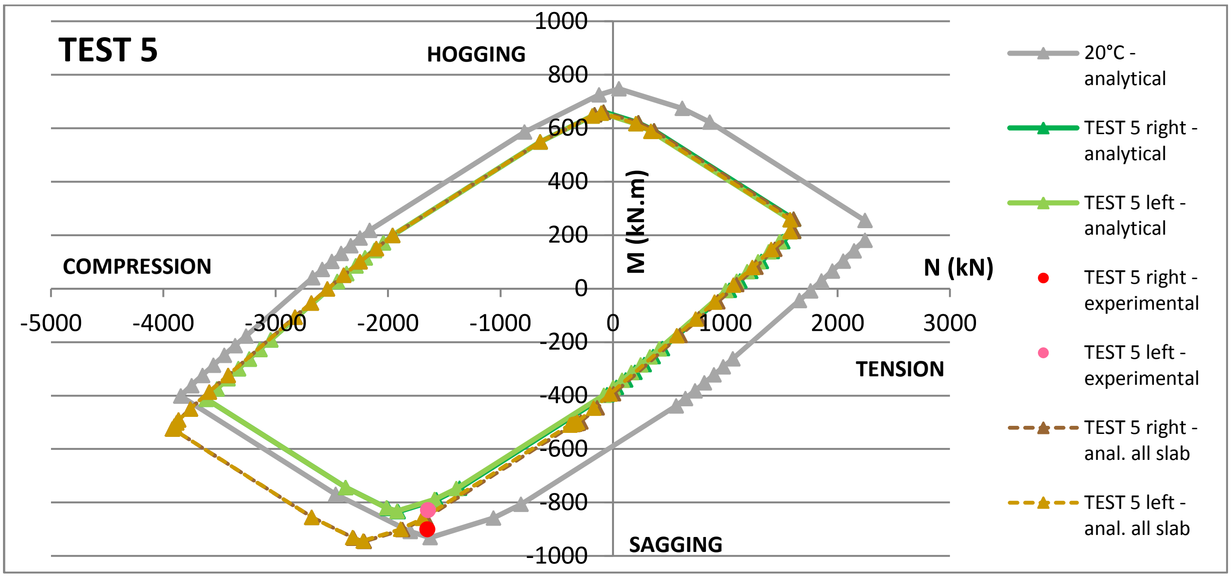


Figure 12. Comparison of the experimental resistances to the analytical curve for TEST 5

