

RECENT DEVELOPMENTS IN THE USE OF QUENCHED AND SELF-TEMPERED HOT ROLLED H-BEAMS

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ABSTRACT

The quenching and self-tempering (QST) installation at the Arcelor heavy sections rolling mill of Differdange in Luxembourg is in industrial operation since 15 years. The possibility of combining high strength with outstanding welding properties, besides a high ductility and good through-thickness properties, made heavy ‘jumbo’ sections in QST steels an immediate success in specific construction applications such as members of long-span space frames, heavily loaded columns of high-rise buildings. Besides these conventional applications, the hot rolled beams in QST steel grades have become an integral part of special applications such as deep foundations, the American ‘strong column-weak beam’ concept for high-rise structures in seismic areas as well as for members of offshore structures.

QST steels are known as HISTAR (High-Strength-Arcelor) grades. They are covered by European and national standards for structural steels. Eurocode 3 also takes into consideration these new high strength steels.

This paper summarises the main application fields as well as the latest developments in research projects aimed at optimising design parameters and the improvement of the efficiency in new applications of QST beams.

KEYWORDS

Quenching and self-tempering, beam, welding, fire engineering, composite design, high strength steel, offshore, deep foundation, cellular beam, cost saving, sustainability, hot-dip galvanization

INTRODUCTION

The quenching and self-tempering (QST) installation at the Arcelor heavy sections rolling mill of Differdange, developed in collaboration with the Centre de Recherches Métallurgiques (CRM) in Liège, is in industrial operation since 15 years. The possibility of combining high strength with outstanding welding properties, besides a high ductility and good through-thickness properties, made heavy ‘jumbo’ sections in QST steels an immediate success in specific construction applications such as members of long-span space frames and heavily loaded columns of high-rise buildings.

In construction, QST steels are considered conventional structural steels and are known in the market as HISTAR (High-Strength-Arcelor) grades. They are covered by European and national standards like EN 10025-4:2005, ASTM A913-01 and DIN 18800-7:2002. Eurocode 3 also takes into consideration these new high strength steels by proposing specific design parameters and buckling curves.

Over the years, the application possibilities of hot rolled beams in QST steel grades evolved so that these sections have become an integral part of sophisticated applications such as high capacity bearing piles for deep foundations, the American ‘strong column-weak beam’ concept for high-rise structures in seismic areas as well as for members of offshore structures.

Latest research projects cover topics such as the behaviour of high strength QST steels during galvanisation and the improvement of weld design parameters. Research has also been performed on asymmetrically fabricated castellated beams (Arcelor Cellular Beams - ACB) where QST steels

are used especially in the parts where their full strength can be activated as well as high performance composite structures combining H-beams in QST grades with high strength concrete.

1. DESCRIPTION OF THE QST PROCESS

The conventional method for producing high-strength steels consists in adding alloying elements to the steel and rolling at controlled temperatures. This rolling technique is however limited by:

- the mechanical power of the rolling mills as this process asks for high deformation rates at relatively low temperatures,
- the impossibility of substantially reducing the carbon equivalent (CE) value of the steel and, as a consequence, of improving its weldability.

The QST process uses water and the rolling heat as working substances. After the last pass of a thermomechanical (TM) rolling, an intense water-cooling is applied to the whole surface of the beam. Cooling is interrupted before the core is affected and the outer layers are tempered by the flow of heat from the core to the surface. Fig. 1 schematically illustrates the QST treatment and the temperature flow. At the exit of the finishing stand, directly at the entry of the cooling bank, the rolling temperature of the beam lies typically at $\sim 850^{\circ}\text{C}$. After the quenching over the whole surface of the section, self-tempering is achieved at $\sim 600^{\circ}\text{C}$. The industrial process is controlled by computer.

