STRONGER STEELS IN THE BUILT ENVIRONEMNT: STRUCTURAL RESPONSE AND APPLICATION OF S460 TO S700 HOT ROLLED AND FABRICATED SECTIONS

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SYNOPSIS:

Steel structures maintain a dominant presence in the construction industry because of continuous advances in material properties, production methods and innovative design and construction techniques. Modern production techniques, such as thermomechanical rolling, and quenching and tempering, now enable the economic production of steels with yield strengths between 460 and 700 MPa and the weldability, fracture toughness and ductility required for structural applications.

The use of high strength steels (HSS) can lead to significant reduction in the quantity of steel used, leading to a lighter structure, thus requiring smaller foundations and shorter transportation and construction times. It also results in lower CO_2 emissions and energy use (both directly and indirectly). Despite the advantages of HSS, the use of steels S460 and above in structures remains rather low (around 5%) and there is great potential for wider use in building structures across the world. A better understanding of how to maximize the benefit of a higher strength will help designers make informed decisions on material selection and related benefits at the conceptual stage of a project, hence overcoming reluctance to use a material they are not familiar with, and which is less widely available.

This paper presents the outcome of a recently completed European RFCS (Research Fund for Coal and Steel) collaborative research project, *Stronger Steels in the Built Environment* (STROBE*)*, that studied the structural response of HSS from S460 to S700, considering both hot rolled and fabricated I shaped sections (homogeneous and hybrid). Focus is on basic issues allowing for usage of HSS with lower ductility values, exploiting plastic capacity, leading to more slender and highly utilized profiles. The benefits are quantified by design comparisons and importantly, life cycle assessments (LCA) and cost comparisons. Attention is given to both single and multi-storey building structures. However, the results have generic applicability to a far wider range of structures where HSS can be applied.

Keywords: Higher, Strength, Steel, S460, S700, Structural, LCA, Construction.

INTRODUCTION

Structural steels cover a wide range of steel product types, from rolled plates, I-sections, H-beams, pilings, channels, angles, flat bar through to reinforcement bar, rods and formed products from strip such as hollow sections. Despite these key structural products being around for well over a hundred years, the yield strength grade of the vast majority remains at ≤355MPa for plates, sections etc. and ≤500MPa for reinforcement bar. Although, the use of grade S355 is considered the norm in several countries across the world, it is still not as prevalent as many would believe. Figure 1 highlights the general evolution in strength of commercially available hot rolled structural steels [1]. Today, it is fair to say that in general most steel producers and users would class anything above these strengths as High Strength Steel (HSS). This is reflected in the steel materials products standards (e.g., EN10025, 10149, 10210 and 10219), the design standards (e.g., Eurocode 3 (EN 1993)) and execution standards (EN1090) wherein HSS structural grades up to and including S960 are catered for, or provisions are currently under development.

As demands grow on the steel construction sector to become more environmentally sustainable and an integral part of the circular economy towards a net zero-carbon future, the use of HSS is increasingly becoming an attractive part of the solution. Today it is well recognised that the use of HSS can afford several advantages resulting in significant cost and environmental benefits across the supply chain. In general, higher strengths permit a reduction in the steel thickness meaning a lower quantity of steel, which directly leads to lower material costs, less fabrication and welding costs, reduced transportation costs and lower Global Warming Potential equivalent (GWPe) contributions etc.

