HIGH STRENGTH STEELS IN STEEL CONSTRUCTION

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Abstract

The new European unified technical design rules for steel structures in Eurocode 3 are applicable to steels S235 to S460. It is intended to extend these rules in a second step to steels S690 and other high strength steels to benefit from the weight saving and reduced fabrication costs of using thin plates. In this contribution some problems in preparing design rules for high strength steels are presented and solutions are given for steels S460 and also for S690 for some applications. These solutions are mainly based on the results of large scale tests for which the Eurocodes provide a standardised evaluation method to achieve sufficient reliability.

Eurocodes: Building Code for Europe

The Eurocodes will become the Europe wide means of designing Civil and Structural engineering works and so, they are of vital importance to both the design and construction sectors of the Civil and Building Industries.

The work of drafting the Eurocodes was originally under the aegis of the Commission, but was transferred to CEN as the official European standards body. After an Examination period, when CEN published versions of the Eurocodes as pre-standards (ENV's), they are now nearing the completion of the conversion to full European Standards (EN).

The Eurocode for steel construction is Eurocode 3. It comprises the EN 1993-series as given in Figure 1. Part 1 of Eurocode 3 contains generic rules to be applicable to various application fields and also specific rules for buildings, Parts 2 to 6 give supplementary rules for bridges, masts, chimneys and towers, silos, tanks and pipelines, piles and sheet piling and crane supporting structures.

EN 1993: Eurocode 3 - Design of steel structures		
Part 1	General rules and rules for buildings	
	Part 1.1	General rules and rules for buildings
	Part 1.2	Structural fire design
	Part 1.3	Cold formed thin gauge members and sheeting
	Part 1.4	Stainless steels
	Part 1.5	Plated structural elements
	Part 1.6	Strength and stability of shell structures
	Part 1.7	Strength and stability of planar plated structures transversally loaded
	Part 1.8	Design of joints
	Part 1.9	Fatigue strength of steel structures
	Part 1.10	Selection of material for fracture toughness and through thickness properties
	Part 1.11	Design of structures with tension elements made of steel
Part 2	Steel Bridges	
Part 3	Towers, masts and chimneys	
	Part 3.1	Towers and masts
	Part 3.2	Chimneys
Part 4	Tanks, silos and pipelines	
	Part 4.1	Tanks
	Part 4.2	Silos
	Part 4.3	Pipelines
Part 5	Piling	
Part 6	Crane Supporting Structures	

Figure 1: Eurocode 3 and its parts.

The generic rules in Part 1 are restricted to steel grades from S235 to S460. However, some rules also apply to S690. There is a strong request to extend the scope further for other high strength steels. This would include weldable steels up to grade S960, in particular for the use in light weight structures as for frames of vehicles or mobile cranes or temporary bridges, Figure 2, and also when thick plates can be avoided in permanent steel structures.

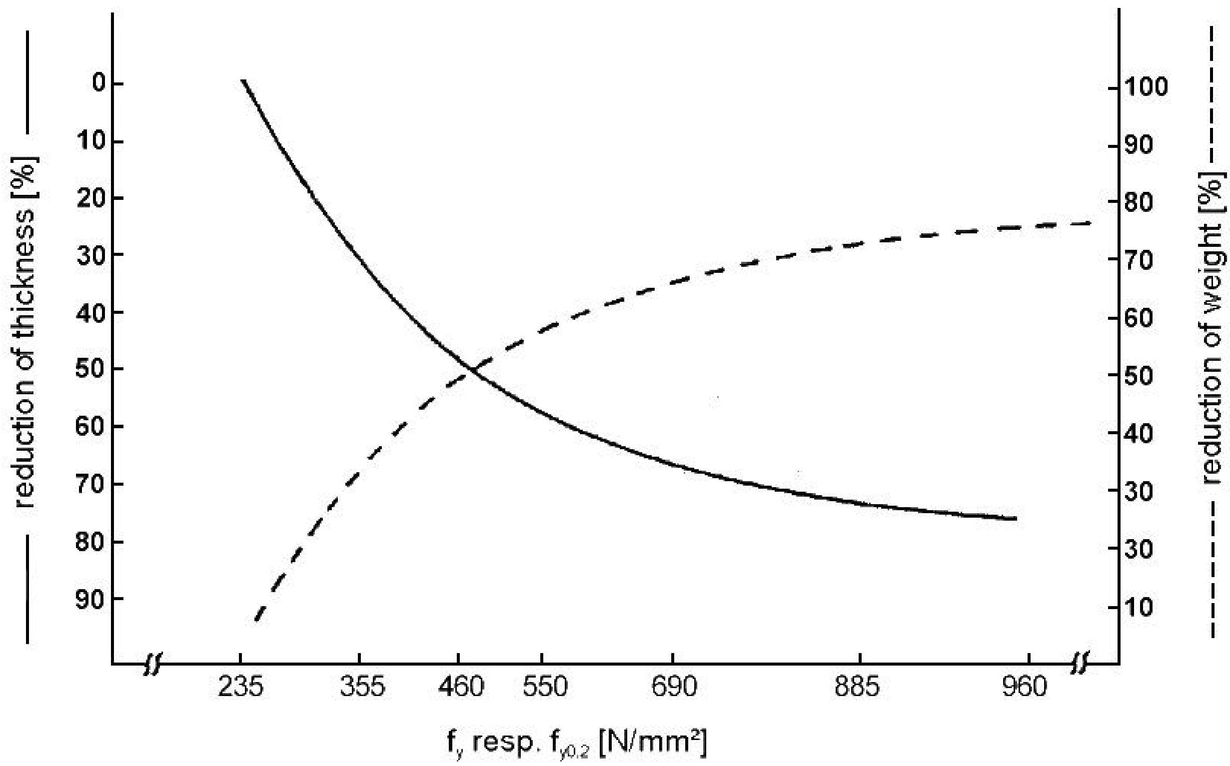


Figure 2: Reduction of wall thickness and weight with increasing strength of steel.

It is therefore of particular concern to see what phenomena of high strength steels may require other design rules than those given in Eurocode 3 – Part 1 for steels up to grade S460.

The true stress-strain curves for all steel grades look similar and only differ by a parallel shift controlled by the yield strength f_y, Figure 3.

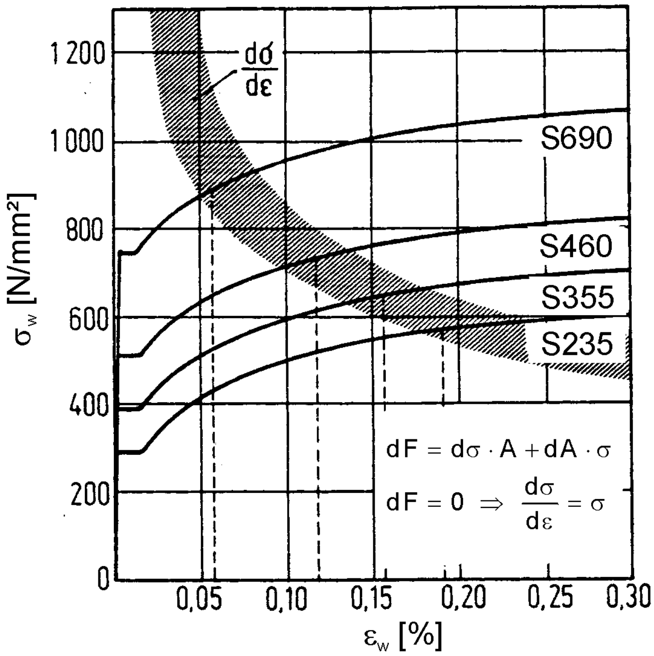


Figure 3: True stress strain lines for different steel grades.

The ultimate tensile strengths f_u obtained from tensile coupon tests, Figure 4 result from the stability criterion

$$\delta A \cdot \sigma_w - \delta\sigma \cdot A = 0 \tag{1}$$

for the load deflection curve. Therefore the true strain e_u associated with the tensile strength f_u is the smaller the higher the strength f_u is, Figure 5.

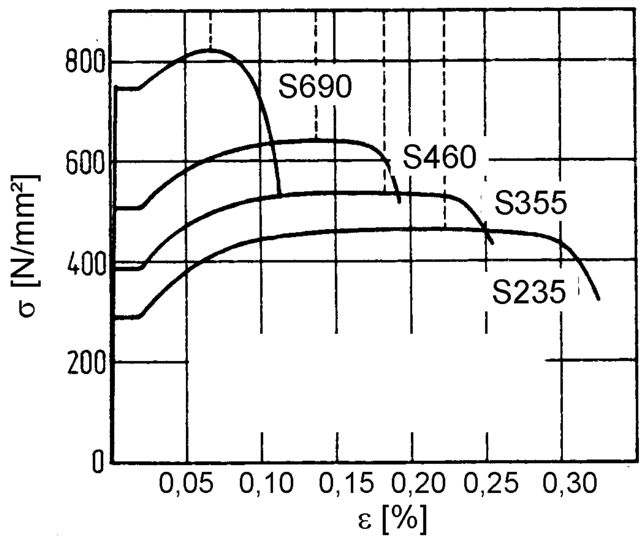


Figure 4: Load-deflection lines for different steel grades.

