THE RIGHT CHOICE OF STEEL
- according to the Eurocode -

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ABSTRACT

In general, the choice of the steel grade is ruled in Eurocode EN 1993-1-1. Several requirements are specified: choice according to the material properties, ductility requirements, toughness properties and through-thickness properties. With reference to these requirements on the mechanical characteristics, modern hot-rolled structural sections are produced by precise control of the temperature during the rolling process. Fine grain steels, produced using thermomechanical rolling (delivery condition M according to EN 10025-4), feature improved toughness values which give a lower carbon equivalent and a fine microstructure when compared with conventional or normalised steels.

This paper gives guidance on and background to the right choice of the steel grade according to the Eurocode. Furthermore, the influence of the production process on this choice is highlighted and the advantages of thermomechanical steels for each criterion are discussed.

KEYWORDS

steel, production, steel grade, material properties, ductility, toughness, weldability

INTRODUCTION

Eurocode 3 [EN 1993-1-1 (2005)] applies to the design of buildings and civil engineering works in steel. It complies with the requirements and principles for the safety and serviceability of structures, the basis of their design and verification that are given in EN 1990 – Basis of structural design. Requirements are provided for resistance, serviceability, durability and fire resistance of steel structures. These are based on the principle of limit state design, which mainly assumes that the resistance of cross-sections and members specified for the ultimate limit states are based on tests in which the tolerances are met according to EN 1090-2, and the material exhibited sufficient ductility to apply simplified design models. Therefore, the material properties, for steel the steel grade, have to be specified in detail to comply with the safety level of Eurocode 3, see Figure 1.

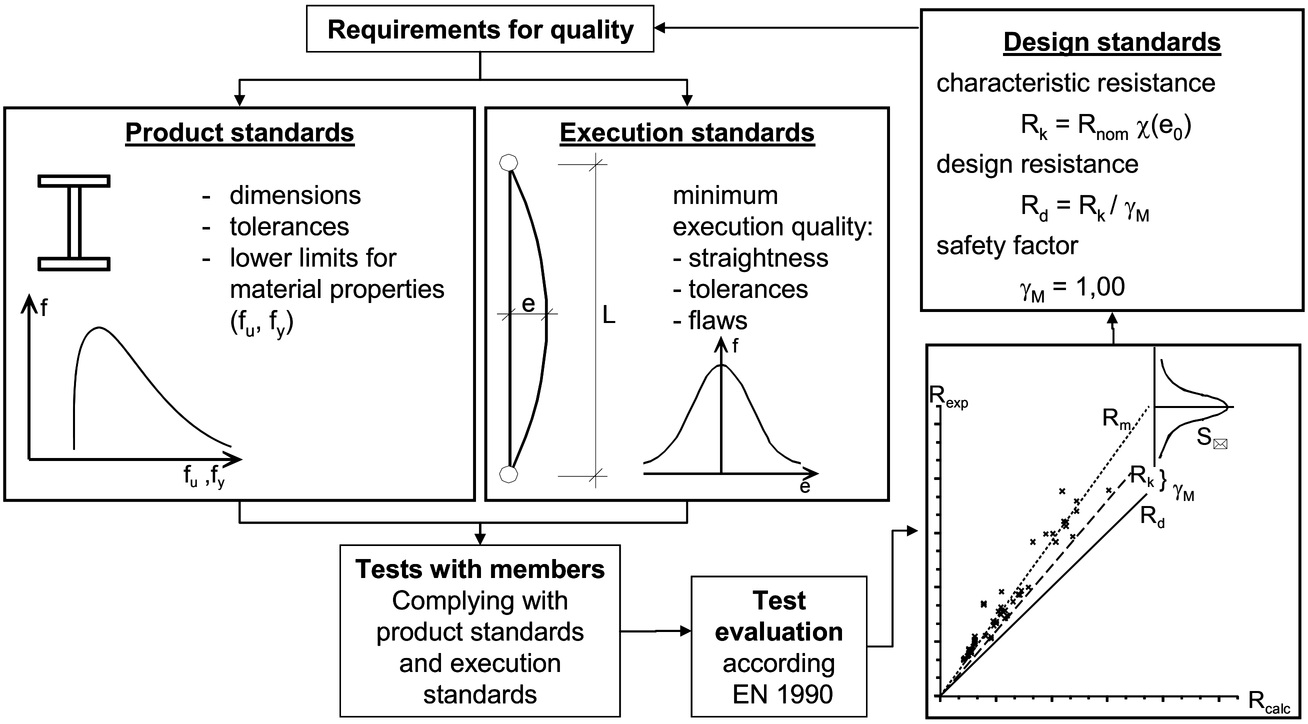


Figure 1: Reliability of strength verification [Schäfer et al (2009)]

These simplified design models and the safety concept of the Eurocode are based on tests at ambient temperature, for which ductile failure occurs as the steel is on the upper shelf region with sufficient toughness. In Figure 2 (left), the conclusions from testing for the partial safety factors and the characteristic strength are shown. If brittle fracture takes place, the assumptions for the design models and the safety concepts are no longer met, see figure 2 (right). Consequently, failure against brittle fracture must be accounted for with an appropriate choice of steel with sufficient toughness.

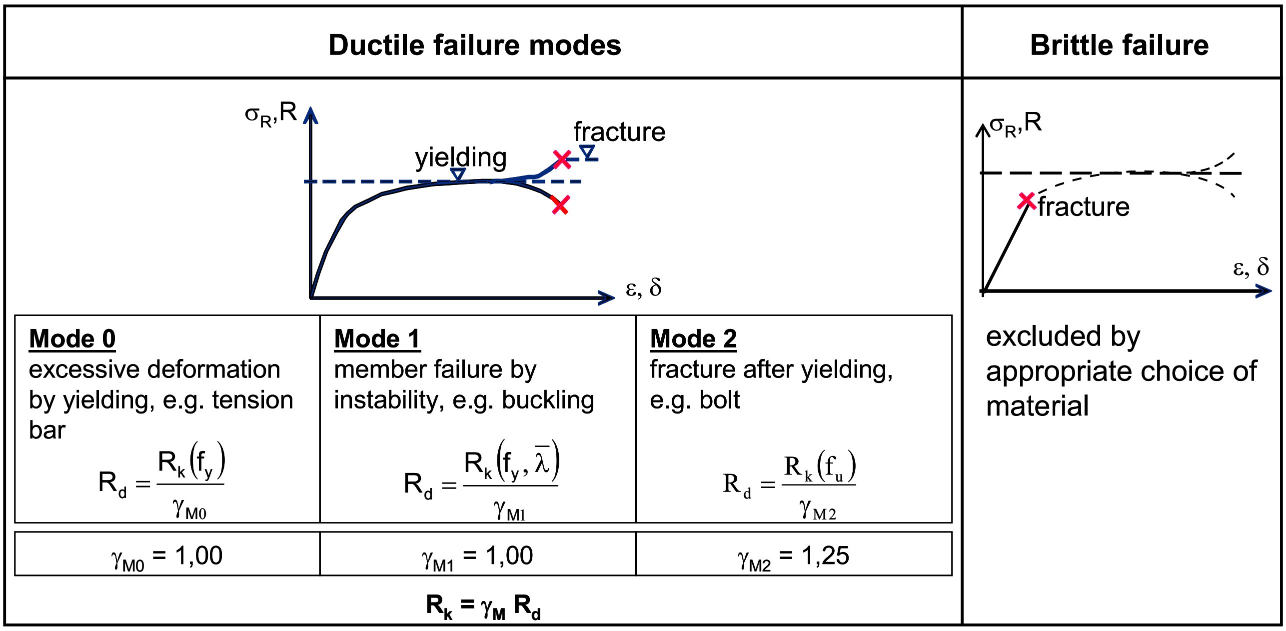


Figure 2: Brittle fracture and ductile failure [Schäfer et al (2009)]

THE CHOICE OF THE STEEL GRADE

In general, the choice of the steel grade is ruled in Eurocode EN 1993-1-1 (2005). Several requirements are specified:

- Choice according to the mechanical material properties
  Nominal values of material properties are defined as characteristic values in design calculations.
- Ductility requirements
  For steels, a minimum ductility is required.
- Toughness properties
  Simplified aids are given to choose the appropriate material with sufficient fracture toughness to avoid brittle fracture.
- Through-thickness properties
  Guidance on the choice of through-thickness properties is given in EN 1993-1-10 (2005).

With reference to these requirements, the designation of the steel grade is defined in the product standard for hot-rolled products and structural steels in EN 10025 (2004), see Figure 3. The classification of steel grades is accordingly based on the minimum specified yield strength at ambient temperature.

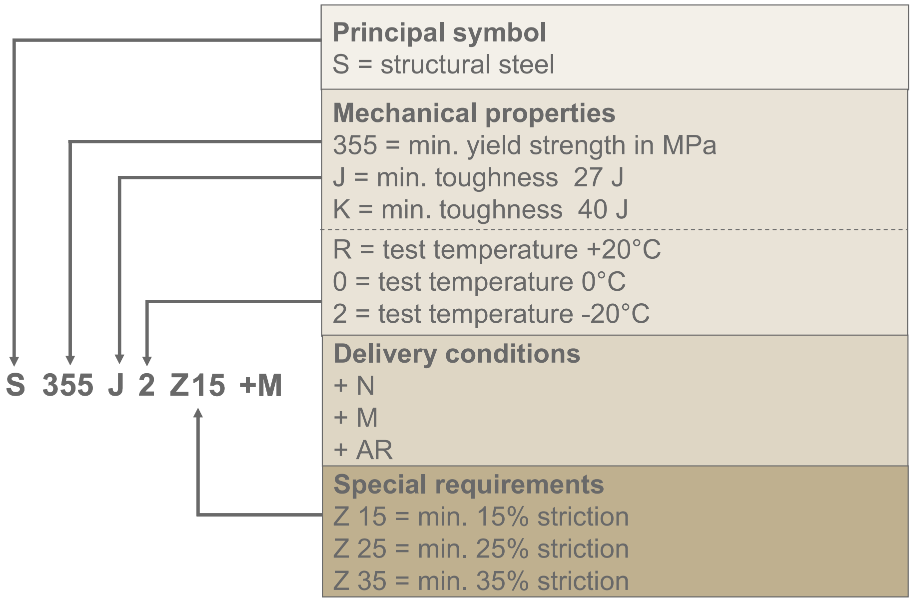


Figure 3: Designation of the steel grade according to EN 10025 (2004)