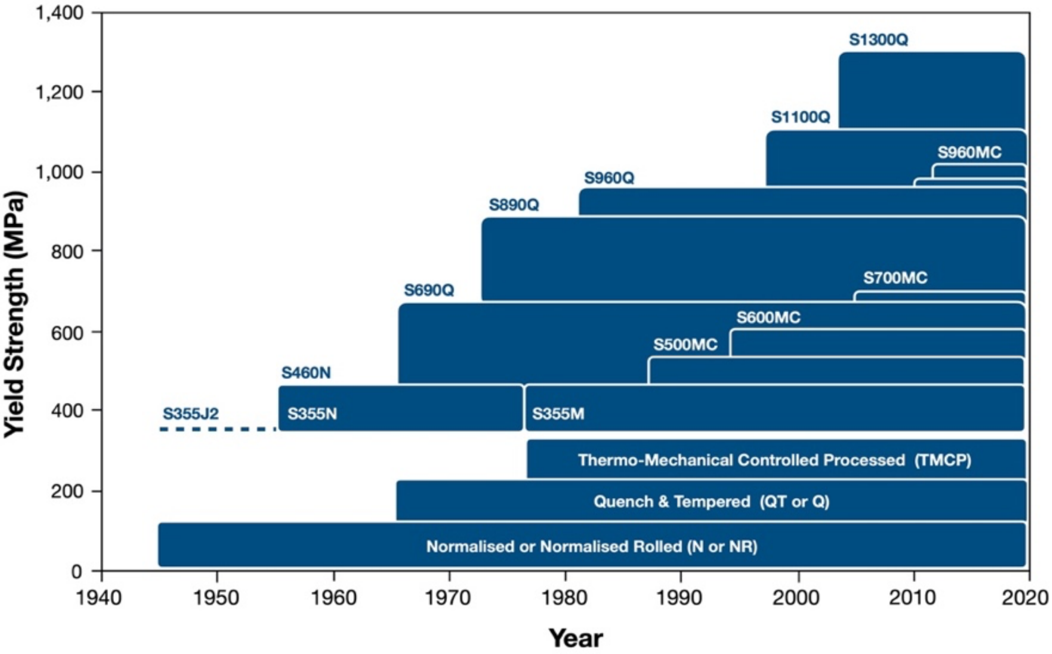


Figure 1 Evolution in strength of commercially available hot rolled structural steels [1]

STRONGER STEELS IN THE BUILT ENVIRONMENT (STROBE)

Despite the availability of a range of high quality HSS products within the market, the existing Eurocode 3 (EN 1993) design rules tend to be slightly conservative towards the use of HSS with yield strength greater than460MPa, consequently limiting their uptake. For example, in some cases it has been found that imposed limiting requirements (e.g., uniform elongation according to EN 1993) have been empirically determined rather than based on mechanical testing.

With a steadily growing demand for sustainable building solutions there was a need to improve and extend the rather conservative design provisions for HSS in EN 1993. To this end, a European RFCS project, *Stronger Steels in the Built Environment* (STROBE) [2], was carried out to study the performance of HSS structural members at both the ultimate and serviceability limit states for use in a number of typical building-type structures. The project was coordinated by The Steel Construction Institute based in the UK. To overcome specific obstacles to the wider use of HSS sections (S460 to S700), both homogeneous and hybrid welded sections were investigated in building structures through: (1) formation of new ductility and toughness requirements; (2) updating rules for plastic design of HSS beams and frames; (3) updating rules for stability of HSS members; (4) development of a floor vibration analysis tool to assess dynamic performance of HSS floors, and; (5) analysis of comparative designs.

To meet these objectives homogenous and hybrid welded steel I-sections were made from steels up to S700 and tested to demonstrate the potential advantages of their appropriate use to designers, and evaluate the benefits of using HSS solutions relative to conventional strength steel (S355) in terms of saving weight, cost and carbon emissions for different structures. Attention was given to basic issues allowing for usage of HSS with lower ductility values, exploiting plastic capacity, leading to more slender and highly utilized profiles and the benefits were quantified by design comparisons and life cycle assessments. The project focused on building structures, both single and multi-storey. However, the results have generic applicability to a range of structures. The following sections highlight some of the key activities and findings from this study. The final summary report and all the Work Package reports are available here: www.steel-sci.com/strobe.html [2]

DUCTILITY AND TOUGHNESS REQUIREMENTS FOR PLASTIC DESIGN WITH REGARD TO HSS

A set of parametric true stress-strain curves were developed for HSS based on a statistical evaluation of a large database (300 sets of data; S235 to S960, 4-80mm thick and a range of delivery conditions), including materials with varying material parameters such as the yield strength, tensile strength, elongation at tensile strength and yield plateau. The material database was also used to derive parametric damage curves which were based on the Johnson-Cook damage model and an analytical relationship between the parameters of the damage model and the material characteristics. These curves were subsequently used to investigate the ductile failure of steel components under tension by means of numerical simulations on notched specimens covering a wide range of material characteristics in order to detect critical combinations.