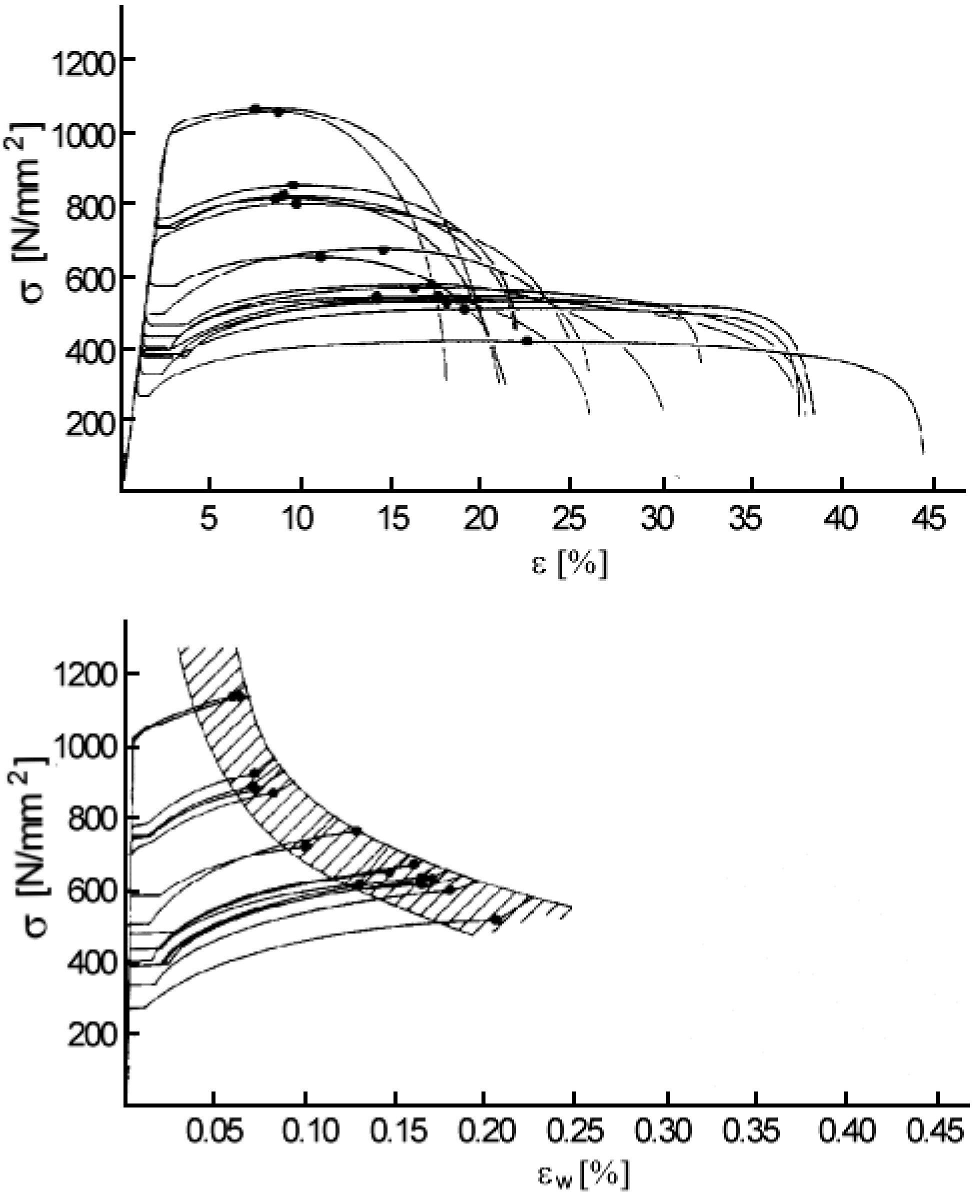


Figure 5: Stress strain lines and true stress strain lines for different steel grades.

This is why high strength steels are considered to be more sensitive than ordinary steels, when high local ductility demands from the structural detailing have to be fulfilled from the material.

A certain minimum ductility of material is assumed to be available in the design rules for ultimate limit state verifications for steel grades up to S460, where, Figure 6

- secondary moments at connections and joints of welded trusses or lattice girders that result from restraints to deformations are disregarded and hinged connections are assumed instead as models for the calculations,
- residual stresses from the production or welding are neglected,
- the notch effects on the strain field from geometric notches, welds, holes, etc. are disregarded and nominal stresses (linear mean stress distributions) are used,
- simplified assumptions are made for plastic distributions of stresses in cross-sections (stress bloc distributions) or forces in connections (equal distributions of forces to bolts in bolt groups with hole clearances or constant shear distributions in fillet welds),

- full unlimited plastic rotation capacity is assumed in “plastic hinges” to achieve economical moment redistributions in frames by plastic hinge actions.

For steel grades S235 to S460 it is assumed that because of yielding resulting from a sufficiently large yielding plateau and strain hardening on the stress-strain-curve these phenomena have no effects on the ultimate limit state behaviour of structural components.

High strength steels with grades higher than S460 are therefore excluded from the general design rules in Eurocode 3 and also indirectly limitations were given by specifying the yield strength ratio $\frac{f_u}{f_y}$ to

$$\frac{f_u}{f_y} \geq 1{,}10 \tag{2}$$

There is however a working group preparing “Recommendations for the design of structures made of high strength steels” that in a later stage shall be implemented into the Eurocodes.

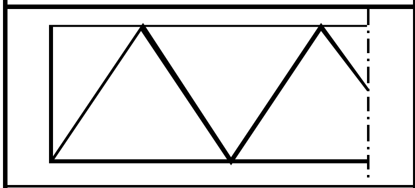
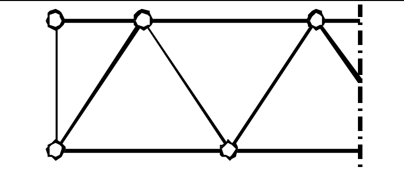
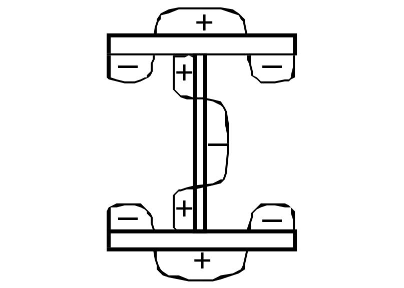
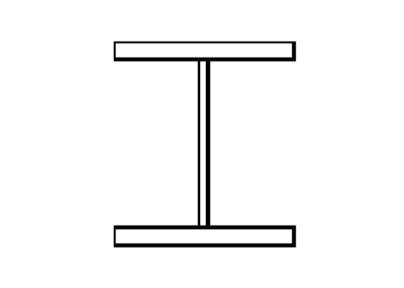
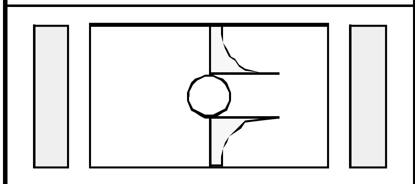
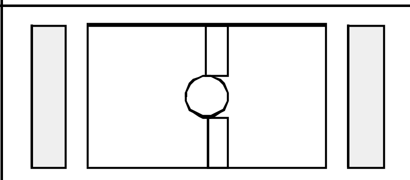
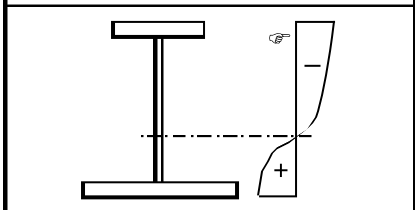
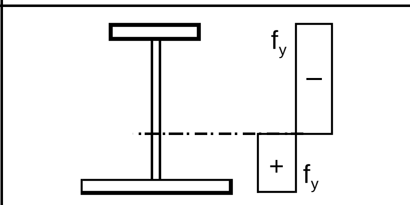
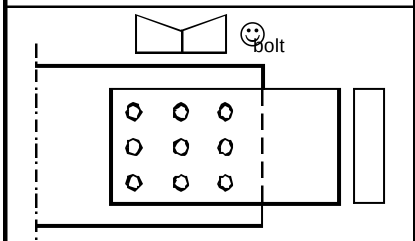
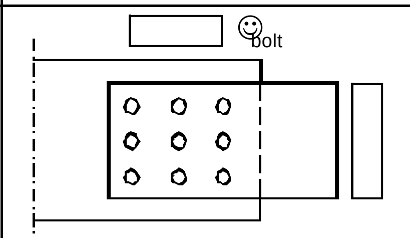
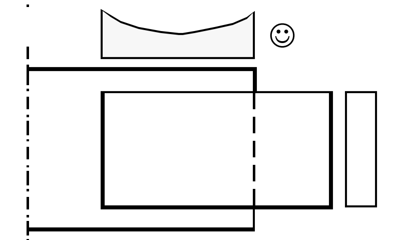
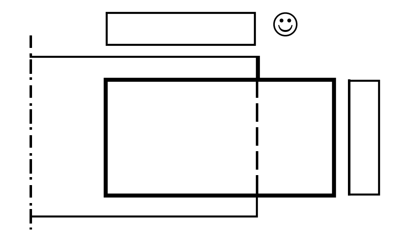
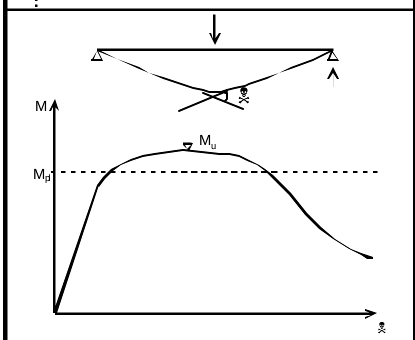
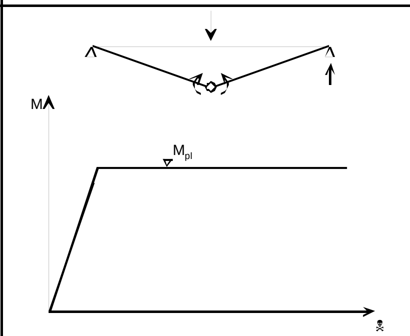
Actual structure	Modelling	Neglected effects
		Local restraints due to deformations
		Residual stresses due to fabrication and erection
		Stress concentration factors
		Limitations of stress blocks due to ultimate tension strains
		Unequal distribution of forces in bolts
		Unequal distribution of forces in welds
		Limits of rotation capacity due to ultimate tension strains