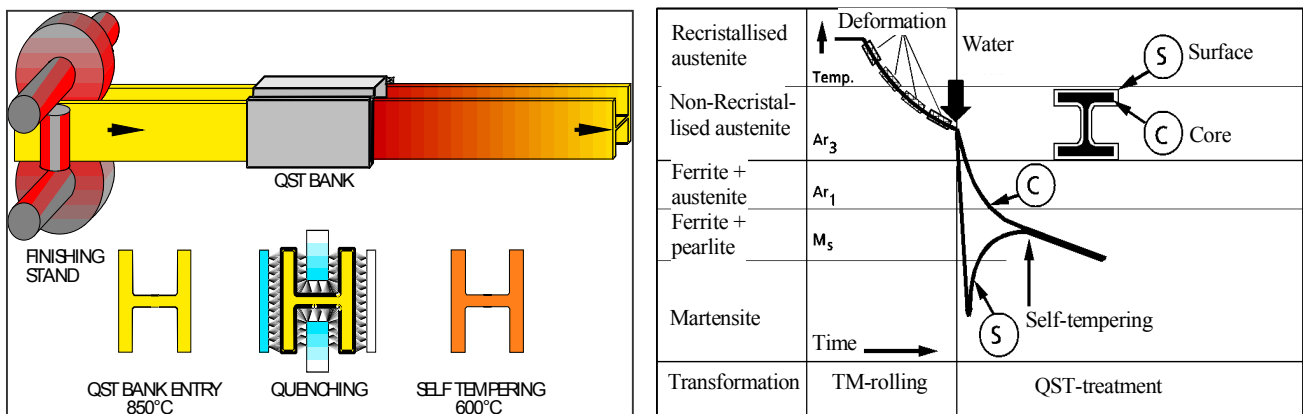


Fig.1: Principle and temperature flow of the Quenching and Self-Tempering (QST) process

2. PROPERTIES OF QST STEELS

The QST process considerably increases the yield strength and the toughness of the steel. Due to much lower carbon equivalent values when compared with conventional structural steel grades, the weldability and the ductility of the steel grades are significantly improved[4][5][6][8].

2.1 Mechanical properties

All HISTAR grades offer improved guaranteed minimum value for yield strength over the whole range of product thicknesses. A comparison between the yield strength of HISTAR grades and conventional thermomechanically rolled fine grain grades in accordance with EN 10025-4:2005 is shown in Fig. 2. The main mechanical properties of HISTAR grades are given in the Table 1.

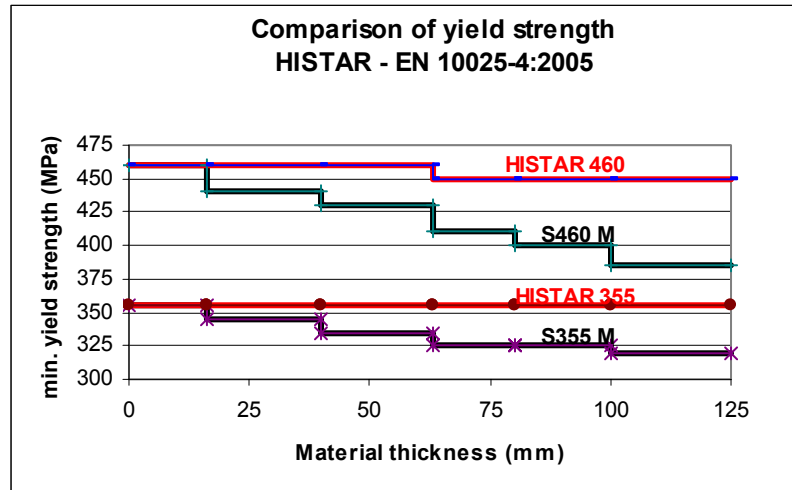


Fig. 2: Minimum yield strength according to material thickness of HISTAR steels versus structural grades in compliance with EN 10025-4:2005

Table 1. Main mechanical characteristics of HISTAR grades

Grade	Yield strength R_{eH} min.	Tensile strength R_m min.	Elongation ($L_0=5.65 \sqrt{S_0}$) min.
	MPa	MPa	%
HISTAR 355	355	450	22
HISTAR 460	460	530	17

2.2 Weldability

Fig. 3 summarizes the relationship between chemical composition, product thickness and yield strength from the conventional rolling processes and the new QST process. In Europe, the highest grade HISTAR 460 has a maximum CE value of 0.43 %. In the range of normal heat inputs during welding (10-60 kJ/cm) and provided that low hydrogen filler metal and auxiliary products are used, a preheating is not necessary for temperatures of the structure over 0°C.