The numerical study included HSS of grades up to S960 and six values of upper-shelf toughness. Different geometries were included in the numerical simulations in order to study the influence that a concentrated load introduction, or multiple cross-sectional weakening may have on the ductility requirements. Based on the numerical results obtained from the centrally notched tensile (CNT) specimens, a procedure for deriving mechanically justified ductility requirements, in the form of diagrams which account for the effect of different material parameters, was developed and subsequently transferred to the other notched geometries. Table 1 summarises the outcome of this part of the study, proposing an amendment to the ductility requirements of HSS in EN 1993. Investigations showed the need for an upper shelf toughness requirement in case of significant hardening behaviour. As upper shelf toughness is not specified in any material code a substitute measure can be fracture strain *A*. Small scale tests showed that a minimum value of *A* ≥ 12% for HSS is sufficient, providing the design is based on a global elastic analysis.

Table 1. Proposed amendment to ductility requirement of HSS according to Eurocode 3

	EN 1993 (1st Edition)		**EN 1993 (next Edition)**	
	$f_y \leq 460$ (EN 1993-1-1)	**$460 < f_y \leq$ S700 (EN 1993-1-12)**	**For plastic global analysis**	**For elastic global analysis**
f_u / f_y	≥ 1.10	≥ 1.05	≥ 1.10	≥ 1.05
***A* (total elongation.)**	≥ 15%	≥ 10%	≥ 15%	≥ 12%
ε_u (elongation at maximum load)	$\geq 15\ f_y / E$	$\geq 15\ f_y / E$	---	---

PLASTIC DESIGN OF HSS FRAMES

In current design provisions plastic design is not allowed for HSS. Therefore, to assess the applicability of plastic design for homogeneous and hybrid HSS beams and indeterminate frames, and to developed design recommendations, an experimental programme on homogeneous HSS beams and hybrid beams with flanges made from HSS was carried out to investigate the cross-sectional resistance and rotation capacity of the beams. Tests showed that most of the beams were able to develop the rotation capacity of R=3 required by EN 1993-1-1 for plastic design. Only two beams, which were characterized by a large web slenderness, were not able to reach the required minimum rotation capacity. Hybrid beams showed higher rotational capacities than the geometrically equivalent homogeneous beams. However, they also showed slightly less ultimate capacity.

The results from the experiments were used to validate a numerical model which was further used to investigate the effect of several parameters on the rotational capacity of HSS I-section beams, including the cross-sectional slenderness, steel grades, hybrid sections, boundary conditions and type of loading. The parametric studies showed that the cross-sectional slenderness and in particular, the slenderness of the web had the biggest influence on the rotational capacity.

In order to investigate the structural response of HSS frames and to quantify the level of plastic redistribution that can be achieved, an experimental programme involving the testing of a series of two-dimensional, single bay, single storey frames was carried out. Homogeneous and hybrid HSS frames were considered. The frames were laterally restrained preventing out-of-plane movement but not restraining any in-plane movement. The frames were subject to different combinations of horizontal and vertical loading in order to enable a beam, sway and combined plastic collapse mechanisms to form.

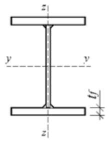
Results from this experimental programme were complemented with numerical simulations. The experimental and numerical investigation on HSS beams and frames showed that the current EN 1993-1-1 Class 2 and 3 slenderness limits are applicable to S690 HSS, while stricter Class 1 limits are shown to be more suitable for both conventional strength steels and HSS. The current plastic design methods set out in EN 1993-1-1 were also found to be generally suitable for HSS frames, provided the stricter Class 1 slenderness limits are employed. The new method of using a modified (reduced) elastic buckling load factor to account for the increased susceptibility to second order effects due to plasticity, as will be included in the next edition of EN 1993-1-1, was found to provide conservative results. Consequently, with slightly stricter slenderness limits, application of plastic design to HSS frames does provide safe-sided results.