Figure 6: Neglected effects justified by ductility.

Figure 7 gives a survey on the resistances in design rules that are related to the yield strength f_y, the tensile strength f_u and the yield strength ratio $\frac{f_u}{f_y}$ that have been investigated for steel grade S460. These also need to be considered for higher steel grades to include them in the Eurocodes.

Material property	Related resistance
Toughness	– Brittle fracture
Tensile strength f_u	– Net section resistance – Bearing resistance – Fillet welds
Yield strength f_y	– Buckling of plates – Buckling of columns – Other buckling phenomena
Yield strength ratio $\frac{f_u}{f_y}$	– Rotation capacity – Sensivity to discontinuities

Figure 7: Survey on resistances related to material properties.

In the following some of these investigations and their results are presented.

In preparing the results advantage was taken from a standardised way of evaluating test results, to obtain characteristic values of resistances and partial factors $?_M$ needed to get design values. Partial factors $?_M$ are “Nationally Determined Parameters” that are in the responsibility of member states; therefore they are only recommended values.

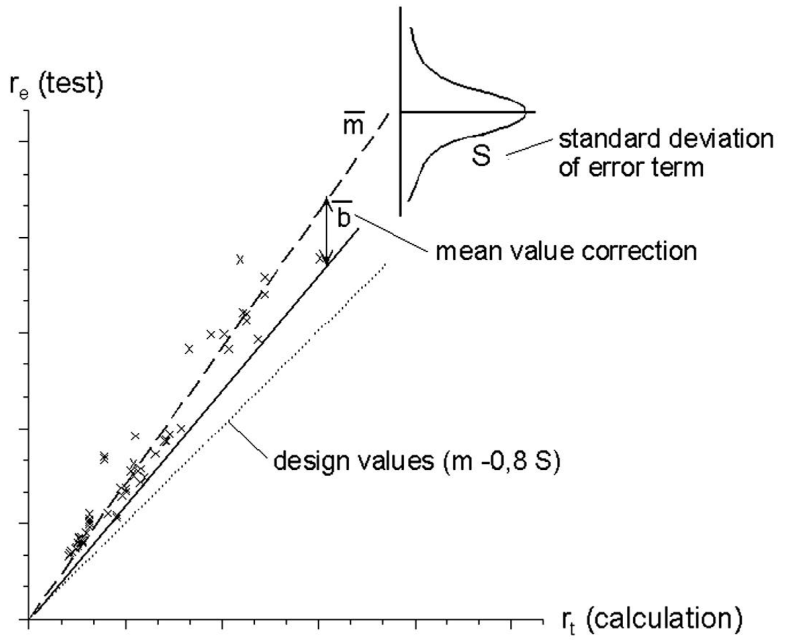


Figure 8: Principle of test evaluation procedure according to Annex D of EN 1990 – Basis of design.

The principle of the evaluation method is given in Figure 8: From a comparison of the calculative results from a suitable resistance formula with the test results a mean value correction factor and the standard deviation of the “error” were determined. From these data both the characteristic value of the resistance formula and the recommended partial factor can be derived.

This standardised method is given in Annex D – Design assisted by testing – of EN 1990 – Basis of structural Design.

Choice of Material to Avoid Brittle Fracture

Rules for the choice of material to avoid brittle fracture are given in EN 1993-1-10.

Figure 9 gives a table with permissible plate thicknesses depending on the lowest service temperature T_{Ed} and the stresses s_{Ed} applied and the steel grade and steel subgrade. S690 steels are included.

The stresses s_{Ed} are those from permanent loads and “frequent” variable loads as defined in Eurocode 1 – Actions on structures.

The table in Figure 9 is based on a safety assessment using fracture mechanics:

$$K^{*}_{appl,d} \leq K_{mat,d} \qquad (3)$$

where $K^{*}_{appl,d}$ (stress intensity factor) is the design value of the action effect and $K_{mat,d}$ is the design value of the toughness resistance.

$K^{*}_{appl,d}$ is determined for representative sizes of surface cracks including crack growth by fatigue, with a correction for plastic strains, figure 10. It covers all details given in EN 1993-1-9 – Fatigue rules.

Steel Grade	Sub-Grade	Charpy Energy CVN		REFERENCE TEMPERATURE T_{Ed} IN °C																				
		at T°C	Jmin.	10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50
				$\sigma_{Ed} = 0.75 \times f_y(t)$							$\sigma_{Ed} = 0.50 \times f_y(t)$							$\sigma_{Ed} = 0.25 \times f_y(t)$						
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	60	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	95	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	110	110	95	80	65	55	200	200	175	150	130	110	95
	ML, NL	-50	27	155	130	110	90	75	60	50	200	155	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	100	100	85	70	60	50	200	185	160	140	120	100	85
	ML, NL	-50	27	135	115	95	80	65	55	45	190	140	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	30	30	25	20	15	10	10	65	55	45	35	30	20	20	120	100	85	75	90	50	45
	Q	-20	30	40	40	30	25	20	15	10	80	65	55	45	35	30	20	140	120	100	85	75	60	50
	QL	-20	40	50	50	40	30	25	20	15	95	80	65	55	45	35	30	165	140	120	100	85	75	60
	QL	-40	30	60	60	50	40	30	25	20	115	95	80	65	55	45	35	190	165	140	120	100	85	75
	QL1	-40	40	75	75	60	50	40	30	25	135	115	95	80	65	55	45	200	190	165	140	120	100	85
	QL1	-60	30	90	90	75	60	50	40	30	160	135	115	90	80	65	55	200	200	190	165	140	120	100

Figure 9: Table of permissible plate thicknesses for various steel grades and subgrades, temperatures of component T_{Ed} and stresses σ_{Ed} from frequent load combinations (from EN 1993-1-10).

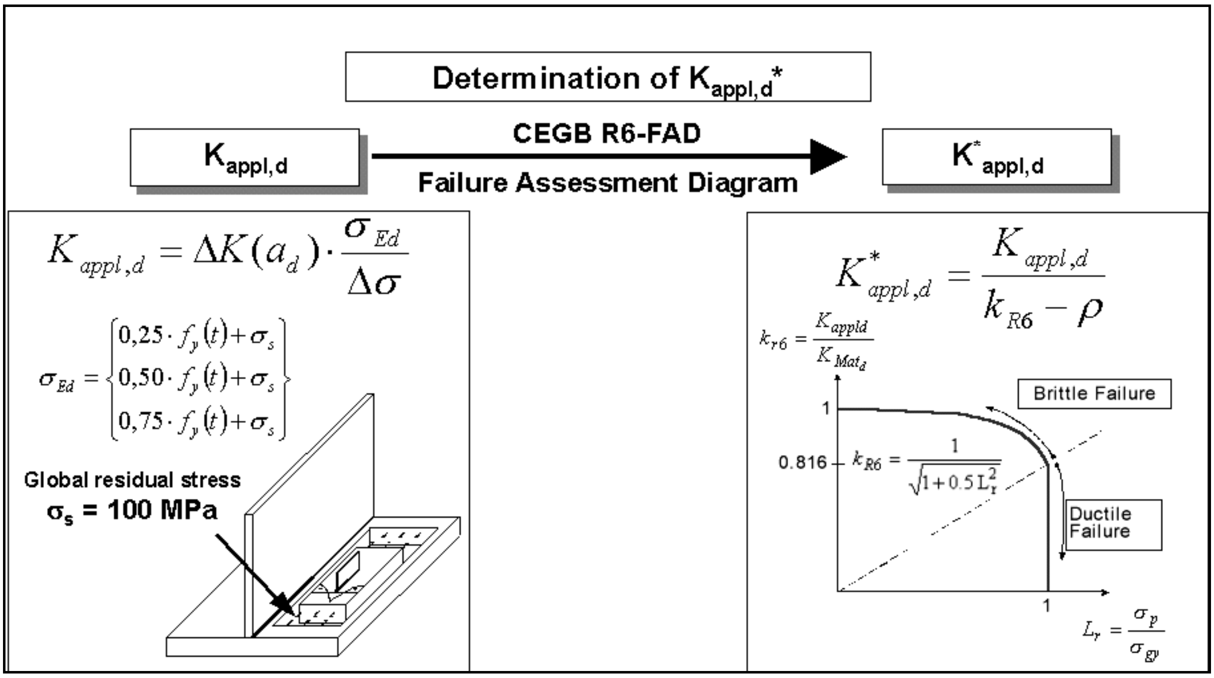


Figure 10: Determination of action effect $K^*_{appl,d}$.