The product standard also differentiates the delivery condition. These are defined by the rolling process of the steel. Conventional hot rolling takes place in the recrystallised austenitic phase (γ) and is followed by a subsequent air cooling, see Figure 4. Without any special rolling control or heat treatment, this material delivery condition is specified to be "as rolled" (AR) in the EN 10025. With an additional normalising thermal treatment (N), the steel microstructure can be refined leading to improved properties specifically described in EN 10025-3, if alloying elements have been added to the steel. The reduction of the grain size leads to an increase of the specific surface of the grain boundaries within the material. Since these grain boundaries represent an obstacle to deformation the yield strength increases. The fine grained structure of normalised steels may further be improved with restriction of the alloying elements via a thermomechanical treatment. This may be quenching (Q) with water or oil, an accelerated cooling to about 500°C after rolling and lastly slower cooling to the room temperature, and a successive tempering (T) to regain ductility. A fine grained microstructure may also be obtained if the hot rolling process is carried out with a control of the temperature during the final deformation (CR). Another possibility to refine the microstructure is to apply a thermomechanical rolling process according to EN 10025-4. Hereby, rolling is also performed with a controlled rolling process in the recrystallised austenitic and further rollings in the non-crystallised austenitic phase, in cases even into the austenitic-ferritic phases ($\alpha + \gamma$) (M/N). For thermomechanical steels (TM), rolling is carried out at lower temperatures than normalising rolling; the rolling temperature in the finishing stand is typically close to the transformation temperature of the austenite ($\gamma_{non\text{-}recr.} \rightarrow \alpha + \gamma$). The grain size of austenite is about 20 µm or larger before the last rolling passes. After rolling, the austenite grains are usually elongated because of the sluggish recrystallization of the microstructure due to the low rolling temperature.

Although controlled rolling leads to an attractive combination of strength and ductility, it also includes substantial disadvantages. The reduction of the rolling temperature brings an increase of the rolling loads and many mills are not designed to resist the additional stresses. Because a waiting time is usually incorporated in the rolling schedule, controlled rolling can increase rolling time and adversely reduce productivity. Moreover, with higher material thickness, the rolling temperature increases and the air cooling rate after rolling decreases, which induces rougher microstructures. To reach the tensile properties, the content of alloying elements has to be adapted. Due to weldability requirements and the limit in equivalent carbon, beams in grade S460 are not produced for thickness larger than 50 mm. To overcome the limitations of thermomechanical rolling, accelerated cooling process of beams after rolling has been developed (TM + QST). Hereby, the fine grained structure is achieved by a minimum of alloying elements with the complex rolling process and a strict temperature control. As the ferrite grain size of conventionally rolled steels is 10 to 30 µm, the grain size of TM + QST steels is usually between 5 to 10 µm. These fine grained steels benefit from a low carbon equivalent value and are to be predominantly used for large material thicknesses in high strength steel to address weldability.

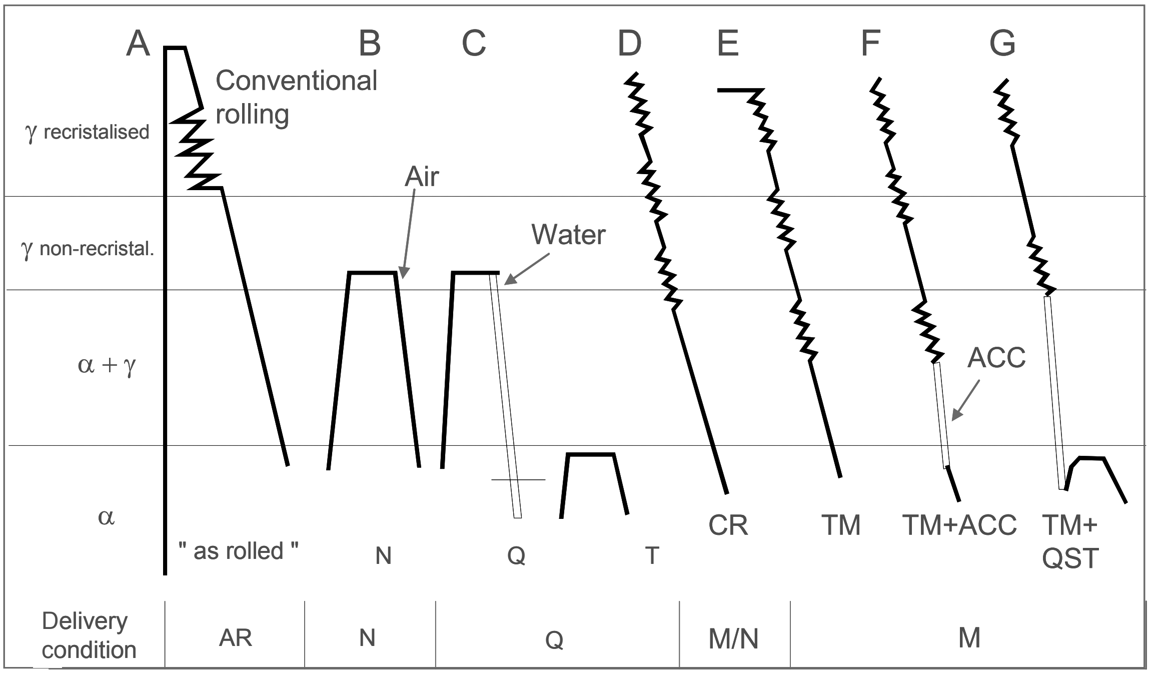


Figure 4: Relation of the delivery condition to the rolling process

\In addition to the group of thermomechanical steels delivered according to EN 10025-4, ArcelorMittal has developed steel grades to fully valorise the potential of quenching and self-tempering (QST) process. These fine grained TM-steels are branded HISTAR® steels [Z-30.2-5] and are characterised by more stringent requirements in terms of mechanical properties and chemical composition.

Mechanical properties

The nominal values of the yield strength f_y and the ultimate strength f_u for structural steel should be obtained by adopting the values $f_y = R_{eh}$ and $f_u = R_m$ direct from the product standard, see Table 1, or by a table drafted from this standard in EN 1993-1-1. It has to be noticed, that the required yield strength decreases with increasing material thickness. This takes into account the effect, that with the increase in material thickness, the addition of alloying elements need to be higher to achieve constant yield strength over the thickness. However, with the increase in addition of alloying elements, the carbon equivalent value raises and welding becomes problematic. Welding is substantial to the application of structural steels. Thus, the normative rules have considered this fact by lowering the required yield strength for thicker plates to account for weldability.

TABLE 1

MECHANICAL PROPERTIES AT AMBIENT TEMPERATURE FOR THERMOMECHNICAL ROLLED STEELS

[EN 10025-4 (2004)]

Designation		Minimum yield strength R_{eH} [a] MPa [b] Nominal thickness mm						Tensile strength R_m [a] MPa [b] Nominal thickness mm					Minimum percentage elongation after fracture [c] % $L_0 = 5{,}65\sqrt{S_0}$
According EN 10027-1 and CR 10260	According EN 10027-2	≤ 16	> 16 ≤ 40	> 40 ≤ 63	> 63 ≤ 80	> 80 ≤ 100	> 100 ≤ 120 [d]	≤ 40	> 40 ≤ 63	> 63 ≤ 80	> 80 ≤ 100	> 100 ≤ 120 [d]	
S275M S275ML	1.8818 1.8819	275	265	255	245	245	240	370 to 530	360 to 520	350 to 510	350 to 510	350 to 510	24
S355M S355ML	1.8823 1.8834	355	345	335	325	325	320	470 to 630	450 to 610	440 to 600	440 to 600	430 to 590	22
S420M S420ML	1.8825 1.8836	420	400	390	380	370	365	520 to 680	500 to 660	480 to 640	470 to 630	460 to 620	19
S460M S460ML	1.8827 1.8838	460	440	430	410	400	385	540 to 720	530 to 710	510 to 690	500 to 680	490 to 660	17

[a] For plate, strip and wide flats with widths ≥ 600 mm the direction transverse (t) to the rolling direction applies. For all other products the values apply for the direction parallel (l) to the rolling direction.

[b] 1 MPa = 1 N/mm^2

[c] For product thickness < 3 mm for which test pieces with a gauge length of L_o = 80 mm shall be tested, the values shall be agreed at the time of the enquiry and order.

[d] For long products a thickness ≤ 150 mm applies.

The producers verify the conformity of their products with the standard by tensile tests, in which for each section, the location of the test specimen is also defined, see e.g. Figure 5 for beams. The result of the tensile test is the stress-strain curve from which the relevant parameters, yield strength f_y and tensile strength f_u, are determined. These parameters are exemplarily indicated in Figure 6, a typical stress-strain curve for a HISTAR®460 (or S460 steel grade according to EN 10025-4 for thermomechanical rolled weldable fine grain structural steels).