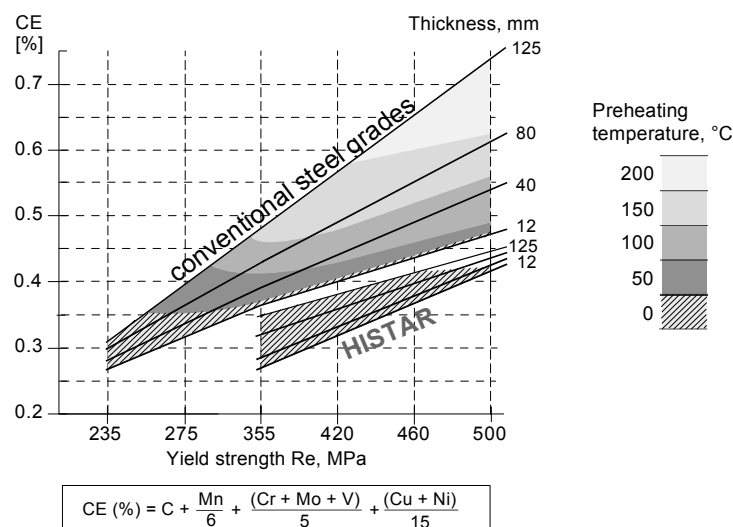


Fig. 3: Weldability of HISTAR and conventional steel grades

In the USA, HISTAR 355 and 460 grades in accordance with ASTM A913 (Grade 50 and Grade 65) have been introduced in the AWS (American Welding Society) codes D1.1 in a category "weldable without preheating" if welded with low hydrogen (< 8 ml/100g) electrodes.

2.3 Toughness

Nowadays, it is well established that a certain level of toughness of the steel is required in order to avoid propagation of cracks associated with brittle fracture in the base material during welding or during seismic loading from earthquakes.

In Europe, HISTAR 355 to HISTAR 460 are typically supplied with guaranteed toughness values of 47J at 0°C. QST steels can also be supplied with better toughness at low temperatures. So, even 'jumbo' sizes HD 400x1086 kg/m in HISTAR 460 can be supplied with notch toughness values of 40J at -20°C ! For offshore purposes, steels with notch toughness values of 50J at -40°C are available.

3. HISTAR STEELS IN DEEP FOUNDATIONS

Provided steel H-bearing piles are driven to highly resistant layers in the subsoil (rock, marl, very dense sand or gravel layers), HISTAR grades develop their full potential as axial load bearing elements for high capacity deep foundations of tall buildings, bridges, industrial halls with heavy crane ways, etc (Fig. 4). Tests performed in Hong Kong have confirmed the safe behaviour of HISTAR bearing piles during installation with heavy diesel and hydraulic impact hammers as well as during static test loadings up to 90% of yield strength.

When driven to rock, bearing piles in grades up to a yield strength of 500 MPa are available.



Fig. 4: Driving of HISTAR bearing piles in Hong Kong

4. HISTAR STEELS IN SEISMIC AREAS

4.1 Toughness requirements

In the USA, after the Northridge earthquake in California, the task group revising the existing standards on earthquake design recommends for base metal minimum toughness requirements of 20J at +21°C for enclosed structures and 20J at +4°C for exposed structures. This is the reason why QST grade 65 /ASTM A913 (= HISTAR 460) is the only steel with a yield higher than 345 MPa (= grade 50 /ASTM A913) that can be used in California for the columns of moment resisting frames.