For the toughness resistance $K_{mat,d}$ the Wallin-Master-Curve and the Sanz Correlation have been used to relate the assessment to the test temperature T_{27J} at which the minimum impact energy $A_V(T)$ = 27J to fracture a Charpy V-notch specimen is required, Figure 11.

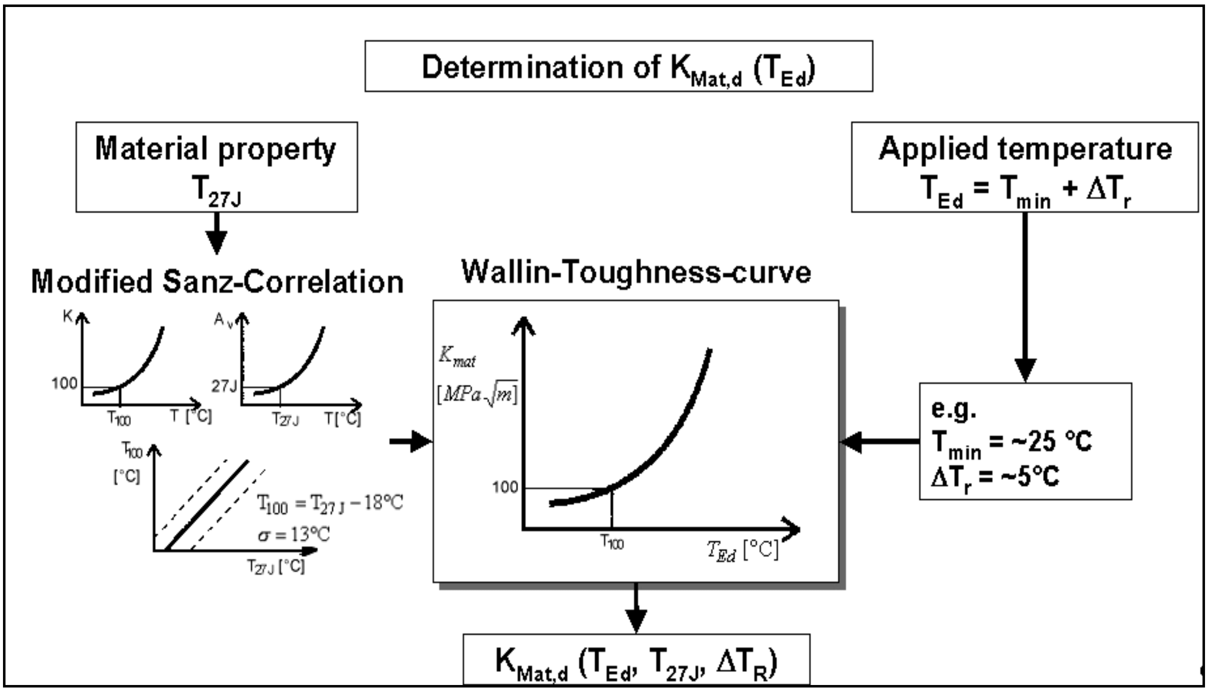


Figure 11: Determination of toughness resistance $K_{mat,d}$.

In order to check the reliability of the assessment method large-scale tests were carried out to identify the safety related correction values, figure 12.

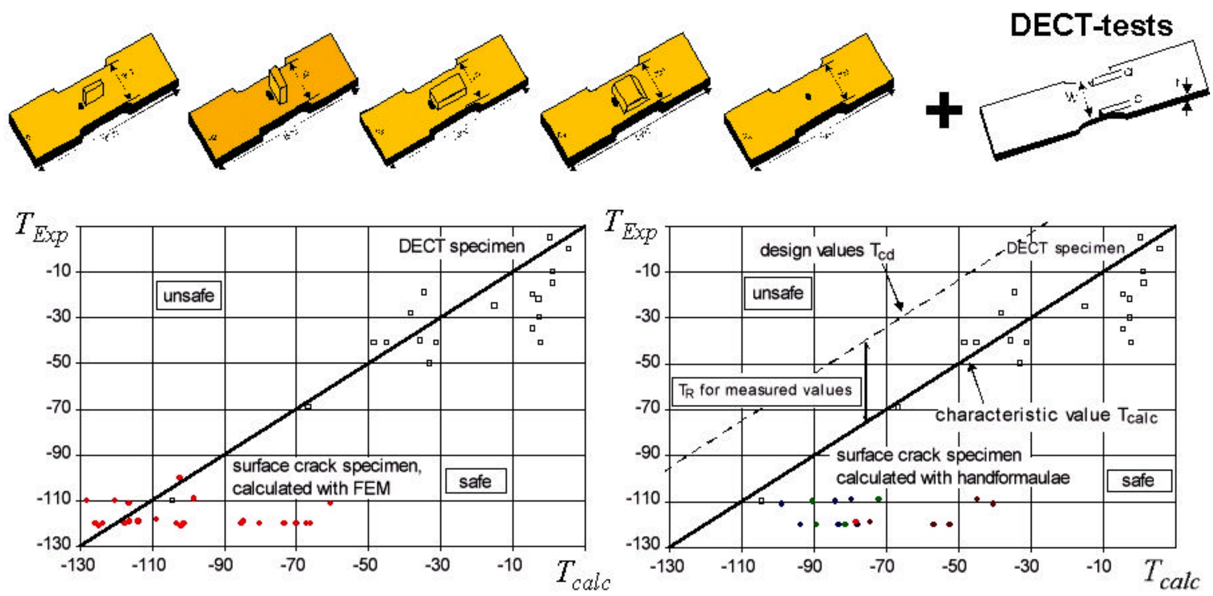


Figure 12: Comparison of calculated values and test values to determine safety elements.

Design Rules Based on the Tensile Strength

<u>Net section Tensile Resistance</u>

The design rules related to the tensile strength f_u are those for the strengths of net sections in bolted connections, for the bearing resistance of bolted connections and the resistance of fillet welds.

The applicability of the net section resistance for steel grade S460 has been verified by the evaluation of wide plate tests with initial cracks and of tests with bolted connections, see Figures 13 and 14.

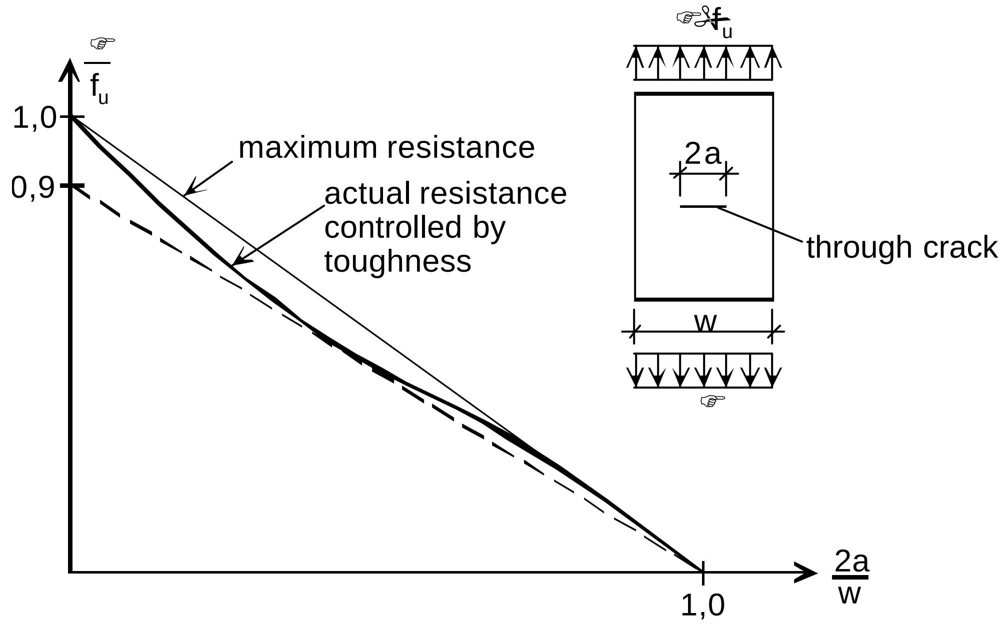


Figure 13: Interpretation of factor 0,9 in the resistance of net sections.