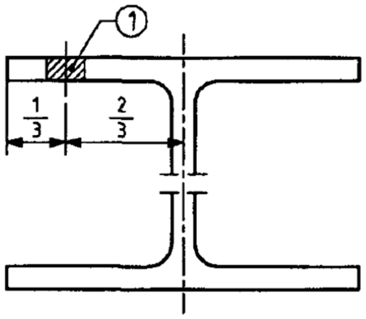


Figure 5: Location of test specimen for tensile test

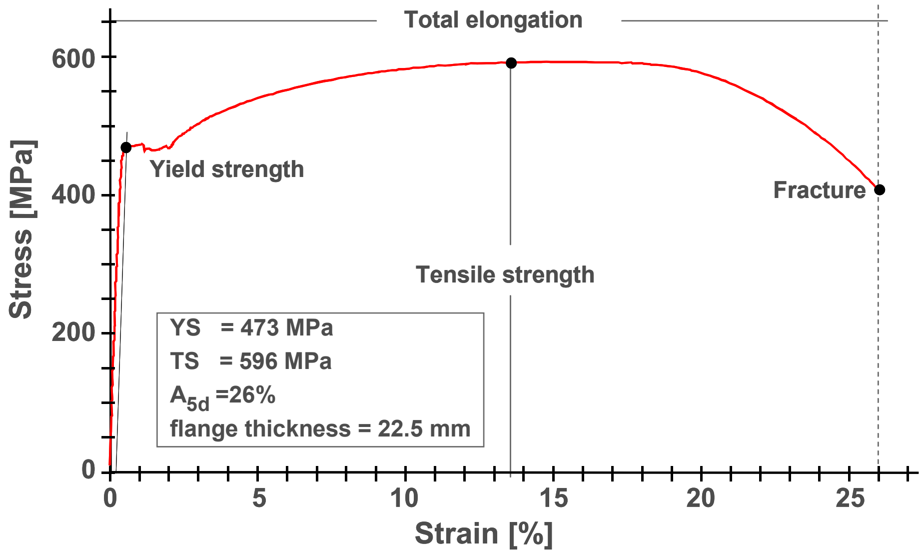


Figure 6: Stress-Strain diagram from a HISTAR®460 steel

For thermomechanical rolled fine grained steels of the new generation using the QST process (e.g. HISTAR® steels), it is remarkable that a decrease of the yield strength in respect to the material thickness can be avoided without an increase of the alloying elements and the carbon equivalent value. A comparison of the material thickness to yield strength in relation to steels according to EN 10025 (2004) and modern HISTAR® steels according to Z-30.2-5 (2008) is given in Figure 7. As a result, the right choice of thermomechanical steel gives the designer an economical advantage in design, as presented in the example of application of this paper.

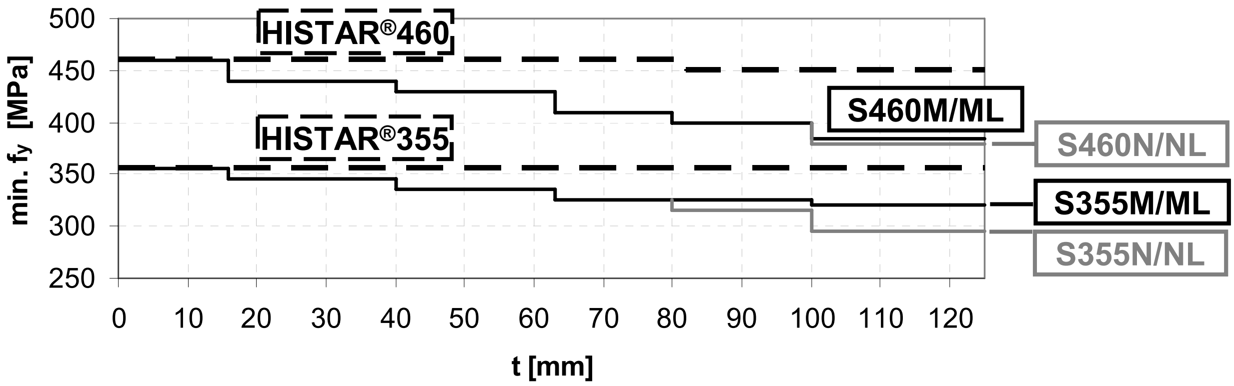


Figure 7: Comparison of the material thickness t to yield strength f_y in relation to steels according EN 10025 (2004) and modern HISTAR® steels according to Z-30.2-5 (2008)

Ductility

Ductility is required to avoid brittle failure of structural elements. For steels, a minimum ductility is required that should be expressed in terms of limits for:

- the elongation at failure on a gauge length of $5.65\sqrt{A_0}$ (where A_0 is the original cross-sectional area); Eurocode recommends an elongation at failure not less than 15%;
- the ratio f_u / f_y of the specified minimum ultimate tensile strength f_u to the specified minimum yield strength f_y; Eurocode recommends a minimum value of $f_u / f_y \geq 1.10$.

Both criteria are of particular interest for high strength structural steels as the grade S460 due to the fact that the higher the yield strength, the less elongation will be present at failure, see Figure 8. The minimum required elongation for structural steels is given in Table 1. Therefore, the product standard offers more ductility than required in EN 1993-1-1. However, Figure 5 also illustrates that the minimum required elongation is in general met with a high safety margin by modern steels of higher strength. The ratio f_u / f_y is in general more critical than the minimum elongation. Therefore, various tensile test have been compiled and the ratio f_y / f_u has been plotted over the yield strength, see Figure 9.

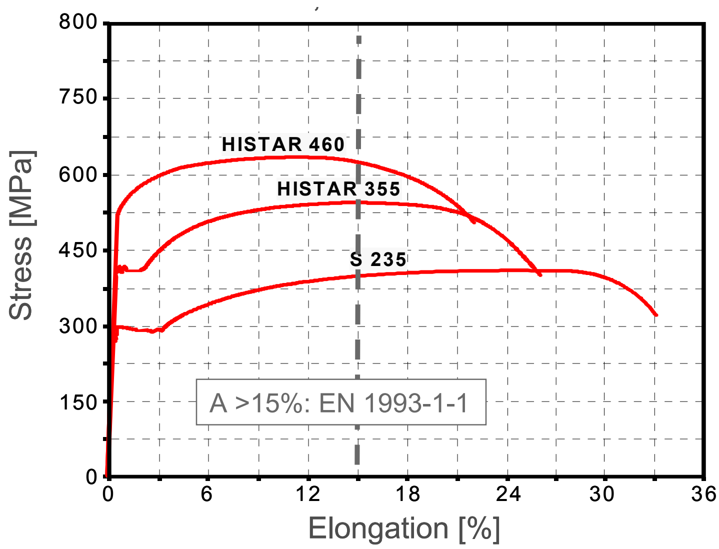


Figure 8: Comparison of stress-strain curves for S235 to S335 and S460 steel of the modern generation

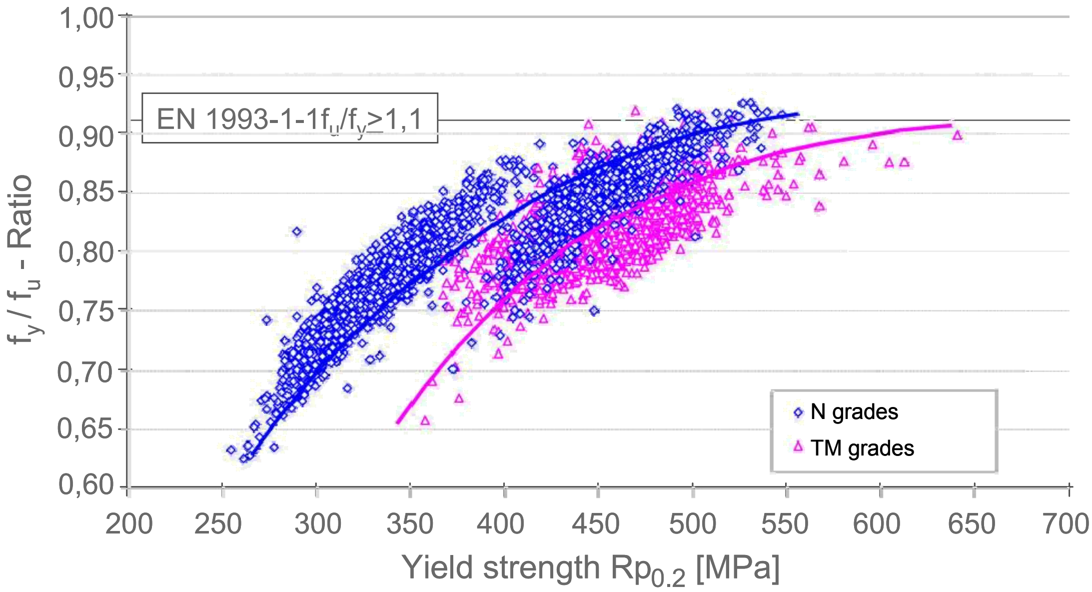


Figure 9: Ratio of yield strength to tensile strength for structural steels of ArcelorMittal

The conclusion from the diagram is that structural steels up to 460 MPa fulfil the ductility criteria. Structural steels with yield strengths higher than 460 MPa seem, on the first look, not to be able to fulfil the ductility criteria. Thermomechanical steels are well adopted to fulfil these criteria with thanks given to their specific strengthening mechanism (refined microstructure and reduced microalloying content).

In the Hong Kong Code of Practice for the Structural Use of Steel (2005) [the Code], a ratio f_u / f_y = 1.2 is required and therefore 9% more conservative compared to the Eurocode and therefore does not allow for high strength, high toughness steels. Further, the elongation at failure to be not less than 15% is required which is in line with the Eurocode requirement. The ration 1.2 used in the Hong Kong Steel Code is reasonable for conventional steels.

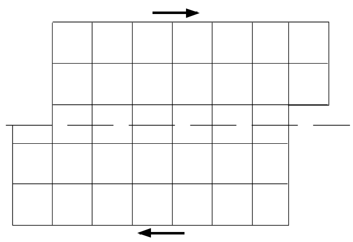
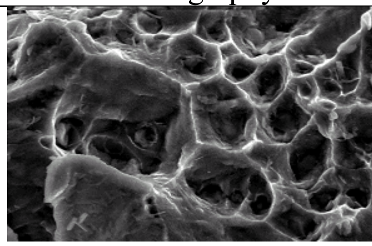
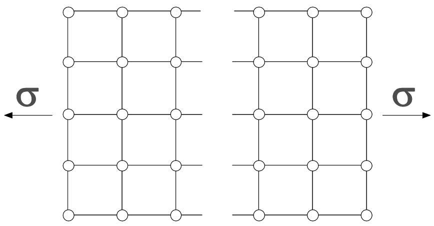
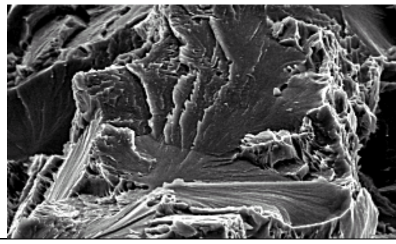
Toughness

Introduction

There are two ways of material failure: ductile failure and brittle fracture, see Table 2.