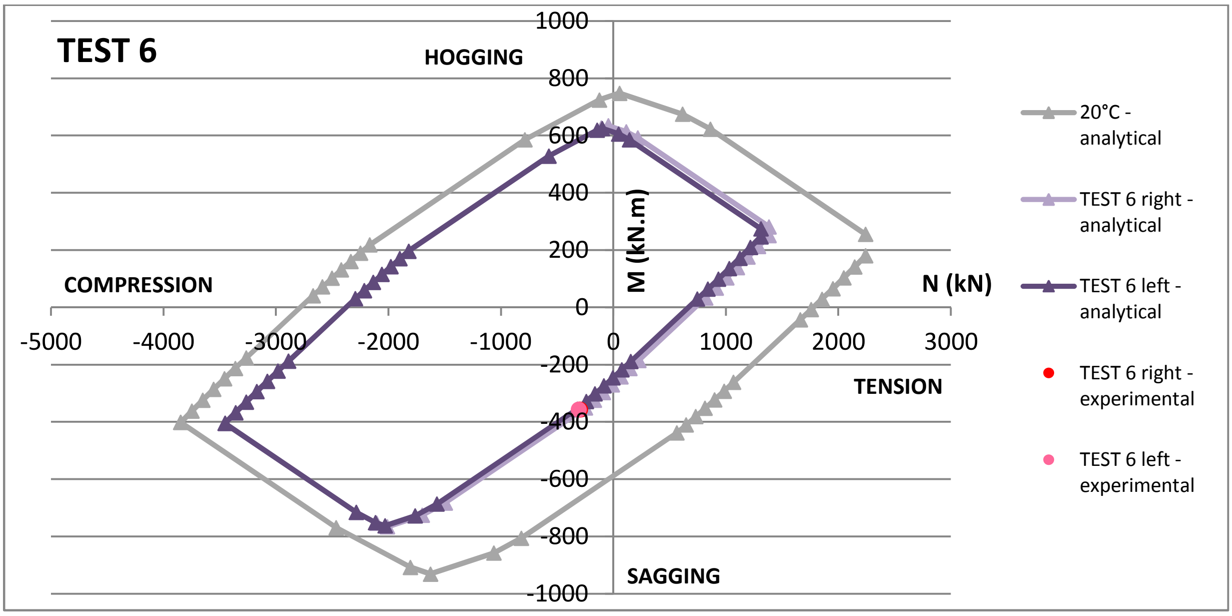


Figure 13. Comparison of the experimental resistances to the analytical curve for TEST 6

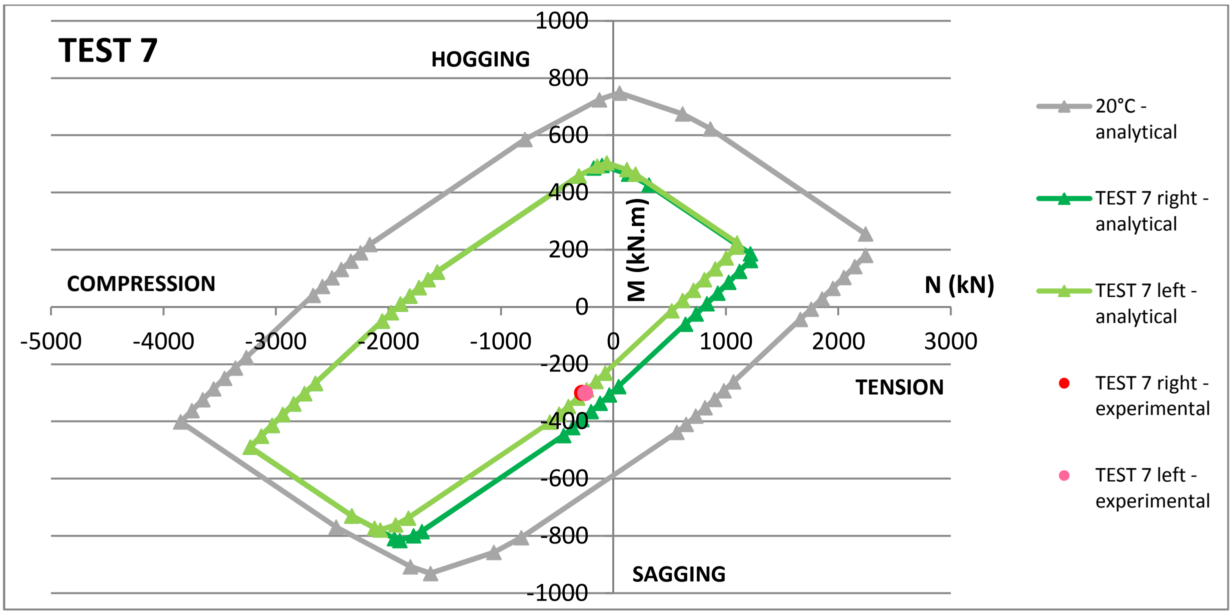


Figure 14. Comparison of the experimental resistances to the analytical curve for TEST 7

These comparisons show good agreement between experimental and analytical results, which validates the model predicting the M-N resistance curve for joints at elevated temperature.

II.5. Application of the model to a practical example

In the previous section, the analytical model has been validated by comparison to experimental tests. For this validation, the method was applied using the temperatures measured during the tests. In practical design situations, the temperature distribution has to be determined. It can be estimated using simplified models or computed with more sophisticated methods such as thermal finite element simulations.