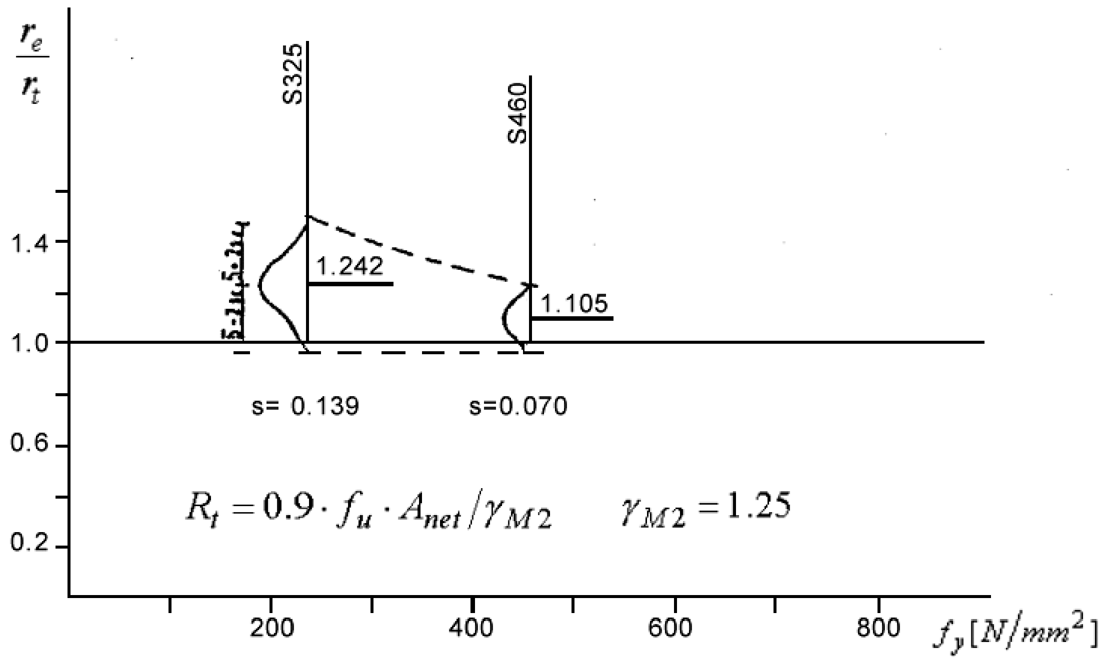


Figure 14: Comparison between the result of the statistical evaluations for the steels S235 and S460.

Bearing Resistance of Bolted Connections

The evaluation of the bearing resistance of bolts which comprises both a shear type and a bending type failure with fracture, has shown that the strength formula in Eurocode 3, Part 1-8 are applicable for steel grades up to S690, Figure 15.

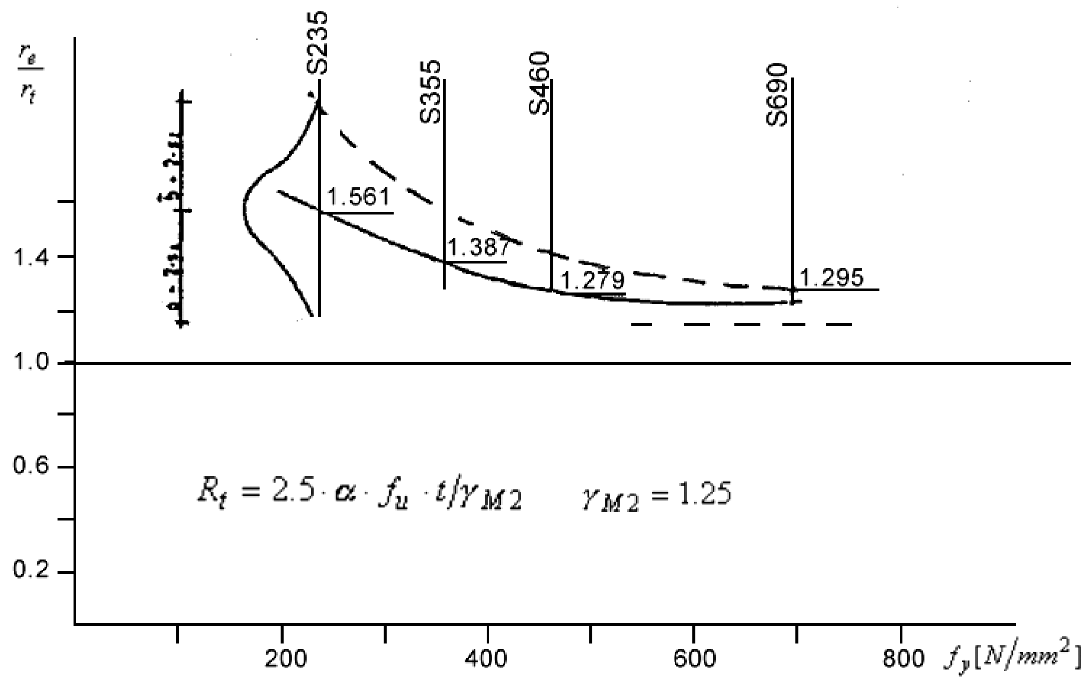


Figure 15: Comparison between the result of the statistical evaluations for the steels S235, S355, S460 and S690.

<u>Strength of Fillet Welds</u>

Tests have been conducted with various weld-configurations with overmatching electrodes for steels up to S460 as indicated in Figure 16.

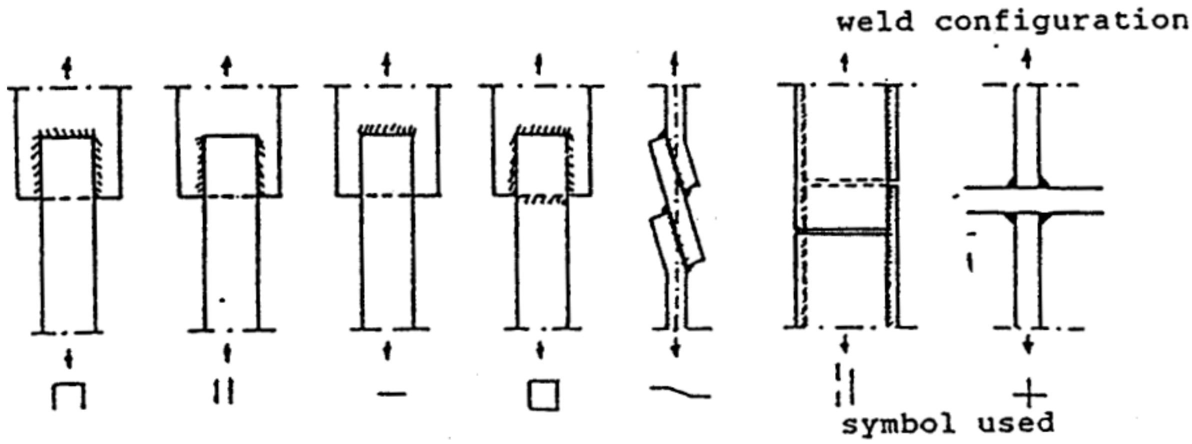


Figure 16: Samples tested.

Figure 17 demonstrates the results of the test evaluation, which justify the use of the strength formula in Eurocode 3 – Part 1-8 for fillet welds with a modified model factor ß.

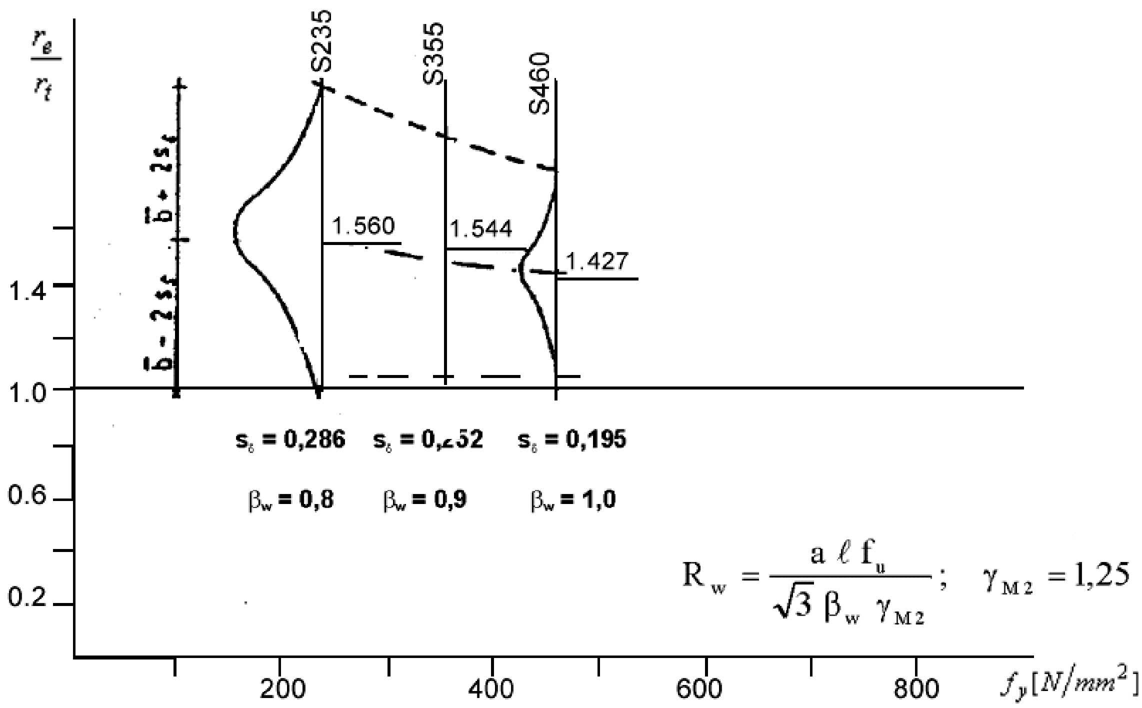


Figure 17: Comparison between the result of the statistical evaluations for the steel grades S235, S355 and S460 for the strength of fillet welds