4.2 Structural concept

QST grade 65 /ASTM A913 is used in order to achieve the ‘strong column – weak beam’ concept, which is nowadays the most economical way in Northern America to design framed structures of high-rise buildings in seismic zones[1][2] (Fig. 5). This concept is often improved by the use of the ‘reduced beam section’ (RBS), a patent of former Luxembourg steel producer ARBED. The RBS has been developed to force the plastic hinge away from the beam-column interface. It relies on the selective removal of beam flange material to reduce the cross sectional area of the beam[7] (Fig. 5).

The main advantages are:

- Reduced moment at the column face thereby reducing the possibility of fracture
- Reduced requirements for column doubler-plates
- Stronger columns even in case of higher yield strength of the beam
- Cost-effective, consistently performing connection
- Established performance based on extensive testing.

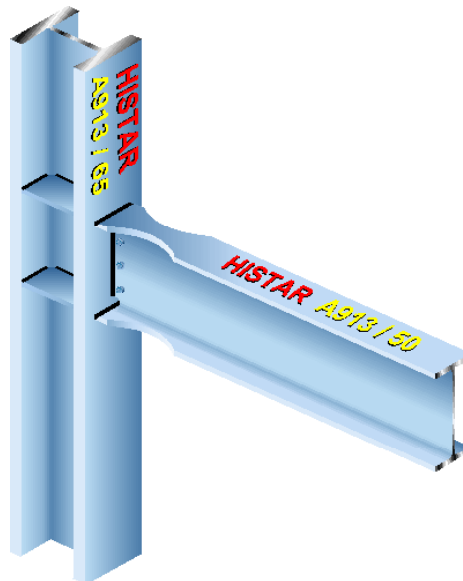


Fig. 5. “Strong column-weak beam” concept combined with the “Reduced Beam Section”

4.3 Through thickness of beam flanges

Through thickness behaviour is one of the major concerns when working with welded moment frame connections under seismic loading using the ‘strong column-weak beam’ concept. Therefore, tension tests were performed in transverse direction on the flanges of heavy H-column sections in HISTAR 460 steel [3] (Fig. 6). All specimens broke in either the weld or the pull-plates at stress levels in excess of 690 MPa, the nominal pull-plate stress. The fracture occurred at stresses higher

than the strength of the column flange because of the existence of triaxial constraint of the column flange material. This created hydrostatic tension stresses that raised the apparent through-thickness strength. Lamellar tearing did not occur in any of the tested joints and it was concluded that the through-thickness strength does not need to be explicitly checked in the seismic design of welded beam-to-column connections.



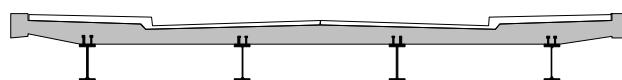
Fig. 6: Through-thickness tension test on ‘jumbo’ column HD 400x1086 in HISTAR 460

5. COST SAVINGS

When used as columns in buildings, for girders or as tension members in trusses, the new generation of high strength beams enables substantial savings in:

- structural weight,
- material costs,
- fabrication costs,
- transportation and erection costs,
- foundation costs.

Typically, the extra cost for HISTAR 460 compared to grade S355 steel is only ~5%. In case full advantage can be taken from the higher yield strength, a HISTAR 460 beam is ~25% lighter than a comparable section in S355 so that the economical advantage on the material side alone is about 15-20%. The savings are even larger in case HISTAR 460 can be used instead of S235 (Fig. 7).



Steel grade	S235	S355	S460	S460
Section	HE 1000 M	HE 700 M	HE 800 A	HE 700 B
Construction depth (m)	1,38	1,09	1,17	1,08
Steel weight	+16%	reference	-25%	-20%
Material cost (beams)	+7%	reference	-21%	-17%

Fig. 7: Material cost comparison for a 17m-span road bridge in function of the steel grades

6. SUSTAINABILITY

HISTAR steels, like the other structural grades for the Arcelor long products, are produced to 100% from recycled scrap in state-of-the-art electric arc furnaces (EAF). In comparison to the

conventional integrated blast furnace route, the EAF production route allows for substantial reductions in energy consumption and emissions of particles and gases (Table 2).