STABILITY DESIGN WITH HSS

To study the stability behaviour of HSS columns, beams and beam-columns members, a set of experimental tests and numerical analyses was undertaken. In addition, a numerical study was also conducted to develop a deformation limit criterion for plates subject to buckling. The experimental programme included four columns subject to major and minor axis flexural buckling, fourteen beams subject to lateral-torsional buckling, and two beam-columns subject to flexural-torsional buckling. The experiments covered steel grades S460 and S690, homogeneous and hybrid sections, as well as monosymmetric beams. The experiments were complemented with material characterization, measurement of residual stresses and the geometric imperfections. Numerical simulations were also conducted to extend the range of steel grades, cross-section and member slenderness, and type of loading conditions covered in the study.

The results showed that higher (i.e., more favourable) bucking curves can indeed be used for HSS beams and columns due to a reduction in the impact of residual stresses as the yield strength of the steel increases. Design rules were hence developed for HSS beams and columns susceptible to global buckling based on the current format of the buckling curves given in EN 1993-1-1 but with smaller imperfections factors. Table 2 highlights the new proposed design rules from the study for buckling curves for columns and it is expected that these rules will be included in the next edition of the standard.

Table 2. Proposed buckling curve for columns

	Fabrication	**Limits**	**Axis**	**EN 1993-1-1**	
				S235-S420	**S460-S700**
Welded Profiles		$t_f \leq 40$ mm	y-y z-z	b c	a b
		$t_f > 40$ mm	y-y z-z	c d	b c

For beam-columns made of HSS, it was concluded that the current interaction equations in combination with the proposed buckling curves for beams and columns are applicable.

RE-DESIGN OF FLOOR SYSTEM IN HSS

The potential benefits of using HSS beams compared to S235 and S355 standard steel grades for building structures was studied by re-designing in HSS the floor systems of four commercial projects involving different types of buildings. This comparative study was carried out using the optimization tool developed in the study for HSS beams for simple beams under uniformly distributed loads. A detailed description of the four case studies is given in the final project report [2]. As an example of the output, Figure 2 shows a comparison of the weight of hot rolled sections in S235, S355 and S460 for a single beam with a design load of 20 kN/m and similar results were obtained for other loading conditions.

It can be seen from Figure 2a that if there is no deflection limit, and lateral-torsional buckling is not critical, the higher strength leads to a reduction in weight. The weight saving is up to 40% for S460 compared to S235. If lateral-torsional buckling has to be considered and there is no deflection limit, the weight saving is decreased to ≤20% for S460 compared to S235. If a deflection limit of span/300 for the total load at serviceability limit state (SLS) is considered, using HSS beams leads to no weight savings, as shown in Figure 2b. Overall, this shows that HSS beams can enable useful weight savings if the deflection limit and lateral- torsional buckling do not govern design.