TABLE 2

FAILURE MECHANISMS OF MATERIALS

Failure mode	Deformation of crystal lattice	Fractography
Ductile failure – shear – slipping – toughness – dull		
Brittle fracture – cleavage – decohesion – brittleness – shiny		

Toughness is the resistance of a material to brittle fracture when stressed. Toughness is defined as the amount of energy per volume that a material can absorb before rupturing. The material toughness depends on:

- Temperature
  Materials loose their crack resistance capacity with decreasing temperature, see Figure 10. This relation can be displayed in an impact energy A_v – temperature T curve with an upper shelf region (3: ductile failure), lower shelf region (1: brittle fracture) and a transition region (2: crack shows shares of cleavage and shear area).
- Influence of loading speed
  The higher the loading speed, the lower the toughness, see Figure 11.
- Grain size
  The orientation of the crystal lattice varies in the adjacent grains, see Figure 12. Whenever the crack tip reaches the grain boundary, the crack would subsequently change his growth direction and thus energy is dissipated. Consequently, fine grained steels are more resistant to brittle failure.
- Cold forming
  With an increase in cold forming, the yield strength increases with decreasing ductility, see Figure 13.
- Material thickness
  In the two dimensional stress state, steel plastic deformation starts at the yield point. In the three-dimensional stress state, the crystal lattice of the steel is compacted from all sides and therefore the steel yield strength is increased significantly. Thus, thinner plates with a higher share of material in the two-dimensional stress state do have more ductility than thicker plates, see Figure 14.

The material toughness is in general experimentally investigated by the Charpy impact test with the resulting impact energy - temperature curve.

Further relevant factors which have also an influence on the resistance of members to brittle fracture are:

- Notch detail
  Crack initiation highly depends on the notch detail and the resulting stress, crack position and crack shape expressed by the notch intensity factors, see Figure 15.
- Load utilisation level of member
  The higher the tension in the member, the higher the failure probability, see Figure 16.

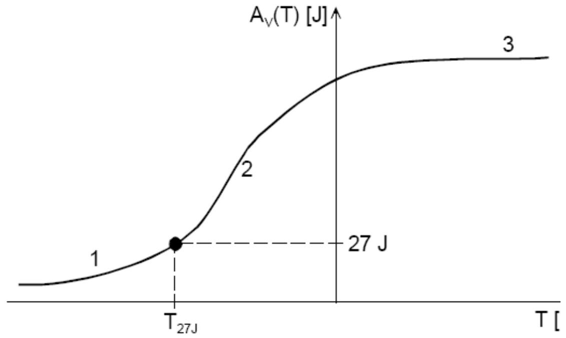


Figure 10: Impact energy A_v – temperature T curve

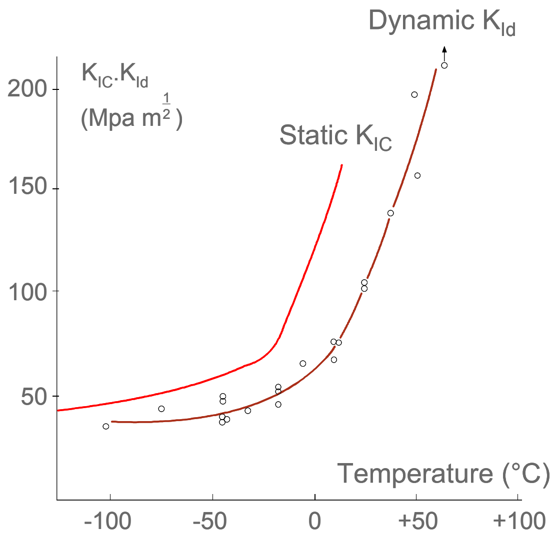


Figure 11: Stress intensity factor - temperature curve for quasi-static and dynamic loading

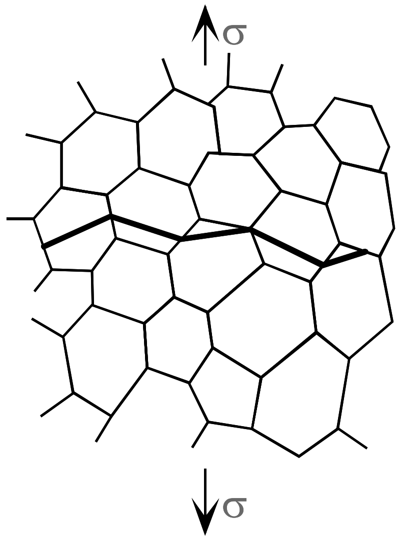


Figure 12: Model of crack propagation in the crystal lattice

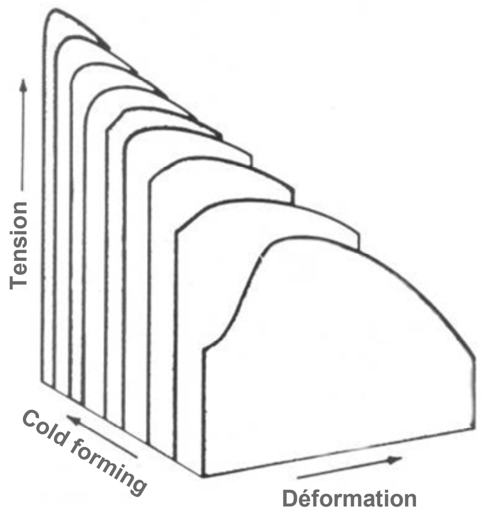


Figure 13: Stress-strain curve in dependency of the degree in cold forming

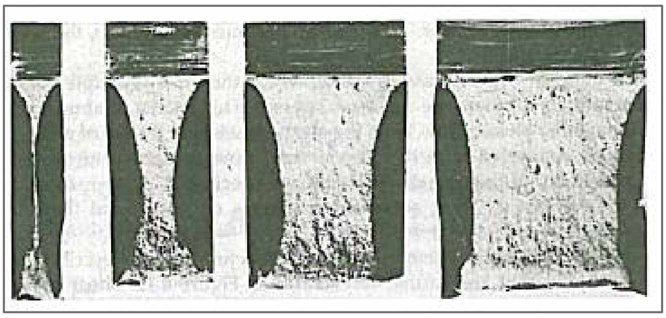


Figure 14: Fracture surfaces of Charpy impact tests for plates with different material thicknesses

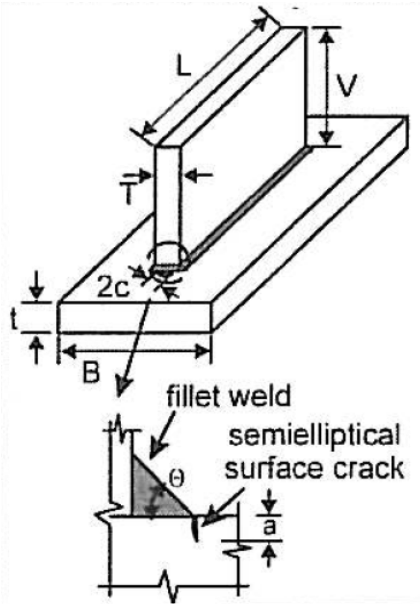


Figure 15: Specification of a notch for the determination of the notch intensity factor

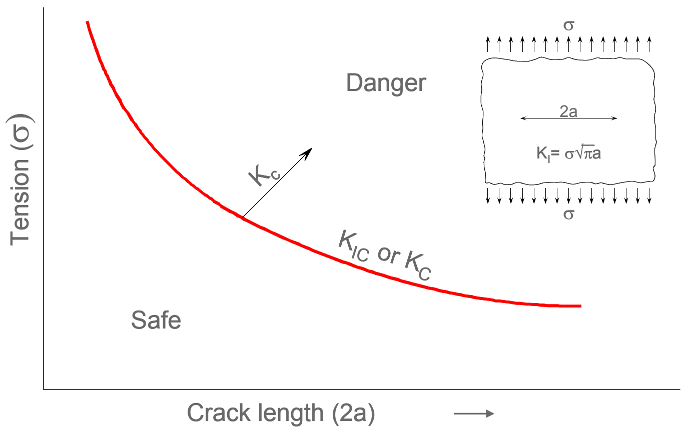


Figure 16: Relation of the failure loading to the crack length

The right choice of steel for toughness assessment

As introduced, it is essential for the safe use of structures designed according to Eurocode 3 that the material has a sufficient toughness to avoid brittle fracture of tension elements exposed at the lowest service temperature expected to occur within the intended design life of the structure. Rules for the selection of steels are therefore offered in Part 1-10 of EN 1993, which allow a simple toughness assessment to avoid brittle fracture. The basis for the assessment is a fracture mechanics approach with the design check for which the design values of the action effect $E_d = K^*_{appl,d}$ (stress intensity factor) are compared to the design values of the toughness resistance $R_d = K_{mat,d}$ in the transition region of the impact energy - temperature curve Kühn (2005), see Figure 17 [Sedlacek et al (2003)] thus as:

$$K^*_{appl,d} \leq K_{mat,d} \tag{1}$$

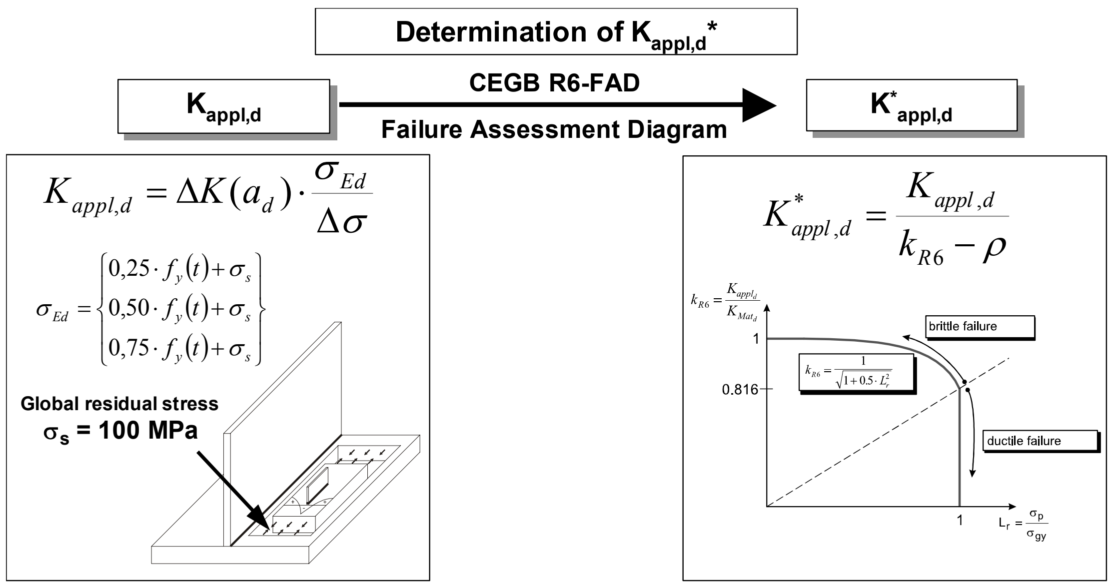


Figure 17: Action side of the toughness assessment [Sedlacek, Müller (2005)]

On the action side, $K_{appl,d}$ is determined for a certain flaw size, modeled by a surface crack. However, the use of the stress intensity factor $K_{appl,d}$ is limited for an elastic fracture mechanics approach and therefore needs to be corrected for plastic strains via the CEGB R6-FAD Failure Assessment Diagram. Consequently, the toughness requirement for the steel is given by the $K^*_{appl,d}$.