Table 2: Environmental advantages of the EAF route in Luxembourg (1993/1998)

Emission particles	Reduction of 99%
Emission CO ₂	Reduction of 78%
Emission waste	Reduction of >70%
Consumption water	Reduction of >50%
Consumption energy	Reduction of 56%

The QST process operates without external supply of energy and substantially reduces the use of alloying elements. In fact, the QST process allows to up-cycle steel scrap as the constructional performance of a beam in HISTAR steel is by far superior to the performance of a standard beam.

Apart from the general advantages of steel structures with regard to sustainability (clean construction sites and fast erection through prefabrication, easy dismantling and re-erection or recycling), HISTAR grades enable the building industry to:

- Reduce its overall steel consumption
- Reduce the impact of transportation of material due to lower weight
- Design slender load carrying elements occupying less space in a building
- Design bold and outstanding structures.

7. SURFACE PROTECTION BY HOT-DIP GALVANIZATION

It is often stated in literature that fine-grained high yield strength steels have a more critical behaviour during galvanization than conventional structural steels. Recent tests have however confirmed that construction components in HISTAR grades behave the same way during hot-dip galvanizing as elements in conventional structural steels. As the hardness of the considered steels typically remains below 340HV even after fabrication, hydrogen induced cracking is not likely to occur.

In any case, it is of outmost importance for all fabricated structural components to perform stress relieving in the critical areas prior to galvanizing. Indeed, the residual stresses from rolling and fabrication will be superimposed by additional internal stresses from differential elongation of the beam parts during their immersion in the hot zinc bath and may sum up to a level which exceeds the mechanical properties of the steel.

8. RECENT DEVELOPMENTS

8.1 Steel-concrete composite bridges

Steel-concrete composite bridges for road and railway applications are basically economical, stiff, long lasting and easy to maintain.

In order to further optimize these bridge types for short and medium spans, prefabricated elements, consisting of 2 T-pieces of an H-beam cut in the middle of the flange in a specific pattern for composite action with the upper concrete part are cast as one piece for easy and fast erection (Fig. 8). Tests were performed in order to confirm the safe transfer of shear forces between the T-pieces in high strength steel and the concrete.



Fig. 8: Double-T arrangement for prefabricated composite bridge element

8.2 Cellular beams

These beams are produced by oxy-cutting twice the web (Fig. 9). The two half parts are then shifted, superimposed and the webs between openings are welded together. In office buildings the market asks for long span, service integration and flexibility. The cellular beams satisfy these new trends. The circular openings allow the arrangement of the service ducts through the profile web (Fig. 10). Moreover, architects appreciate the lightness, transparency and aesthetics of these beams in the structures.

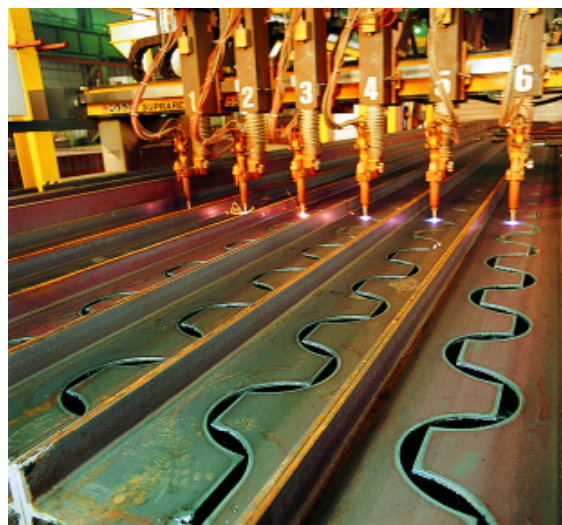


Fig. 9: Oxy-cutting of cellular beams

Cellular beams used in composite construction may be built-up from two different parent profiles and from two different steel grades. In that case, the cellular beam is called hybrid and enables a fine optimisation of weight.