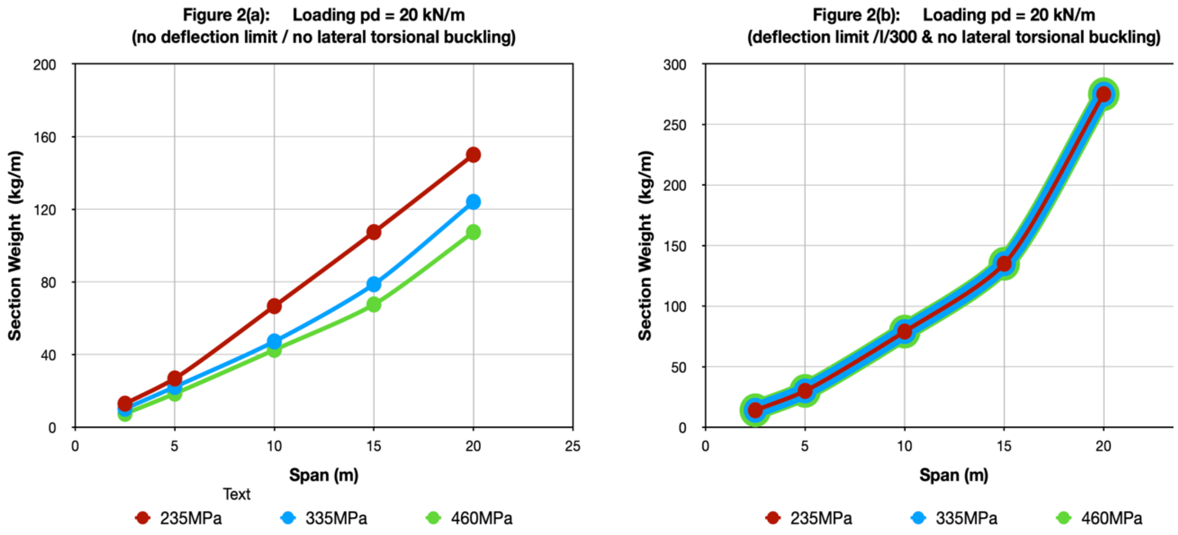


Figure 2(a): Loading pd = 20 kN/m
(no deflection limit / no lateral torsional buckling)

Figure 2(b): Loading pd = 20 kN/m
(deflection limit /l/300 & no lateral torsional buckling)

Figure 2a and 2b Results of a comparative study for hot rolled sections [2]

LIFE CYCLE ASSESSMENT (LCA) OF HSS DESIGNS

To assess the benefits of using HSS solutions for sustainable construction relative to a conventional strength steel (S355) in terms of comparative designs with life cycle assessment, five structural cases were defined in which it was considered that the use of HSS was likely to show savings, both in carbon emissions and/or costs relative to S355 steel: (1) 9m x 9m floor grid for an office building; (2) 15m x 7.5m floor grid for an office building; (3) 15m span transfer beams for 6 residential levels over a commercial space; (4) Columns in 10 and 20 storey buildings, and; (5) Berlin Museum Hall (real case).

All these cases included highly loaded members where serviceability limits do not control or where sections are relatively stocky to overcome the effects of local buckling. Embodied carbon and cost assessments were undertaken on the chosen designs, comparing the HSS designs with the S355 designs. In some cases, rolled sections in S355 steel were compared with fabricated members in HSS, but in general, fabricated members in S355, S460 and S690 were used for comparison.

Table 3. Weight and carbon savings for a 20-storey 9x9m building relative to designs using just S355

	S355 HR	**S460 Welded**	**S690 Welded**	**S460 HR**
Steel material cost	100%	94.8%	87.8%	82.5%
Fabrication cost	100%	173.6%	172.0%	99.5%
Coating cost	100%	95.4%	86.1%	97.5%
Transport cost	100%	73.1%	57.7%	76.9%
Erection cost	100%	100%	100%	100%
Total cost – steelwork	100%	101.2%	94.4%	87.4%
Tonnes	100%	74.6%	56.8%	75.1%
Embodied carbon (module A-C) kgCO_2e	100%	87.8%	69.6%	76.4%

To highlight the outcome from one of these investigated cases: ***Columns in 10 and 20 storey buildings***; consideration was given in the design of 4m high fabricated columns for a 9m x 9m floor grid of a commercial building made from 3 steel plate grades (S355, S460 and S690). In addition, comparison was also made against an as-rolled H-beam readily available in the European market at a strength of S460. The designs were made for 10 and 20 storey buildings in order to demonstrate the benefits of HSS columns with increasing building height.

For the 10-storey buildings, a reduction in steel use in columns was 25% for the S460 as-rolled profile and 20% and 35% for the fabricated profiles in the two HSS steel grades. This represented a reduction of 9% to 18% in overall steel use when combined with the HSS beams in Case 1 (i.e., 9m x 9m floor grid for an office building). The cost of the fabricated columns was +6% and +3.6% for the two HSS grades, but -10% for the as-rolled profile. For the 20-storey building, the reduction in steel use in the columns was 25% for the S460 as-rolled profile and 25% and 43% for the fabricated profiles in the two HSS steel grades. This represented a reduction of 13% and 22% in overall steel use when combined with the HSS beams in Case 1. The cost of the fabricated columns was +1.2% and -5.6% for the two HSS grades but -13.6% for the S460 as-rolled profile.

Finally, for the 10-storey building the reduction in overall embodied carbon was 6% and 21% for the two HSS grades and 24% when using the S460 as-rolled profile. For the 20-storey building, this reduction was 12% and 30% for the two HSS grades and 24% for the S460 as-rolled profile; clearly showing the benefit of using HSS in columns in high-rise buildings. Table 3 summarises the project costs and embodied carbon for the 20-storey 9x9m residential building when comparing an as-rolled S355 to fabricated profiles of S460, S690 and an as-rolled S460 profile.