Design Rules Based on the Yield Strength f_y

<u>Plate Buckling Rules</u>

Plate buckling rules are specified in Eurocode 3 – Part 1-5.

They are given for the following stress situations:

- members with longitudinal stresses s
- members with shear stresses t
- members with transverse loading (patch loading), see Figure 18.

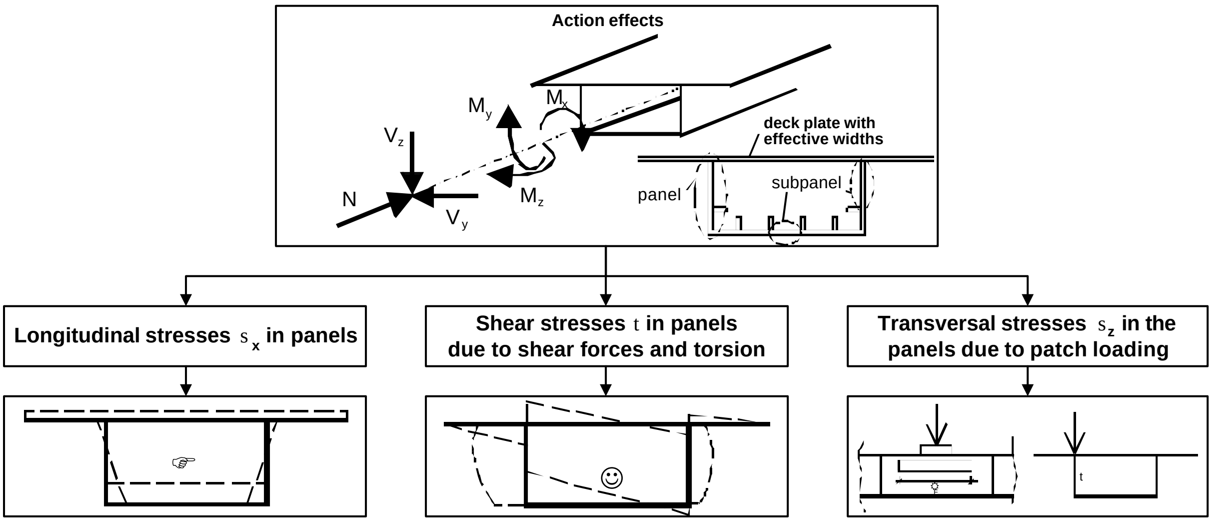


Figure 18: Decomposition of stress components from combined loading of a girder for plate buckling verification.

In case of combined loading the checks are performed for the individual stress components in the first step and by use of an interaction formula in the second step.

Figure 19 shows the results of test evaluations for the design rules for shear buckling versus the yield strength, and Figure 20 gives the evaluation for the design rules for patch loading versus the slenderness that include also S690 steels.

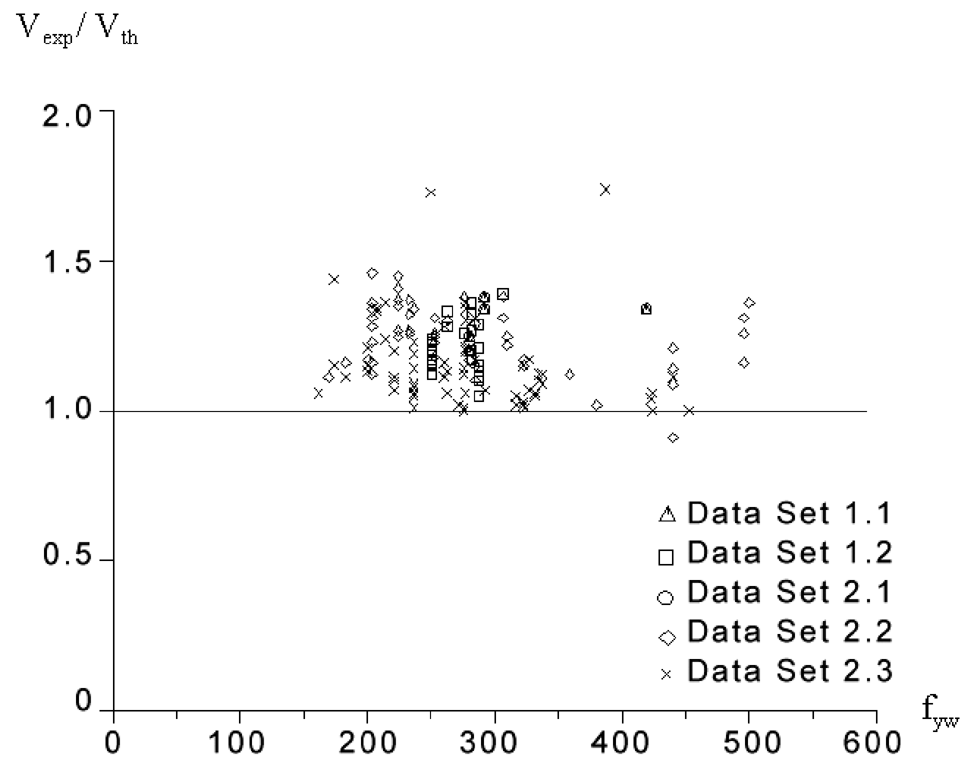


Figure 19: Ratio of test results and calculative results versus yield strength of materials for shear buckling.

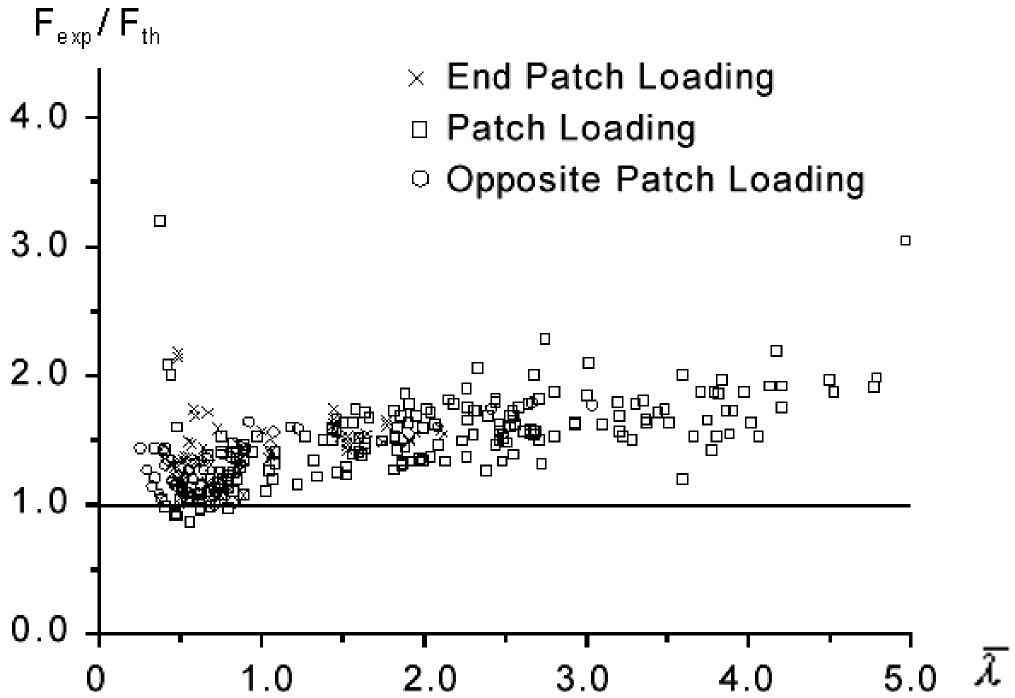


Figure 20: Ratio of test results and calculative results versus plate slenderness $\bar{\lambda}$ for plate buckling under patch loading.

Buckling Resistance of Columns

The buckling resistance of columns made of high strength steels is expected to be higher than that for normal steels because residual stresses caused by production are approximately independent on the yield strength of the material. Hence these are less onerous for high strength steels than for normal steels.