Full-scale tests performed with S460 quality [22] as well as numerical simulations (Fig. 11) have enabled the optimization of the calculations rules. The use of high strength grades is really a key advantage for this type of cross section. Indeed high strength grades do not bring any benefit when deflection criteria become relevant. Through the hybrid character of the cross sections, S460 steel

can be placed where it is really helpful whereas conventional steel is kept in the remaining part of the cross section.

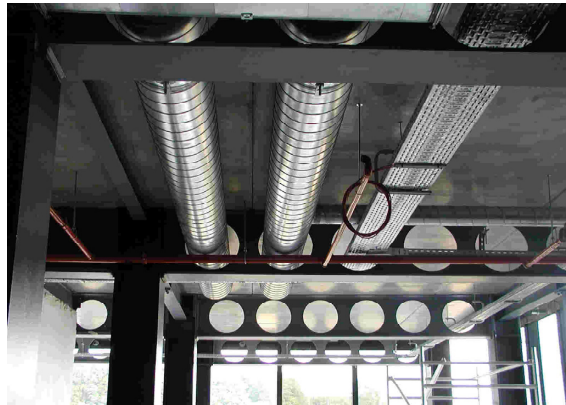


Fig. 10: Service integration in cellular beams

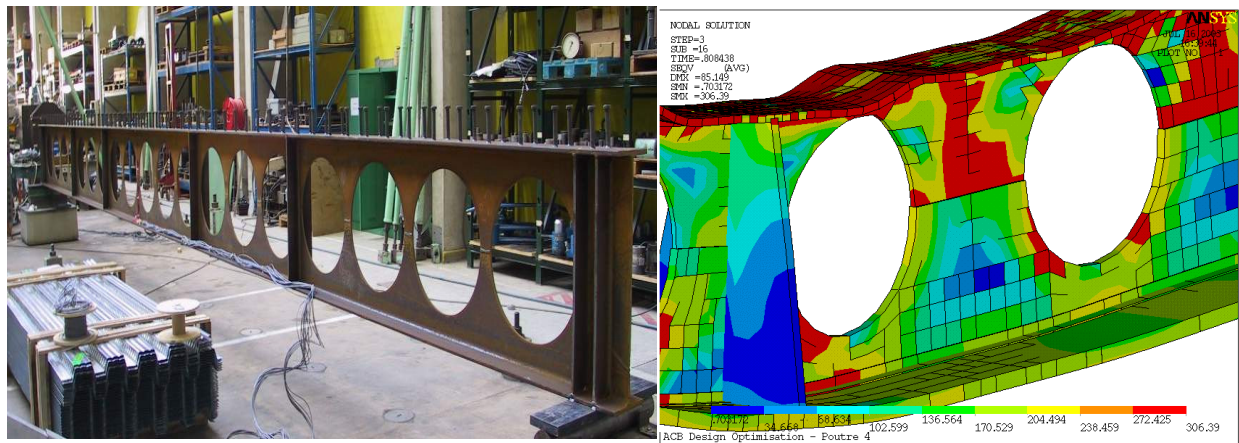


Fig. 11: Experimental test and numerical simulations on a cellular beam

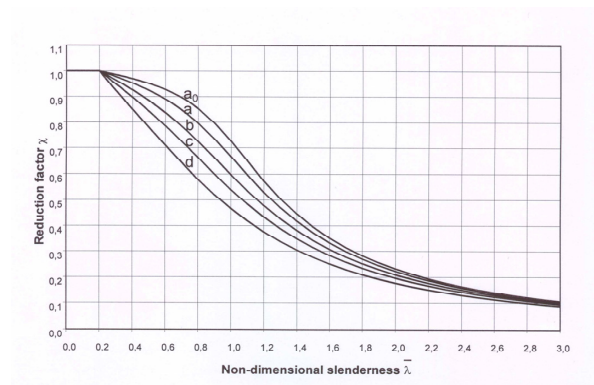
8.3 Design considerations

8.3.1 Buckling Curve

The high strength steel S460 is included in the Eurocodes 3 [12] and 4 [13]. Thanks to the relative smaller residual stresses [23] compared to the yield point, the buckling behaviour is improved and more favourable buckling curves may be used. For instance the buckling curve a_0 has been developed especially for steel S460 (Fig. 12).

