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High temperature full-scale tests performed on S500M steel grade beams

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ABSTRACT

In recent publications, the results of coupon tests performed on high-strength steel (mainly S460M and S460N) have been presented. Some of these tests led to ratios between the coupon resistances at elevated temperatures and at room temperature lower than the Eurocode reduction factors. The authors of these publications have consequently questioned the validity of these factors for these steel grades, without referring to any full-scale fire tests.

Two experimental full-scale fire tests have been performed at the University of Liege in order to assess the mechanical resistance of S500 M steel grade at high temperatures. Two similar 4.4 m-long steel beams have been respectively subjected to fast (standard ISO curve) and slow (fixed 5 K/min heating rate) elevations of temperature under a constant mechanical loading. The tests have been successfully reproduced in subsequent finite element analyses using Eurocode 3 steel material law at elevated temperatures, in which a creep component is implicitly taken into account.

1. Introduction and state-of-the-art

High-strength steels are more and more widely used in steel and steel-concrete composite structures throughout the world. In many countries like UK, USA, Canada and Scandinavia, the use of S355 steel grade (or Grade 50) currently represents >90% of the steel consumption in structural applications whereas the S235 or S275 were still the most commonly-used steel grades in the 90′s. The extra cost of high-strength steels compared to normal steel grades is largely counter-balanced by the design optimization (lighter sections), the reduction of welding time and work on site (reduced number of welding passes) as well as the reduction of beam and column bulk.

S500 M steel grade will be integrated into the future versions of EN 10025-4 [2] and EN 1993-1-1 European standards [3] and Grade 70 (yield point ≥ 485 MPa) has already been included into A193/A913M – 15 American standard [4]. However, the stress-strain relationship at elevated temperatures currently defined in EN 1993-1-2 (Table 1) with the reduction factors for effective yield strength $k_{y,\theta}$, for proportional limit $k_{p,\theta}$ and for the slope of the linear elastic range $k_{E,\theta}$ is limited to steel grades from S235 to S460. Similarly, AISC code defines mechanical properties of steels at elevated temperatures for grades up to Grade 65 only [5]. Experimental investigations are therefore needed to see whether the use of these relationships and factors could be extended to S500 M and Grade 70 steels.

The EN 1993-1-2 material model has been defined on the basis of experimental coupon tests and large-scale tests performed predominantly on mild steels [6]. This Eurocode material model has been deduced from transient-state tests [7,8] performed on grades equivalent to S235, S275 and S355 applying heating rates situated between 5 K/min and 32 K/min, the major part following a 10 K/min heating rate.

When deriving the material model of Eurocode 3, the choice has been made to use a model that does not contain an explicit term for creep. This simplification was essentially made to facilitate calculations by the simple design equations which are described in detail in Eurocode 3. Indeed, the absence of an explicit creep term makes the calculated load bearing capacity a function of temperature only; time will only intervene in the development of the material temperature, see Eq. (2).

Explicit creep model:

$$R_{\mathrm{fi,d,t}} = f_1\left(f_{\mathrm{y,e}}(T_{\mathrm{s}};t)\right)\text{with } T_{\mathrm{s}} = f_2(t) \quad (1)$$

Implicit creep model

$$R_{\mathrm{fi,d,t}} = f_1\left(f_{\mathrm{y,i}}(T_{\mathrm{s}})\right)\text{with } T_{\mathrm{s}} = f_2(t) \quad (2)$$

where $R_{\mathrm{fi,d,t}}$ is the design value of the load bearing capacity of a steel element at time t in the fire situation; t is the time under consideration; T_s is the temperature at time t; f_1 describes the mechanical behaviour of the element (tension, bending…); f_2 gives the evolution of

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Table 1
Reduction factors for stress-strain relationship of carbon steel at elevated temperatures [1].

T°	$k_{y,\theta}$	$k_{p,\theta}$	$k_{E,\theta}$
20 °C	1.000	1.000	1.000
100 °C	1.000	1.000	1.000
200 °C	1.000	0.807	0.900
300 °C	1.000	0.613	0.800
400 °C	1.000	0.420	0.700
500 °C	0.780	0.360	0.600
600 °C	0.470	0.180	0.310
700 °C	0.230	0.075	0.130
800 °C	0.110	0.050	0.090
900 °C	0.060	0.0375	0.0675
1000 °C	0.040	0.0250	0.0450
1100 °C	0.020	0.0125	0.0225
1200 °C	0.000	0.0000	0.0000

the steel temperature as a function of time and $f_{y,e}$ is the explicit model for the yield strength and $f_{y,I}$ is the implicit model for the yield strength.

As only the implicit model $f_{y,I}$ is given in Eurocode 3, it became *de facto* the model used also for advanced calculation models whereas, in fact, it would not be a great difficulty to utilise an explicit model in the non-linear finite element software that apply the advanced calculation models.

Verifying that the Eurocode model is applicable to a certain steel grade thus implies verifying that 1) the simplification of an implicit model is a sufficiently good approximation of the real behaviour and, 2) that the reduction factors proposed in the Eurocode, see Table 1, describe correctly the behaviour. A necessary condition to have a positive answer to these two questions is certainly that the characteristic time used in the tests is of the same order of magnitude as the one used for the tests that are at the base of the Eurocode steel model. This can be expressed in total duration of the test (from 15 to, say, 120 min as relevant for most fire durations) or, in other words, in term of heating rate, from 2 to 50 K/min according to EN 1993-1-2.