Test evaluations were carried out that showed that for columns made of S460 more favourable buckling curves may be used, figure 21. This would also apply to S690 columns.

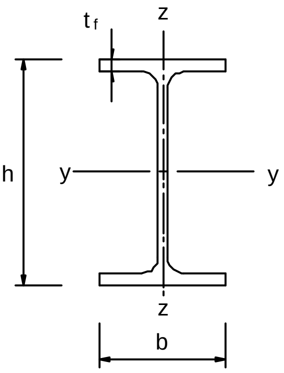
Cross-section	Limits	Buckling about axis	Buckling curve S 235 S 275 S 355 S 420	 S 460
Rolled I-sections  	h/b > 1,2 $t_f \le$ 40mm	y - y	a	a_0
		z - z	b	a_0
	40mm < $t_f \le$ 100mm	y - y	b	a
		z - z	c	a
	h/b ≤ 1,2 $t_f \le$ 100mm	y - y	b	a
		z - z	c	a
	t_f > 100mm	y - y	d	c
		z - z	d	c

Figure 21: More favourable buckling curves for columns made of high strength steels.

Lateral Torsional Buckling

Test evaluations have shown that the resistance rules for lateral torsional buckling for high strength steels are as for normal steels.

Design Rules Based on the Yield Strength Ratio $\frac{f_u}{f_y}$

Rotation Capacity of Beams in Bending

In order to save steel weight it is advantageous for hyperstatic structures to take profit of moment redistributions from highly stressed zones to zones that are less stressed by applying the plastic hinge method.

The plastic hinge method is restricted to shapes of cross-sections with compact plate elements in compression that exhibit a sufficient plastic moment plateau length in the moment rotation curve, Figure 22, so that plastic hinges can form with adequate rotation capacity.

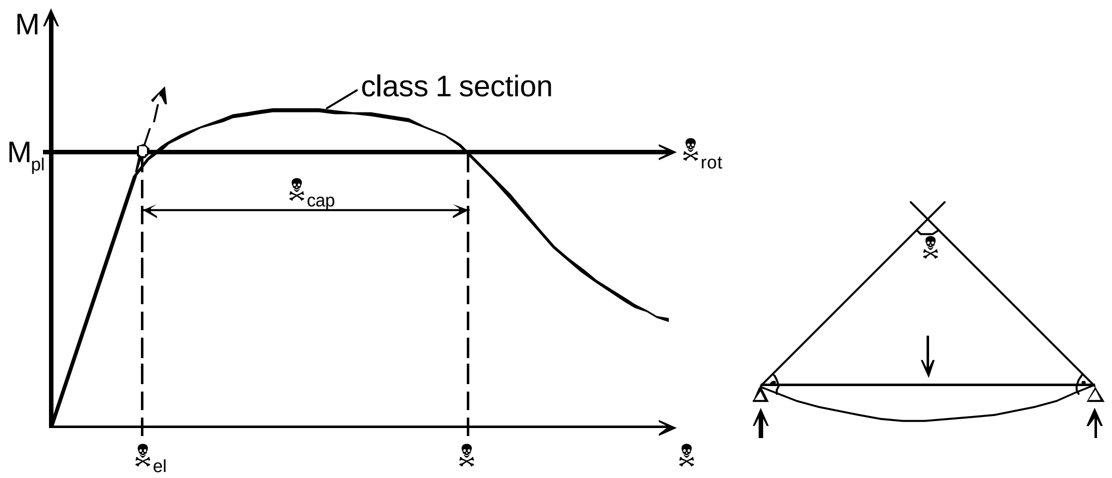
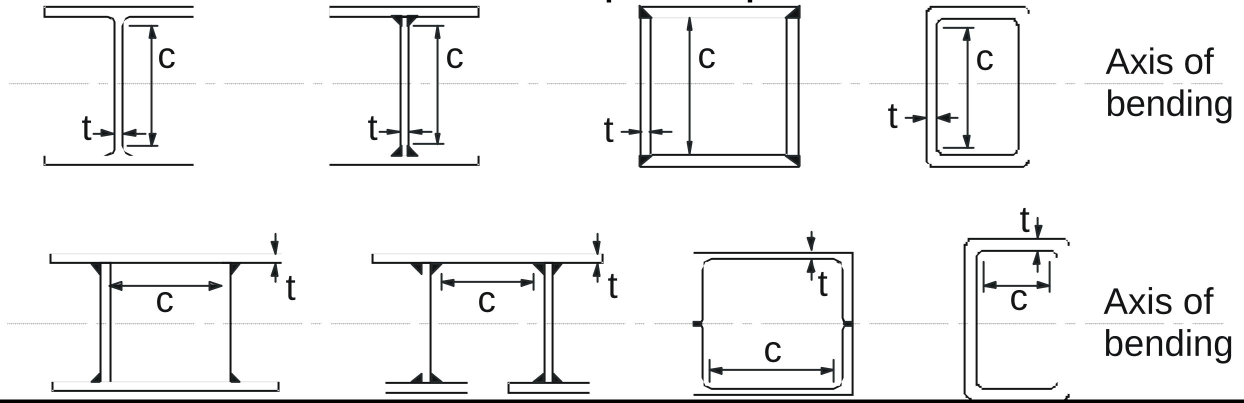
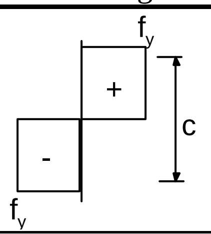
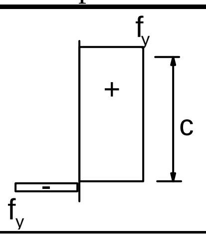
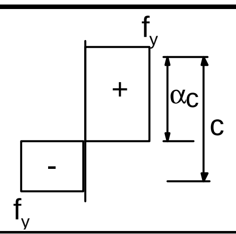
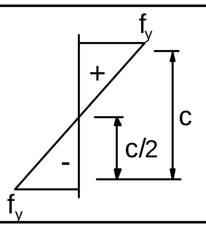
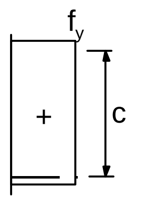
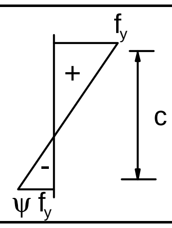


Figure 22: Definition of rotation capacity ϕ_{cap} from the moment-rotation curve determined from 3-point bending tests.

The restriction is expressed in terms of c/t · e factors, see Figure 23, where e is a reduction factor for yield strengths lower than 235N/mm².

Internal compression parts



Class	Part subject to bending	Part subject to compression	Part subject to bending and compression
Stress distribution in parts (compression positive)			
1	$c/t \leq 72\varepsilon$	$c/t \leq 33\varepsilon$	when $\alpha > 0{,}5: \; c/t \leq \frac{396\varepsilon}{13\alpha - 1}$ when $\alpha \leq 0{,}5: \; c/t \leq \frac{36\varepsilon}{\alpha}$
2	$c/t \leq 83\varepsilon$	$c/t \leq 38\varepsilon$	when $\alpha > 0{,}5: \; c/t \leq \frac{456\varepsilon}{13\alpha - 1}$ when $\alpha \leq 0{,}5: \; c/t \leq \frac{41{,}5\varepsilon}{\alpha}$
Stress distribution in parts (compression positive)			
3	$c/t \leq 124\varepsilon$	$c/t \leq 42\varepsilon$	when $\psi > -1: \; c/t \leq \frac{42\varepsilon}{0{,}67 + 0{,}33\psi}$ when $\psi \leq -1^{*)}: \; c/t \leq 62\varepsilon(1-\psi)\sqrt{(-\psi)}$

$\varepsilon = \sqrt{235/f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71

Figure 23: Classification of cross sections (here: internal compression elements).

In order to bypass the penalisation by e numerous tests have been performed to identify the realistic moment rotations behaviour for inclusion in the plastic hinge method.

Figure 24 gives the formulae for the rotation capacity and Figure 25 shows the relationship to test results. Figure 25 shows that rotation capacities can also be determined from FEM-calculations when the yield strength ratio $\frac{f_u}{f_y}$ goes down to 1.0.

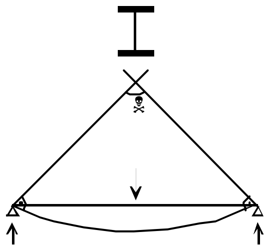
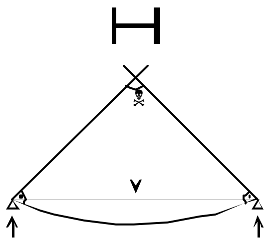
No.	bending about	rotation capacity ϕ_{cap}
1	strong axis 	$\frac{4k_{fy}}{(f_{y,fl}+\Delta\sigma)bh}\left[\frac{4Ebw^3}{5h^2}+\sqrt{(f_{y,web}hw)^2+4f_{y,web}btwh\Delta\sigma}-f_{y,web}hw\right]$ where $\Delta\sigma = 150\ N/mm^2$, $k_{fy} = \frac{1,3}{\frac{f_{y,fl}}{400}+0,25}$
2	weak axis 	$\frac{0,2}{1-\frac{2b}{\ell}}+\frac{2t}{b}-\frac{2\left[M_{pl}-\frac{(h-2t)w^2f_{y,web}}{4}\right]}{b^3(f_{y,fl}+\Delta\sigma)}$ where $\Delta\sigma = 150\ N/mm^2$

Figure 24: Formulae for rotation capacity ϕ_{cap} determined from 3-point bending tests.