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Cross-section	Limits	Buckling about axis	Buckling curve S 235 S 275 S 355 S 420	S 460
	$h/b > 1,2$ $t_f \leq 40\text{mm}$	y - y	a	a_0
		z - z	b	a_0
	$40\text{mm} < t_f \leq 100\text{mm}$	y - y	b	a
		z - z	c	a
	$h/b \leq 1,2$ $t_f \leq 100\text{mm}$	y - y	b	a
		z - z	c	a
	$t_f > 100\text{mm}$	y - y	d	c
		z - z	d	c



Numerous tests [17] have been performed on composite beams to determine the plastic bending moment in case of S460 steel.

It is generally possible to take benefit of the full resistance of both materials, concrete and steel. However in some cases the compression strain in the concrete slab reaches its limit and the plastic bending moment must be reduced by a factor β_{pl} between 0.85 and 1 according to Fig. 13.

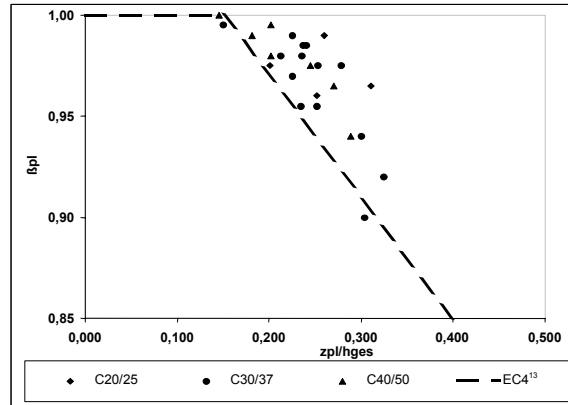


Fig. 13: Plastic bending moment reduction

8.3.2 Welding

For the welded connections, high strength steels are penalized because the resistance of the weld is affected by a factor β_w of 1.0 [18]. In fact a value β_w of 0.83, close to the 0.8 for normal steel, should be adopted as demonstrated by recent tests on S460 steel performed at Technical University of Karlsruhe [19] (Fig. 14).

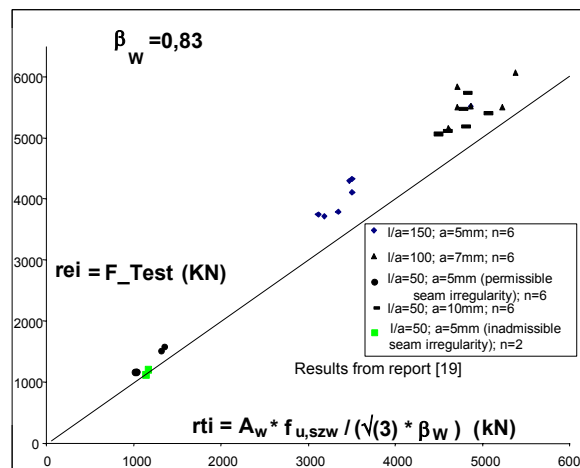


Fig. 14: Correction factor for welded connections in S460 grade

9. HISTAR STEELS IN MODERN FIRE DESIGN

The Eurocode fire parts[14][15] cover steel S235, S355 and S460 of EN10025 parts 2 to 5 and provide design calculations methods based on an effective yield strength $f_{y,\theta}$ function of the steel temperature according to Fig. 15. That curve has been deduced from numerous experimental tests[9][10][11][21] at the beginning of the nineties. It has been validated by more recent tests[16][20].