Table 4. Weight and carbon savings relative to designs using just S355

Case No.	Description	Weight saving	Carbon saving (Modules A-C)
1	9m x 9m floor grid for an office building	24 – 38%	11 – 24%
2	15m x 7.5m floor grid for an office building	18 – 31%	16 – 27%
3	5m span transfer beams for 6 residential levels over a commercial space	21 – 41%	19 – 36%
4	Columns in a 10-storey building	22 – 39%	9 – 26%
	Columns in a 20-storey building	25 – 48%	12 – 36%
5	Berlin Museum Hall (real case example)	8 – 48%	20 – 45%

Overall, the LCA study concluded that: (i) steel weight savings of between 8 and 49% are achievable using HSS up to S690; (ii) cost savings of up to 14% are achievable using HSS, and; (iii) embodied carbon savings of between 9% and 45% are achievable using HSS. Table 4 summarises weight and carbon savings relative to designs using just S355 (note, that greater savings will be made if the base is ≤S275).

The benefits to steelmakers in producing higher strength structural steels, and thus value adding products, is sometimes misplaced when it comes to increased profitability. More than often comment is made that although HSS do carry a premium, less overall tonnage will be required to be sold and this does not necessarily lead to an increase in profitability. However, this is not the case as highlighted in Table 5, which summarises the project costs for a 10-storey 9x9m residential building using 4m long column pieces. The example demonstrates that by increasing the steel grade from S355 to S460, the project can save 10% in total steelworks cost and which will naturally lead to a reduction in GWP. Furthermore, for the steelmaker, there is an increased 10% (or € 73/t) in price per tonne despite 25% less actual steel being consumed, which is an additional saving in raw material costs (iron-ore in particular).

Table 5. Creating added-value using S460 H-beams in a residential building

	S355	S460	S460 vs S355
Designation:	HD360 x 196	HD360 x 147	
Dimensions:	372 x 374 x 196	360 x 370 x 147	
Section weight:	196 kg/m	146 kg/m	25.5% lighter
Tonnes required:	117.6 tonnes	88.2 tonnes	29.4 tonnes saved
Total length of columns:	600 m	600 m	
Steel material cost:	€ 87,600	€ 72,100	€ 15,500 saved or 18% cheaper
Other costs = fabrication + coating + transportation + erection	€ 90,300	€ 87,700	€ 2,600 saved or 3% cheaper
Total cost - steelwork	€ 177,900	€ 159,900	€ 19,000 saved or 10% cheaper

CONCLUSIONS

The STROBE project has sought to overcome some of the obstacles relating to unduly conservative design rules and shown there is significant potential for designing more efficient higher strength steel structures. The potential scope of application of the results of this project is far reaching. Once construction practitioners are able to design more efficient HSS structures, demand will grow and the procurement obstacles, such as limited source of supply and inexperience in fabrication, are likely to reduce in response.

The most important exploitation activity relating to the findings of STROBE relates to the inclusion of the design recommendations into the next edition of Eurocode 3. The experimental work completed makes a significant contribution to the body of data on HSS material, cross-sections and members. The main outcome of the ductility and toughness requirements study for plastic design has already been included in the next edition of EN 1993-1-1. The other Eurocode recommendations from STROBE have been submitted to the relevant Technical Committees and will either be included in the imminent revisions to these standards, or as amendments shortly after.

The work on STROBE has played a useful role in developing more economic design rules. There seems little doubt that the use of HSS in construction will significantly increase in the coming years, especially with the growing appreciation of the need to address climate change. It is important that designers are encouraged to consider using HSS where appropriate for reductions in weight, carbon, and cost.

The work on LCA case examples will help designers to identify the types of scenario where significant savings can be made and indicate the approximate size of the savings. In concluding, case examples highlight advantages in moving to higher strength, value-adding structural steel grades, where further savings in emissions and costs can be realised across the supply chain, including steelmakers towards a sustainable built environment.

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