During the last two decades, several authors have published results of experimental transient tests performed on coupons. Transient tests performed by Outinen on S460M steels showed that the EN 1993-1-2 was slightly safe-sided above 500 °C but unsafe between 100 °C and 500 °C [9]. Schneider and Lange [10] observed from transient tests performed on steel coupons in tension that the reduction of mechanical properties was more important for normalized rolled steels S460N than for thermomechanical rolled steels S460M. Their results show that, for numerous cases, the reduction factors obtained from tests are below the recommended values of EN 1993-1-2. Qiang et al. [11] performed investigations on the mechanical properties of S460N steels at elevated temperatures. They also stated that the current EN 1993-1-2 reduction factors on yield strength could not be applied to S460N and proposed new predictive equations. Recent investigations by Knobloch [12] also underlined that the loading rate in steady-state tests has a significant impact on the stress-strain relationships of carbon steels at elevated temperatures. Finally, another type of tests was performed by Kodur [13]. Creep strains are measured under constant temperature and constant stress level. These tests show that failure may occur for stress levels lower than $k_{y,\theta}$ but it has to be noted that this testing procedure is more severe than real conditions that prevail during a fire as the maximal temperature (and maximal stress level) was applied from the beginning of the test.

The aim of the two tests presented in this paper is to assess the capability of stress-strain relationships presented in EN 1993-1-2 to represent at the structural level the behaviour of steel beams made of high-strength steel.

2. Description of the tests

Two experimental tests have been performed on full scale steel beams. The first one was performed on an unprotected steel beam subjected to standard ISO 834 fire curve [13] in a gas furnace. In the second one, the steel profile was heated by electric resistances and covered by insulating blanket so that the central part of the beam was heated with a constant rate of 5 K/min. This very low heating rate is representative of fire-protected steel beams that must satisfy to R120 requirement (the increase of temperature after 2 h is 600 °C).

Whereas the first test is representative of a qualification test performed on a loaded beam according to NBN EN 1365-3 [14] and covered by the accreditation under ISO17025 of the laboratory, the second one is closer to the better controlled conditions of a scientific experiment. The use of a controlled heating in the second test was driven by the desire to ensure a temperature distribution that is as uniform as possible in the critical sections of the beam (similarly to [8]). In particular, the temperature differences that are observed between the upper flange and the lower flange in the gas furnace test should be reduced. The behaviour of the beam at any time is then influenced only by the steel properties at one temperature.

The two tested specimens are 4.4 m long and based on a HEB 300 section heated on 4 sides. The tested beams are simply-supported (clear span = 4.2 m) with one fixed support and one rolling support, allowing longitudinal displacements induced by thermal elongations and by the beam deflections to develop. The two specimens have not been extracted from the same batch and therefore exhibit different chemical composition and mechanical properties.

2.1. Test n°1

The yield strength of the steel profile has been measured by two specific coupon tests (Fig. 1). The measured value of R_{eH} was 528 MPa in the flange and in the web. In Table 2, R_m, R_{eH} and A are respectively the values of the tensile strength, the upper yield limit and the elongation at rupture measured on the flange coupon test.

The mechanical loading is kept constant during the whole test and applied in the two sections situated at L/3 from each support, so that the central zone is subjected to a uniform bending moment. The total load applied to the specimen is 2 × 307 kN = 614 kN. The load ratio, defined as the ratio between the applied bending moment at mid-span and the plastic bending moment of the section, was expected to be 0.5 based on the nominal value of the yield strength of steel of 460 N/mm^2. The coupon tests performed at room temperature after the fire tests demonstrated that the yield strength was much higher and that the load ratio was actually equal to 0.5 × 460/528 = 0.435.

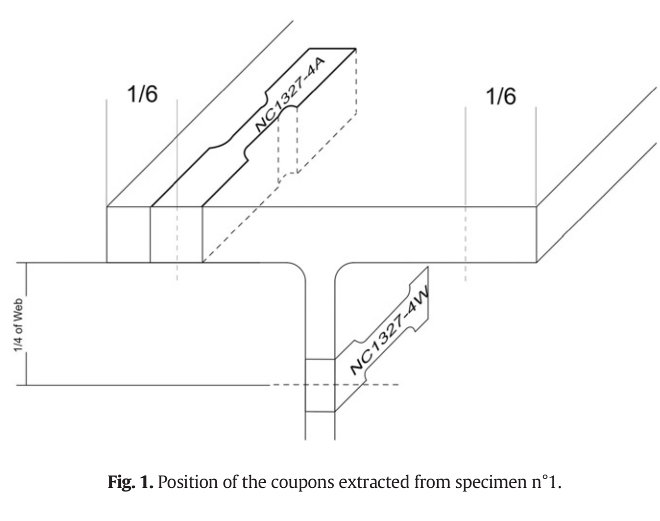

Fig. 1. Position of the coupons extracted from specimen n°1.