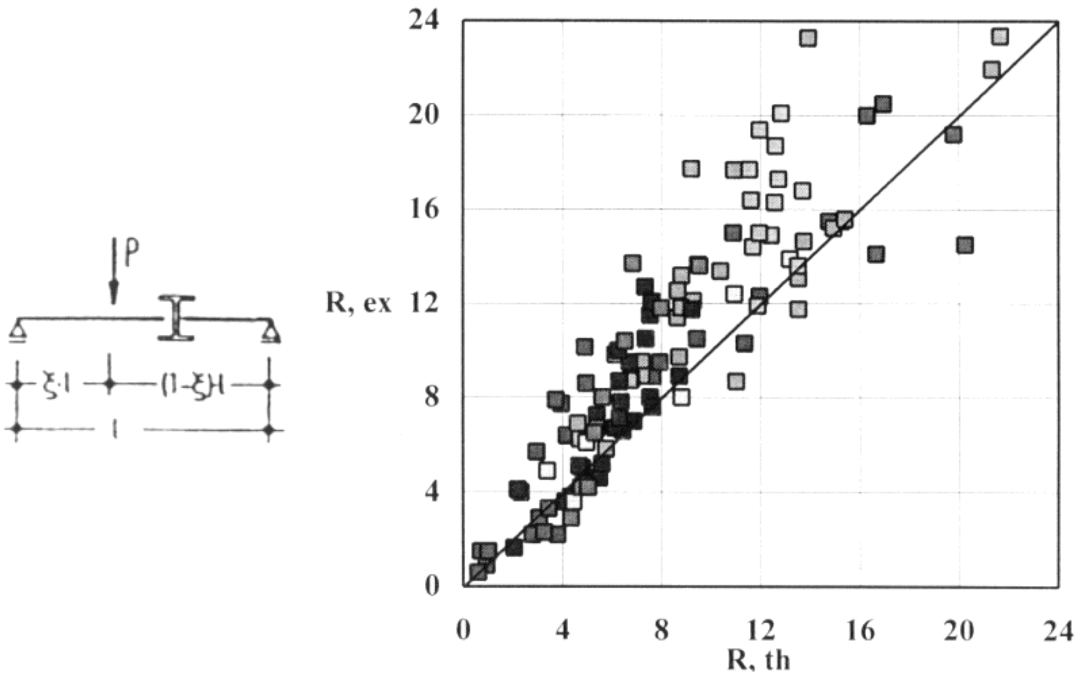


Figure 25: Comparison of test results and calculative results for related rotation capacity $R = \frac{\phi_{cap}}{\phi_{el}}$.

Sensitivity to Discontinuities in the Base Material and in Welds

In case of a plate with the crack size 2 a subjected to tension the rule for capacity design as required for achieving plastic zones is (e.g. for energy dissipation from plastic hysteresis in earthquake resistant structures or in plastic zones for the plastic hinge method), that cross-section yielding proceeds to net section failure, see Figure 26, case C.

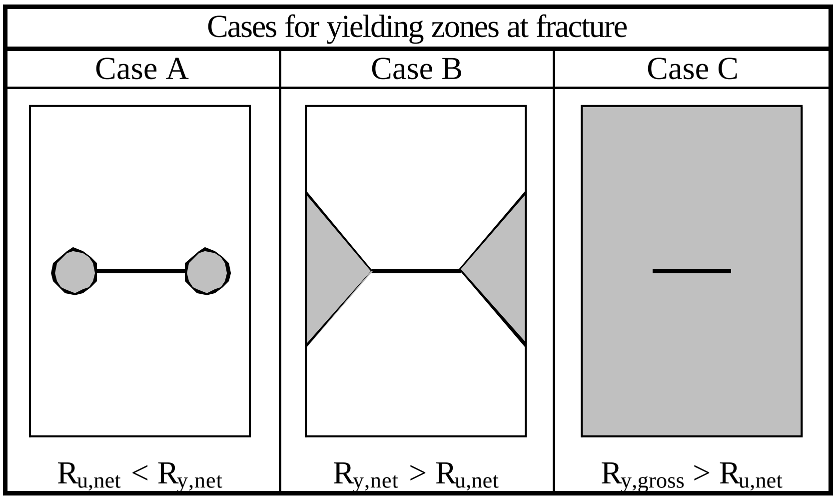


Figure 26: Various yielding patterns before fracture.

Figure 27 shows how the actual fracture resistance in the net section of a tension element with a central crack depends on the crack size and the yield strength ratio.

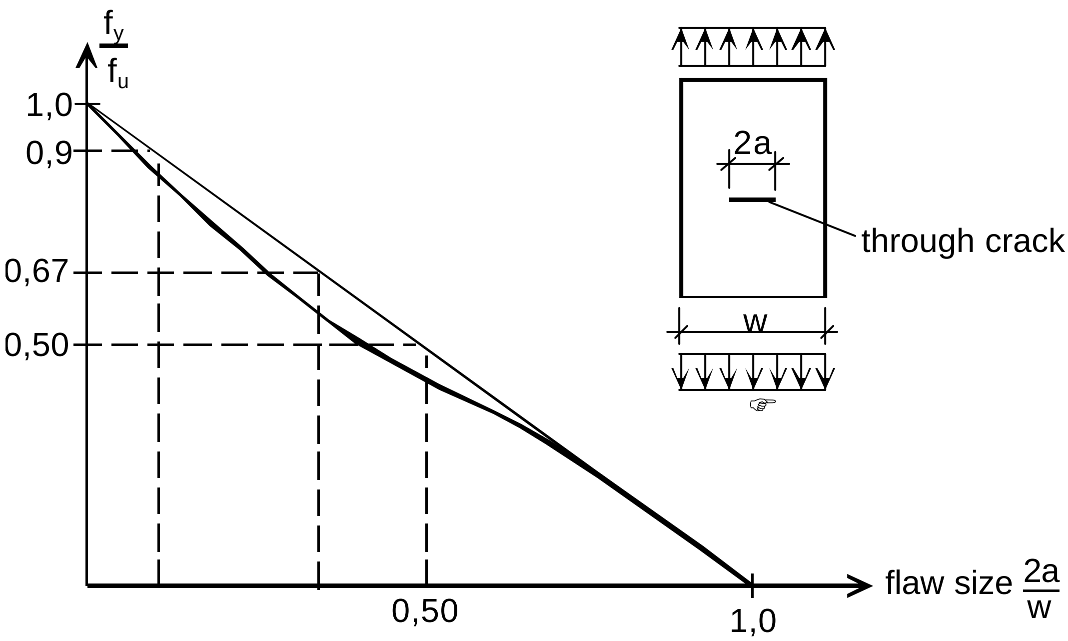


Figure 27: Sensivity of steels with various $\frac{f_u}{f_y}$ - ratios to flaw sizes.

From this follows that materials with a low yield strength ratio $\frac{f_u}{f_y}$ would fracture at lower crack sizes a/w and hence are more sensitive to material discontinuities, when the capacity design principle applies.

Therefore for high strength steel structural detailing should be adequate to prevent excessive plastic straining at locations where flaws may occur; for ultra high strength steels even a strain oriented design would be appropriate.

Fatigue

Fatigue rules are given in Eurocode 3- Part 1-9. As test results have revealed the fatigue rules are approximately the same for low strength steels and high strength steels if the same conditions for weld geometry or other notch factors apply.

As structures made of high strength steels are normally fabricated with enhanced quality requirements advantage can be taken from the reduced local notch effects resulting from such quality and hence higher fatigue classes may be used if proofed by tests.

Conclusions

Eurocode 3 contains already design rules for high strength steels up to grade S460; some of the rules are also applicable to S690 steels.

There is a request to extend the Eurocode rules to high strength up to grade S960; because by the reduction of plate thickness by higher strength the volume and cost of welds could be reduced (proportionate to the square of the plate thickness).

Tests carried out for determining resistances of components with high strength steels have revealed that for some resistances high strength leads to over proportionate resistances as for column buckling or plate buckling. Resistances are under proportionate for fillet welds.

Restrictions for the use of plastic design can be bypassed by appropriate rotation assessments for which capacity data are available.

For reasons of sensitivities to flaws it seems that for steel grade higher than S460 a strain oriented design would be appropriate.

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(4) M. Feldmann: Zur Rotationskapazität von I-Profilen statisch und dynamisch belasteter Träger, Stahlbau RWTH Aachen, Schriftenreihe Heft 30, Aachen 1994.

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