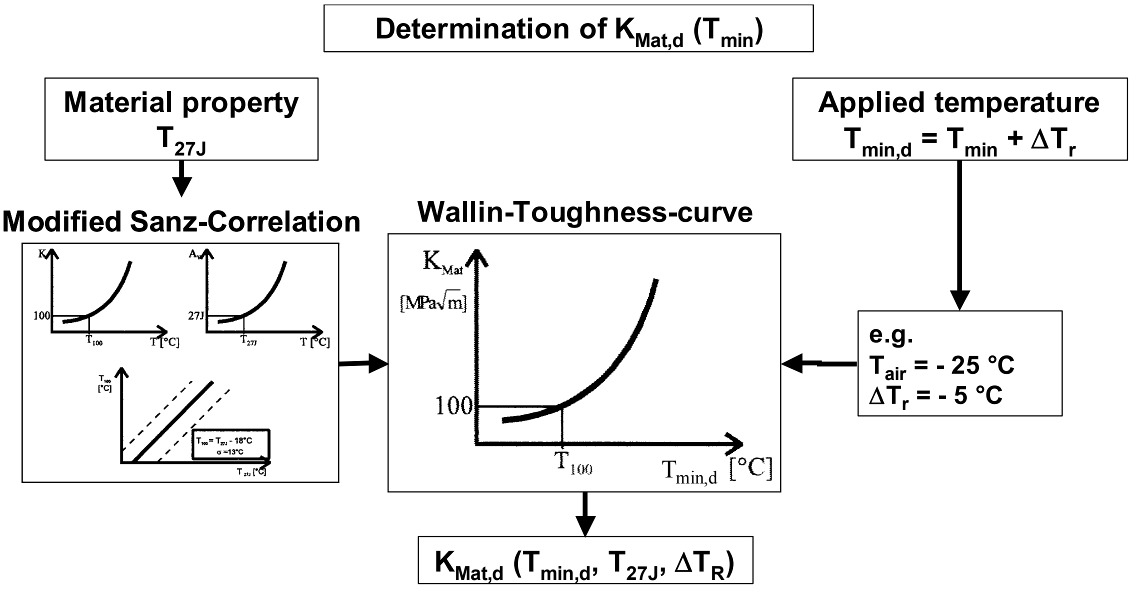


Figure 18: Resistance side of the toughness assessment [Sedlacek, Müller (2005)]

On the resistance side, the temperature for 27J derived from the Charpy impact test is transferred with the modified Sanz-Correlation ($T_{K100} = T_{27J} - 18°C$) in the T_{K100} temperature as input value for the Wallin-Toughness-curve. From this curve, the threshold value for brittle fracture $K_{mat,d}$ is finally derived for the assessment, see Figure 18.

As the assessment is now presented in terms of the K-values:

$$K^*_{appl,d} = \frac{K_{appl,d}}{k_{R6} - \tilde{n}} \leq 20 + \left[70 \left\{ \exp \frac{T_{Ed} - T_{27J} + 18°C + \Delta T_R}{52} \right\} + 10 \right] \left(\frac{25}{b_{eff}} \right)^{0.25} \tag{2}$$

A transformation in the temperature format needs to be carried out:

$$T_{Ed} - 52 \cdot \ln \frac{\left(K^*_{appl,d} - 20\right)\left(\frac{b_{eff}}{25}\right)^{0.25} - 10}{70} + \Delta T_R \geq T_{27J} - 18°C \tag{3}$$

resulting in the design check format as per EN 1993-1-10 for toughness requirement:

$$T_{Ed} \geq T_{Rd} \tag{4}$$

Hereby, all relevant parameters from the action and from the structure are included in T_{Ed}, whereas T_{Rd} contains the material properties from the tests only. The results of this assessment have been summarized and are presented in the EN 1993-1-10 by a table for permissible material thickness for the choice of the steel grade, see Table 3. This table represents therefore a simple design aid for the practising engineer.

Input parameters are hereby

- reference temperature T_{ed} in °C which can also be used to consider toughness reducing effects due to cold forming, impact loading by a fictive transformation of the reference temperature ($T^*_{Ed} = T_{Ed} - \Delta T_{Ed}$);
- the stress state σ_{Ed} assumes to occur simultaneously with the reference temperature;
- the steel grade in accordance to the delivery condition.

With the double checking according to Figure 2: on one side, the appropriate choice of the steel grade for the reference temperature in relation to the stress state to be in the transient region of the impact energy – temperature curve of the toughness; and on the other side, the resistance of the members according to EC3-1-1 in the upper region of the impact energy – temperature curve the safety requirements according to the Eurocodes, are both satisfied. As alternative methods to the simplified toughness assessment are presented above, the fracture mechanics method (in this method the design value of the toughness requirement should not exceed the design value of the toughness property) as well as the numerical evaluation (this may be carried out using one or more large scale test specimens) may be used in the Eurocode.

TABLE 3

SIMPLIFIED METHOD FOR THE DETERMINATION OF PERMISSABLE MATERIAL THICKNESSES FOR STANDARDIZED DETAILS [EN 1993-1-10, TABLE 2.1]

Steel grade	Sub-grade	Charpy energy CVN		Reference temperature T_{Ed} [°C]																				
		at T [°C]	J_{min}	10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50
				σ_{Ed} = 0,75 $f_y(t)$							σ_{Ed} = 0,50 $f_y(t)$							σ_{Ed} = 0,25 $f_y(t)$						
S235	JR	20	27	60	50	40	35	30	25	20	90	75	65	55	45	40	35	135	115	100	85	75	65	60
	J0	0	27	90	75	60	50	40	35	30	125	105	90	75	65	55	45	175	155	135	115	100	85	75
	J2	-20	27	125	105	90	75	60	50	40	170	145	125	105	90	75	65	200	200	175	155	135	115	100
S275	JR	20	27	55	45	35	30	25	20	15	80	70	55	50	40	35	30	125	110	95	80	70	60	55
	J0	0	27	75	65	55	45	35	30	25	115	95	80	70	55	50	40	165	145	125	110	95	80	70
	J2	-20	27	110	95	75	65	55	45	35	155	130	115	95	80	70	55	200	190	165	145	125	110	95
	M,N	-20	40	135	110	95	75	65	55	45	180	155	130	115	95	80	70	200	200	190	165	145	125	110
	ML,NL	-50	27	185	160	135	110	95	75	65	200	200	180	155	130	115	95	230	200	200	200	190	165	145
S355	JR	20	27	40	35	25	20	15	15	10	65	55	45	40	30	25	25	110	95	80	70	60	55	45
	J0	0	27	60	50	40	35	25	20	15	95	80	65	55	45	40	30	150	130	110	95	80	70	60
	J2	-20	27	90	75	60	50	40	35	25	135	110	95	80	65	55	45	200	175	150	130	110	95	80
	K2,M,N	-20	40	110	90	75	60	50	40	35	155	135	110	95	80	65	55	200	200	175	150	130	110	95
	ML,NL	-50	27	155	130	110	90	75	60	50	200	180	155	135	110	95	80	210	200	200	200	175	150	130
S420	M,N	-20	40	95	80	65	55	45	35	30	140	120	100	85	70	60	50	200	185	160	140	120	100	85
	ML,NL	-50	27	135	115	95	80	65	55	45	190	165	140	120	100	85	70	200	200	200	185	160	140	120
S460	Q	-20	30	70	60	50	40	30	25	20	110	95	75	65	55	45	35	175	155	130	115	95	80	70
	M,N	-20	40	90	70	60	50	40	30	25	130	110	95	75	65	55	45	200	175	155	130	115	95	80
	QL	-40	30	105	90	70	60	50	40	30	155	130	110	95	75	65	55	200	200	175	155	130	115	95
	ML,NL	-50	27	125	105	90	70	60	50	40	180	155	130	110	95	75	65	200	200	200	175	155	130	115
	QL1	-60	30	150	125	105	90	70	60	50	200	180	155	130	110	95	75	215	200	200	200	175	155	130
S690	Q	0	40	40	30	25	20	15	10	10	65	55	45	35	30	20	20	120	100	85	75	60	50	45
	Q	-20	30	50	40	30	25	20	15	10	80	65	55	45	35	30	20	140	120	100	85	75	60	50
	QL	-20	40	60	50	40	30	25	20	15	95	80	65	55	45	35	30	165	140	120	100	85	75	60
	QL	-40	30	75	60	50	40	30	25	20	115	95	80	65	55	45	35	190	165	140	120	100	85	75
	QL1	-40	40	90	75	60	50	40	30	25	135	115	95	80	65	55	45	200	190	165	140	120	100	85
	QL1	-60	30	110	90	75	60	50	40	30	160	135	115	95	80	65	55	200	200	190	165	140	120	100

As mentioned previously, fine grained steels as the HISTAR® thermomechanical grades exhibit a high toughness and therefore are perfectly suited for use in heavy sections.