A thermal finite element simulation of a composite joint subjected to the ISO fire curve has been performed (it is detailed in Deliverable II: Haremza et al., 2012 – section V.2).The joint was similar to the one presented in II.2 except that a solid concrete slab was considered. The temperature at the location of the different components was recorded after 10, 20, 30 and 60 minutes and the corresponding M-N resistance curves were computed. They are represented in Figure 15 and compared with the resistance at ambient temperature. For this practical example, the nominal resistance curves were determined, which means the nominal yield stresses were considered, as well as the security factors (γ_{M0}=1.0; γ_{M2}=1.25; γ_s=1.15; γ_c=1.5).

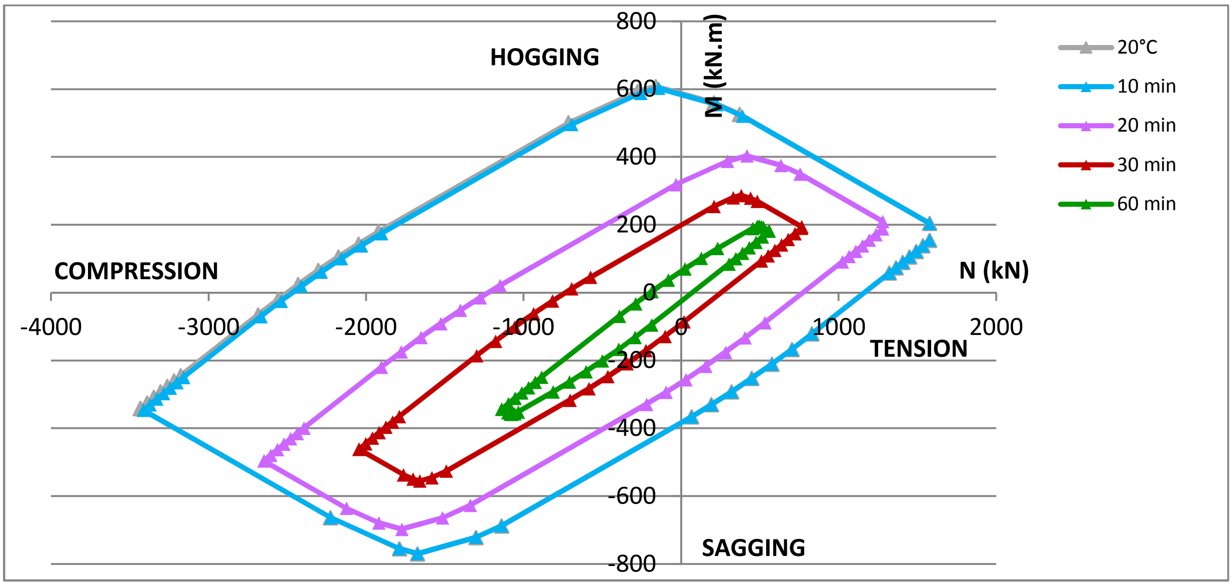


Figure 15. Shrinkage of the M-N resistance curve with the increase in temperature

III. Concluding remarks

The WP2 validated and made available the sophisticated and simplified behavioural models of individual beam, column and joint components, which were used in WP3 when investigation of the sub-structures and the structures at the sophisticated and simplified levels.

The present deliverable (DIII) was about the development of simplified behavioural models. The analytical procedure for the prediction of the M-N interaction resistance of steel and composite joints, already developed for ambient conditions, has been extended to elevated temperature and validated against experimental results. This model can be applied provided the temperature distribution within the joint is known, which can be determined using simplified or sophisticated models.

The simplified models for beams and columns were developed and validated within this WP2, and the so-validated tools for the investigation of the structural components were used in WP3 when investigation the sub-structures and the structures at the simplified levels; they are described in the deliverables IV and V (Fang et al., 2012a and 2012b).

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