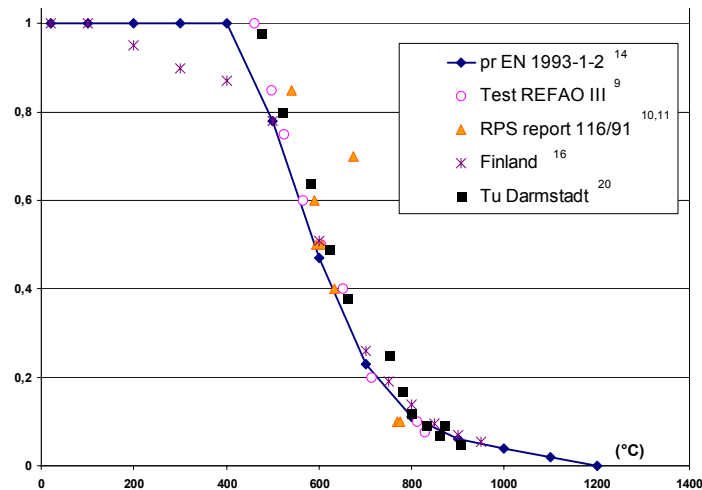


Fig. 15: Effective yield strength reduction in function of temperature

The curve of Fig. 15 may be translated in terms of load ratio for a given steel element in an office building (Fig. 16).

If S235 grade is chosen, the safety required by the Standards at room temperature leads to a load ratio of about 0,5. Knowing that deflection criteria are very often relevant and that the designer has to choose amongst a given set of profiles, a load ratio of 0,45 is representative. This leads to a critical temperature of 600°C. If the S235 steel is substituted by a S460, this overdesign results in an increase of about 100°C of the critical temperature.

The selection of an IPE 400 leads to an increase of the ISO fire resistance from 13' to 18'. This increase is quite small if an ISO requirement has to be fulfilled. However, the difference may become relevant when natural fire curves are used. In the example of Fig. 16, if the peak of the heating curve is between 600 and 700 °C, a structure in S460 will survive the fire whereas the same structure in S235 will not.

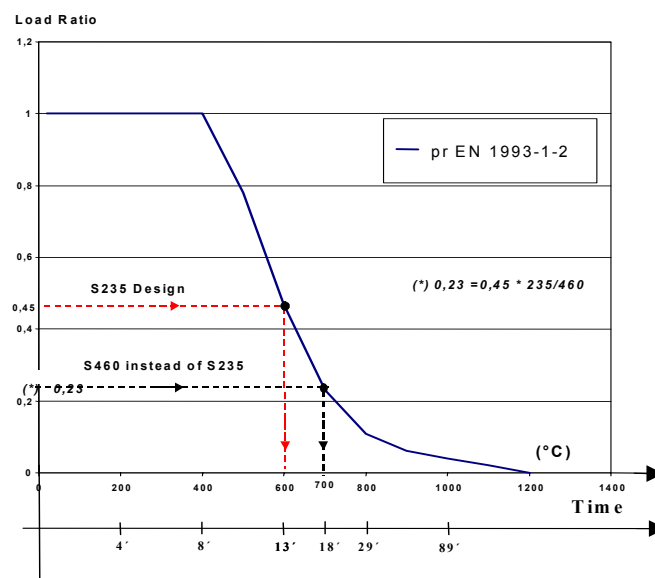


Fig. 16: Maximum load ratio in case of fire

10. CONCLUSIONS

QST research has enabled the development of modern structural steels combining high strength with excellent weldability and ductility. These steels comply and even exceed the requirements of the European and national standards. The outstanding properties QST steels are nowadays fully

recognized in the construction market where innovative and economical design, backed by the valorisation of research results, allows for their application in high capacity deep foundations, composite bridges, earthquake resistant systems, cellular beams and offshore. Over-design with high strength QST steels also leads to economical solutions in case of modern fire engineering.

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