The Code outlines the necessity to prevent brittle fracture. Similar to the Eurocode, the assessment procedure of the Code is also based on fracture mechanics approach – however, the assessment itself is more refined. In the simplified approach of the Eurocode, the toughness requirement is determined for longitudinal attachments, as this is known as the most severe detail. In the Code, the maximum allowable material thickness is assessed from the maximum basic thickness (for a specified minimum service temperature, 27J Charpy impact value and the strength grade of steel) multiplied by a K-factor (for type of joint detail, stress level and strain conditions). Therefore, the toughness assessment according to the Code may benefit from the consideration of the structural details investigated – however, advantages of higher toughness addressed by the Eurocode (subgrades, see Table 3) stay disregarded.

Through thickness properties

Lamellar tearing is a type of weld-cracking that occurs beneath a weld, see Figure 19. It may form when certain plate materials presenting low ductility in the thickness (or through) direction are welded to a perpendicular element. The failure by tearing is generally located within the base metal outside the heat-affected zone and parallel to the weld fusion boundary. The problem is caused by welds that the base metal is subjected to high shrinkage stresses in the thickness direction. The main parameter governing the deformation behavior in its through-thickness direction on the material side is the sulphur, contained as a residual element in the steel. However, it is known that only the deformation behavior and not the strength in through thickness direction can be improved by the steel manufacturing process.

Therefore, if necessary, lamellar tearing is avoided by the choice of the base material with adequate ductility in the thickness direction. This choice defines the quality class for through-thickness properties according to EN 10164 (2004), the Z-grade as special requirement in the steel designation (Z 15, Z 25, Z 35), see Figure 3, and should be selected depending on the consequences of lamellar tearing.

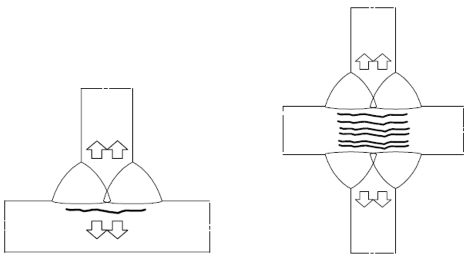


Figure 19: Lamellar tearing
[EN 1993-1-10 (2005)]

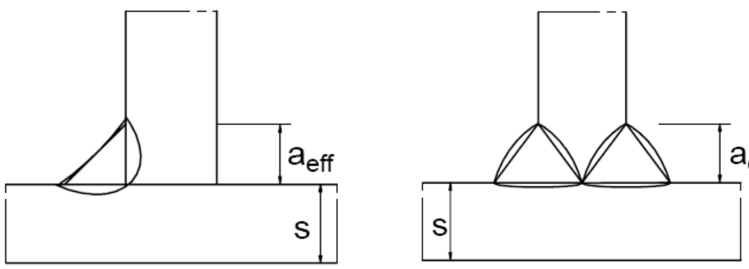


Figure 20: Effective weld depth a_{eff} for shrinkage
[Figure 3.2 of EN 1993-1-10 (2005)]

The following aspects should be considered in the selection of steel assemblies or connections to safeguard against lamellar tearing, see also Table 4:

- The criticality of the location in terms of applied tensile stress and the degree of redundancy.
- The strain in the through-thickness direction in the element to which the connection is made. This strain arises from the shrinkage of the weld metal as it cools. It is greatly increased where free movement is restrained by other portions of the structure.
- The nature of the joint detail, in particular the welded cruciform, tee and corner joints.
- Chemical properties of transversely stressed material. High sulphur levels, in particular, even if significantly below normal steel product standard limits, can increase the risk of lamellar tearing.

The susceptibility of the material should be determined by measuring the through-thickness ductility quality to EN 10164, which is expressed in terms of quality classes identified by Z-values. Lamellar tearing may be neglected if the following condition is satisfied according to EN 1993-1-10 (2005):

$$Z_{Ed} \geq Z_{Rd} \tag{5}$$

where Z_{Rd} is the available design Z-value for the material according to EN 10164 and
Z_{Ed} is the required design Z-value determined using:

$$Z_{Ed} = Z_a + Z_b + Z_c + Z_d + Z_e \tag{6}$$

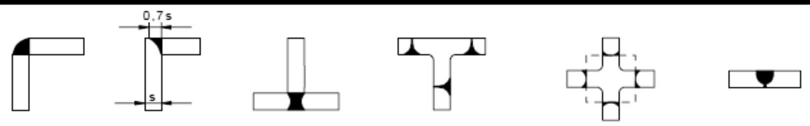
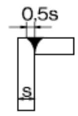
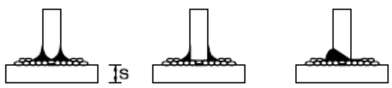
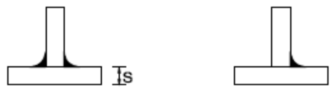
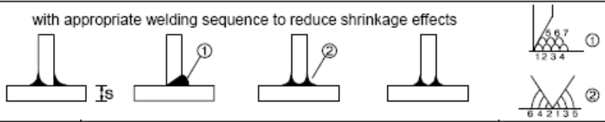
in which Z_a, Z_b, Z_c, Z_d and Z_e are as given in Table 4 and a_{eff} according to Figure 20.

The Code also addresses the properties of steel in the direction perpendicular to the product surface. In the Code, it is stipulated that for design stresses in through-thickness exceeding 90%, steel with guaranteed through-thickness properties shall be specified.

Consequently, lamellar tearing is in general not an issue in design if materials with an appropriate through-thickness quality produced with modern production techniques are chosen and if a rational design of the welds has been carried out. Further, the improved through-thickness properties are generally appreciated to mitigate the risk of lamellar tearing during fabrication only (which may typically occur after welding of heavily restrained welds on thick products) and to a lesser extent to mitigate the risk of fracture in service (e.g. columns of moment frames in seismic conditions).

TABLE 4

CRITERIA AFFECTING THE TARGET VALUE OPF Z_{ED} [TABLE 3.2 OF EN 1993-1-10 (2005)]

a)	Weld depth relevant for straining from metal shrinkage	Effective weld depth a_{eff} (see Figure 3.2) = throat thickn. a of fillet welds		$\mathbf{Z_i}$
		$a_{eff} \leq$ 7mm	a = 5 mm	$\mathbf{Z_a = 0}$
		$7 < a_{eff} \leq 10$mm	a = 7 mm	$\mathbf{Z_a = 3}$
		$10 < a_{eff} \leq 20$mm	a = 14 mm	$\mathbf{Z_a = 6}$
		$20 < a_{eff} \leq 30$mm	a = 21 mm	$\mathbf{Z_a = 9}$
		$30 < a_{eff} \leq 40$mm	a = 28 mm	$\mathbf{Z_a = 12}$
		$40 < a_{eff} \leq 50$mm	a = 35 mm	$\mathbf{Z_a = 15}$
		$50 < a_{eff}$	a > 35 mm	$\mathbf{Z_a = 15}$
b)	Shape and position of welds in T- and cruciform- and corner-connections			$\mathbf{Z_b = -25}$
		corner joints		$\mathbf{Z_b = -10}$
		single run fillet welds $Z_a = 0$ or fillet welds with $Z_a > 1$ with buttering with low strength weld material		$\mathbf{Z_b = -5}$
		multi run fillet welds		$\mathbf{Z_b = 0}$
		partial and full penetration welds		$\mathbf{Z_b = 3}$
		partial and full penetration welds		$\mathbf{Z_b = 5}$
		corner joints		$\mathbf{Z_b = 8}$
c)	Effect of material thickness *s* on restraint to shrinkage	$s \leq 10$mm		$\mathbf{Z_c = 2}$*
		$10 < s \leq 20$mm		$\mathbf{Z_c = 4}$*
		$20 < s \leq 30$mm		$\mathbf{Z_c = 6}$*
		$30 < s \leq 40$mm		$\mathbf{Z_c = 8}$*
		$40 < s \leq 50$mm		$\mathbf{Z_c = 10}$*
		$50 < s \leq 60$mm		$\mathbf{Z_c = 12}$*
		$60 < s \leq 70$mm		$\mathbf{Z_c = 15}$*
		$70 < s$		$\mathbf{Z_c = 15}$*
d)	Remote restraint of shrinkage after welding by other portions of the structure	Low restraint:	Free shrinkage possible (e.g. T-joints)	$\mathbf{Z_d = 0}$
		Medium restraint:	Free shrinkage restricted (e.g. diaphragms in box girders)	$\mathbf{Z_d = 3}$
		High restraint:	Free shrinkage not possible (e.g. stringers in orthotropic deck plates)	$\mathbf{Z_d = 5}$
e)	Influence of preheating	Without preheating		$\mathbf{Z_e = 0}$
		Preheating ≥ 100°C		$\mathbf{Z_e = -8}$

* May be reduced by 50% for material stressed, in the through-thickness direction, by compression due to predominantly static loads.

WELDABILITY OF MODERN STEEL GRADES

The weldability of steels highly depends on the hardenability of the steel, which is an indication of the prosperity to form martensite during cooling after heat treatment. The hardening of steel depends on its chemical composition, with greater quantities of carbon and other alloying elements resulting in a higher hardenability and thus a lower weldability. In order to be able to compare alloys made up of many distinct materials, a measure known as the equivalent carbon content (CEV) is used to evaluate the relative weldability of different alloys. As the equivalent carbon content rises, the weldability of the steel decreases. There is a trade-off between material strength and weldability: low alloy steels are characterised by a reduced resistance and higher alloying contents by a poor weldability. However, with the thermomechanical rolling process, high strength steel can be produced without substantial increase in the carbon equivalent and therefore, keeping an excellent weldability even for thick products. A comparison of the resulting carbon equivalent value for a normalised, thermomechanical rolled and HISTAR®steel over the material thickness is shown in Figure 21.

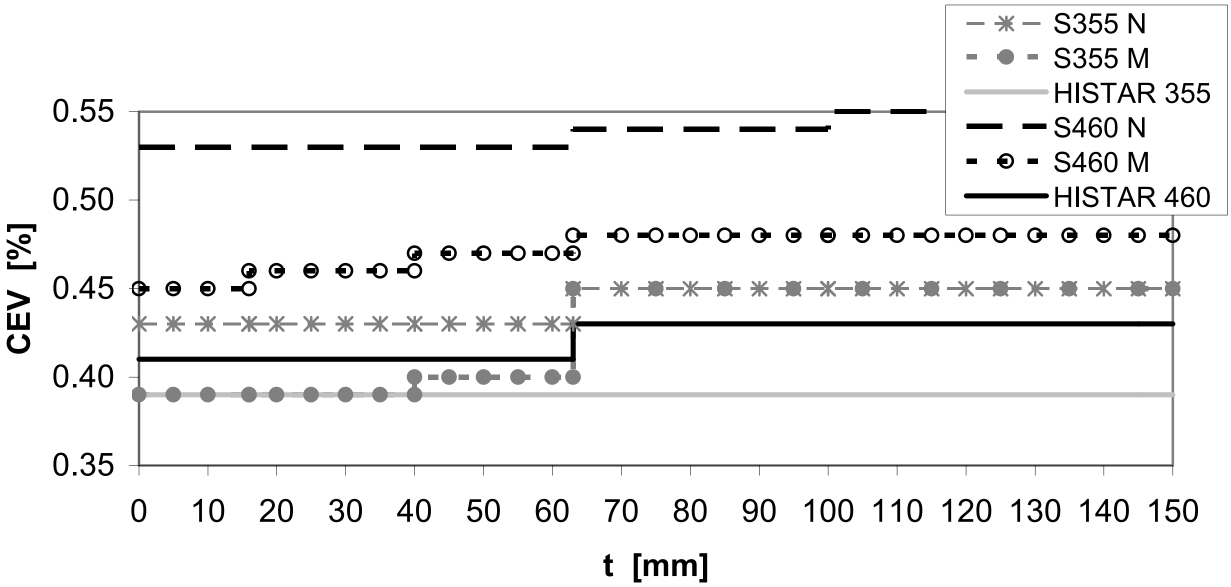


Figure 21: Comparison of the maximum CEV for nominal product thickness acc. to [EN 10025] with CEV of the HISTAR® steels

Hereby, the resulting carbon equivalent values have been calculated as follows:

$$CEV = C + Mn / 6 + (Cr + Mo + V) / 5 + (Ni + Cu) / 15 \quad (5)$$

Consequently, thermomechanical rolled steels with a reduced carbon equivalent value do simplify the welding. The forming of martensite, however, can be avoided using preheating which increases the $t_{8/5}$-time during welding but decreases the productivity of the welding workshop. Due to the low carbon equivalent value of HISTAR® steels, welding of structural sections with flange thicknesses up to 125mm thickness is even possible without preheating in ambient temperature > 0°C, see Figure 22.

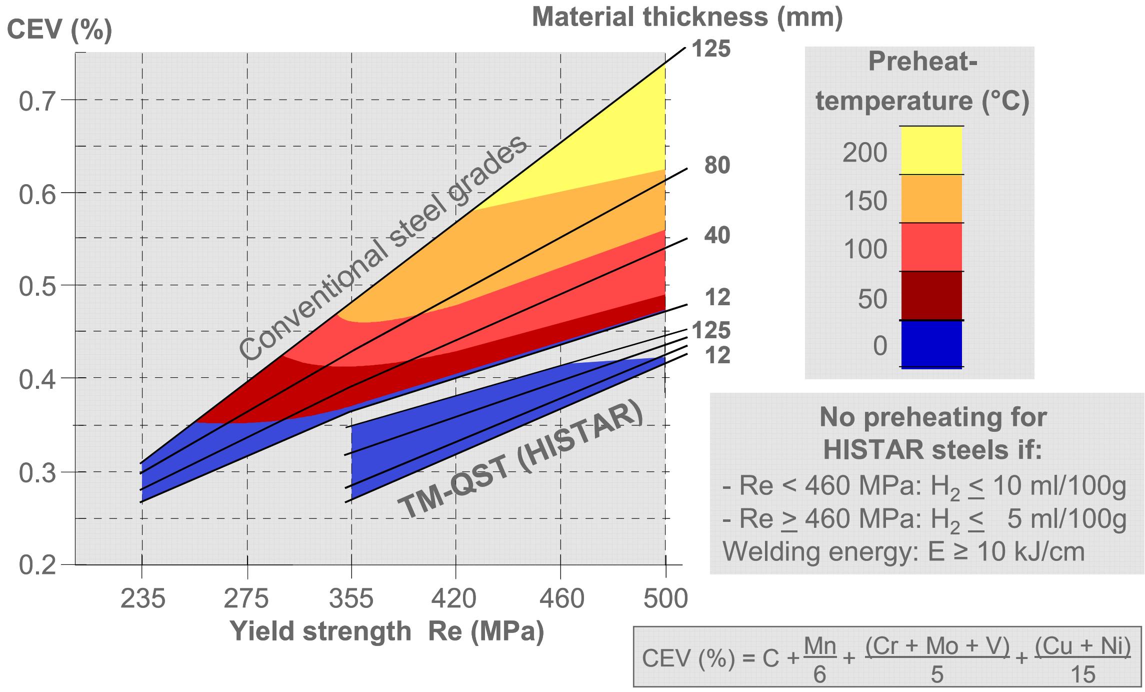


Figure 22: Weldability and preheat temperatures (EN 1011-2)

As a result, a remarkable gain in economy is achieved. For example, the welding of a column with an HD 400 x 1086 section with a flange thickness of t_f = 125 mm and a web thickness of t_w = 78 mm, 140 passes are required for a full penetration weld, talking about 8 hours of welding, see Figure 23. For example, for normalized S355 steel, preheating is required to 110°C which consumes an additional 4 hours. With the use of thermomechanical steel in HISTAR® quality by ArcelorMittal, consequently 1/3 of the welding time can be saved. Further welding becomes much more convenient for the welder.

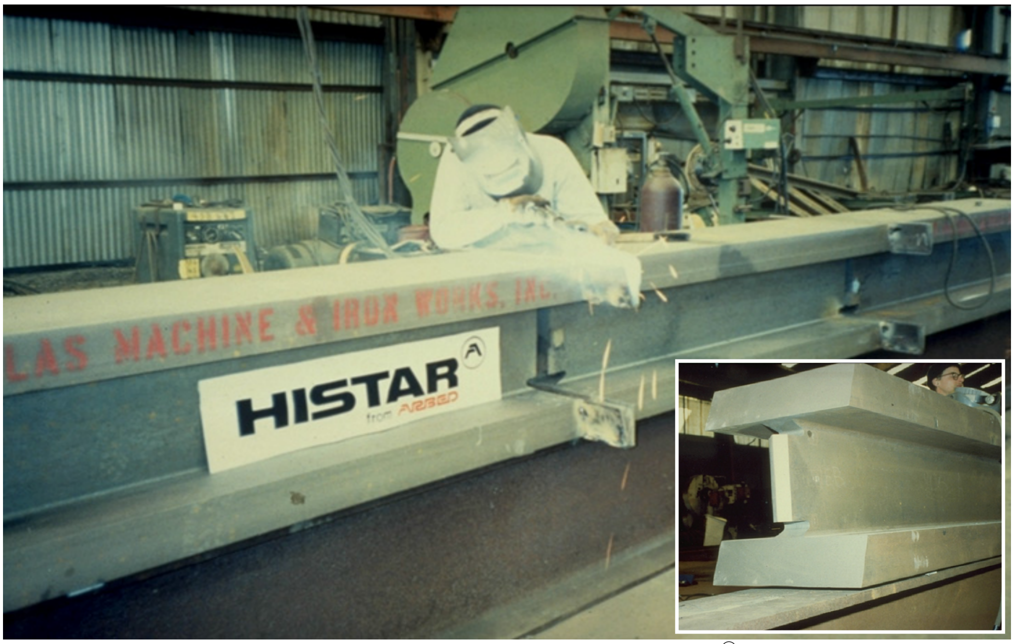


Figure 23: Welding of a column HD 400 x 1086 kg/m in HISTAR® 460 (t_f = 125 mm, t_w = 78 mm)

Weldability is also addressed in the Code by limiting the carbon content to 0.24%, the sulphur and phosphor content to 0.03% and the carbon equivalent value to 0.48%. For steels according to the EN 10025-4 (2004) and HISTAR® , these requirements are satisfied and they can therefore be used.

FURTHER FABRICATION OF MODERN FINE GRAIN STEELS

European recommendations about shaping of structural steels are given in document TR 10347 (2006). In essence, the following is mentioned therein:

- Cold forming
  Structural steel grades can be cold-formed regardless whether their delivery condition AR, N, or M. Cold forming decreases ductility of steel and increases its yield strength (valid for all grades), see Figure 13. Straining requirements for certain bending radius/thickness and the plate thickness are stipulated in EN 1993-1-8.
- Hot-forming
  M grades are not dedicated to hot-forming. Only N grades can be hot formed. N grades have to be renormalized after hot forming. Hot forming (rerolling, hot bending) is not economical and very rarely applied to long products (i.e. beams).
- Heat straightening
  Heat straightening is used in fabrication of steel to remove or give a structural component a certain shape. It is carried out by a fast and short heating of the steel locally with oxy-acetylen burners. If needed, to increase the effectiveness of the process, additional restraint is applied, i.e. by means of hydraulic jacks, clamping or a dead load. Recommended maximum flame straightening temperatures to be respected are according to Table 5 [Table 2 from TR 10347 (2006)]. The table shows that up to grade S460, the same maximum value of flame-straightening temperature for N (normalized) steels as for M (thermomechanical) steels applies.

TABLE 5

RECOMMENDED MAXIMUM VALUES OF THE FLAME-STRAIGHTENING TEMPERATURE

[TABLE 2, TR 10347 2006]]

Delivery condition	Recommended maximum values of the flame-straightening temperature		
	Short superficial heating °C	Short full section heating °C	Full section heating with longer holding time °C
normalized	≤ 900	≤ 700	≤ 650
thermomechanical rolled up to S460	≤ 900	≤ 700	≤ 650
thermomechanical rolled S500 to S700	≤ 900	≤ 600	≤ 550
quenched and tempered	≤ tempering temperature applied to the original product – 20 K (generally below 550 °C)		

- Post weld heat treatment (PWHT)
  In addition to CEN TR 10347, it should be noted that if stress relieving (PWHT) is required, which is generally uncommon in fabrication of structural steel shapes, the same recommendations apply to structural steels, regardless of the delivery conditions AR, N and M. The generally recommended PWHT procedures are to apply temperatures between 530 to 580 °C and a holding time of 2 minutes per mm product thickness, but not less than 30 minutes and not more than 90 minutes.

With regard to their technological properties, the thermo-mechanically rolled steels have therefore good cold-forming properties. Similar to conventional structural steels, they can be flame straightened provided specific maximum temperatures are not exceeded. In case stress relieving is considered for reducing residual stresses, the usual parameters concerning temperature range and heating time according to the rules of practice must be applied. Hot-forming, which is however uncommon for the fabrication of sections, must not be performed.

EXAMPLE OF THE APPLIANCE OF MODERN STEELS IN HIGH RISE BUILDINGS

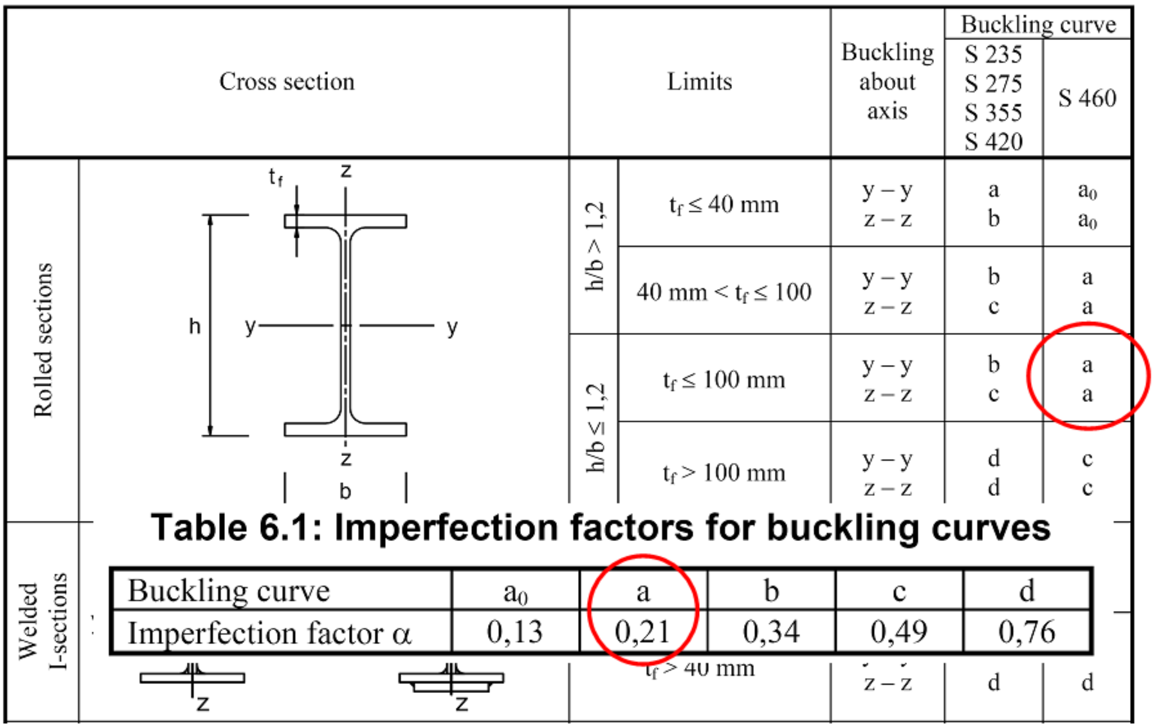
The advantages of the application of HISTAR® high strength steels can be perfectly demonstrated on two similar buildings in the Spanish city of Barcelona, see Figure 24.

Both 40-storey buildings consist of the same structural concept, similar dimensions and a comparable base grid. As a result, the values of the column loads resulting from dead load and life loads are comparable for the same type of column of every building.

While the structural steel construction of the first erected building is fabricated based on S 355 steel grade, the later erected second building is made of HISTAR®460. The result is significant: For the highest loaded columns in the lower part of the building, the column weight of the HISTAR®460 columns is reduced by 28% compared to those of S 355.

The higher yield strength of the HISTAR®460 steel is not the only reason for the same column capacity of the lighter section: Because of the controlled fabrication process resulting in lower imperfections, EN 1993-1-1 (2005) classifies hot rolled sections in S460 / HISTAR®460 in buckling curve a or a_0, see Figure 25, depending on the sections dimension. The second effect is through reduced dimensions and plate thicknesses due to higher allowable stresses, S 460 / HISTAR®460 are already in the more favourable range for the buckling curves definition.

Figure 24: Hotel Olympia (S 355) and Mapfre Tower (HISTAR®460) in Barcelona, Spain



Cross section		Limits		Buckling about axis	Buckling curve S 235, S 275, S 355, S 420	Buckling curve S 460
Rolled sections		h/b > 1,2	$t_f \leq 40$ mm	y – y z – z	a b	a_0 a_0
			40 mm < $t_f \leq 100$	y – y z – z	b c	a a
		h/b ≤ 1,2	$t_f \leq 100$ mm	y – y z – z	b c	a a
			$t_f > 100$ mm	y – y z – z	d d	c c
Welded I-sections			$t_f > 40$ mm	z – z	d	d

Table 6.1: Imperfection factors for buckling curves

Buckling curve	a_0	a	b	c	d
Imperfection factor α	0,13	0,21	0,34	0,49	0,76

Figure 25: Choice of column buckling curves according to EN 1993-1-1 (2005)

These effects give the most favourable results with the biggest economical advantages for high loaded columns with usual buckling length of 3-4m (one storey floor to floor height). For the above given example, globally 24% weight reduction for all columns are achieved, see Figure 26.

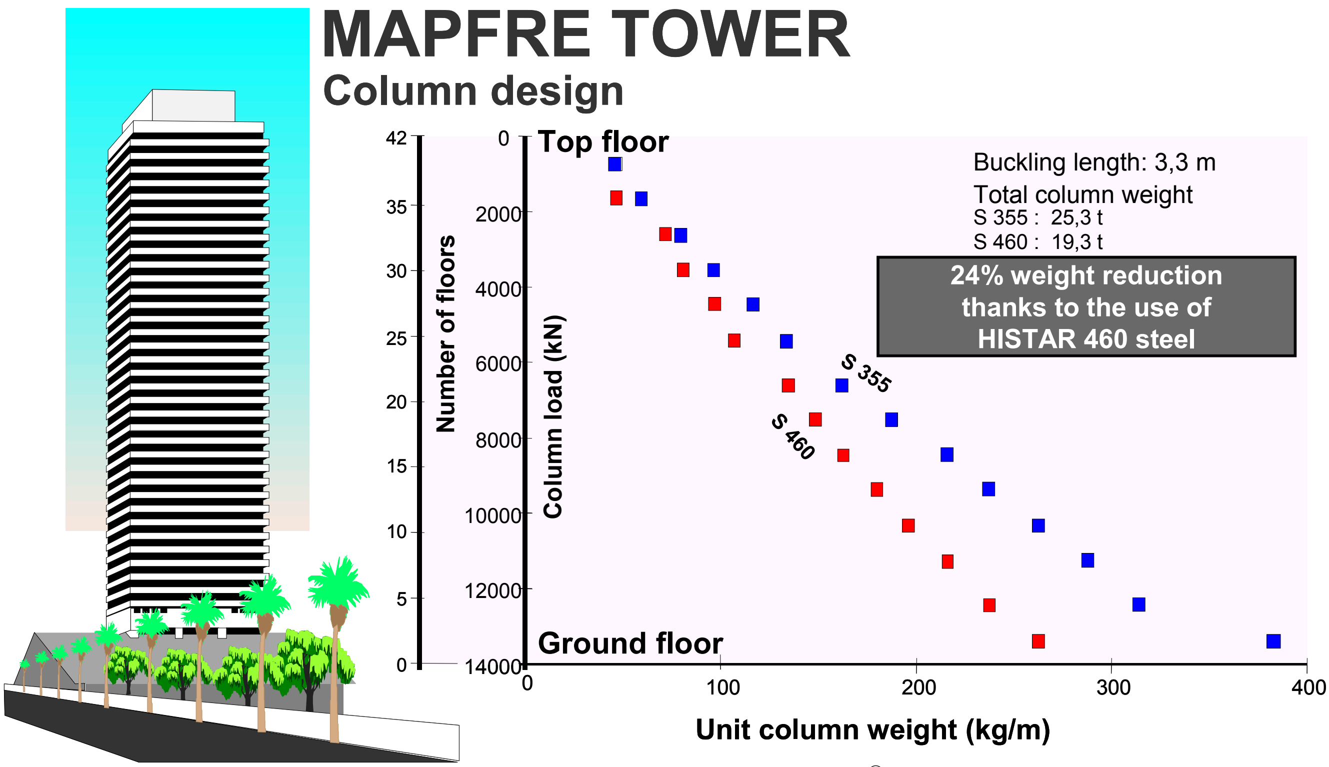


Figure 26: Column weight comparison of S355 to HISTAR®460 for the Mapfre Tower

SUMMARY

The European practice for the right choice of the steel grade is ruled in Eurocode EN1993-1-1, which defines requirements on the mechanical material properties, ductility, toughness properties and through-thickness properties. In this paper, the requirements have been described and discussed. With reference to these requirements, modern hot-rolled structural sections, which are produced by precise control of the temperature during the rolling process, have been introduced. These steels, produced using thermo-mechanical rolling according to EN 10025-4 (2004), feature improved toughness values which give lower carbon equivalent values and a fine grained microstructure when compared with normalised steels. Further, high performance steel grades are available, e.g. the HISTAR® by ArcelorMittal. The high yield strength, good toughness at low temperatures and excellent weldability of HISTAR® steels make them a cost-effective choice, in particular for the design of multi-storey buildings, large span trusses and heavily loaded industrial construction. Compared with basic steels, these exceptional mechanical properties can reduce the construction weight by 25-50 %, depending on structural layout and can provide high strength and exceptional durability.

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