Bending-shear interaction of steel I-shaped cross-sections

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Bending-shear interaction of steel I-shaped cross-sections

Statistical investigation

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ABSTRACT

Clause 6.2 of EN 1993-1-1 covers the cross-sectional resistance of steel sections. The bending-shear interaction design rules for I-shaped cross-sections make use of a reduced yield stress for the web area. On this basis, a reduced design plastic resistance moment allowing for the shear force is presented. The effect of shear on the bending resistance may be neglected if the shear force is less than half of the plastic shear resistance of the cross-section. Plasticity in the Eurocode is described by the well-known Von-Mises yield criterion, however, the formula used for the reduced yield stress deviates from this criterion, resulting in sometimes greater and sometimes smaller values. The background of the Eurocode formula for reduced yield stress can be found in a publication by Drucker. The purpose of the present research is to investigate the influence of shear on the bending resistance of I-shaped steel cross-sections with as result a possible reconsideration of the Eurocode design rules.

At Eindhoven University of Technology an experimental investigation on bending-shear interaction in rolled steel I-shaped sections was performed. A numerical model was developed in Abaqus Finite Element software to simulate the experiments. With the validated numerical model a larger database of numerical ‘test’ results was generated, which was subsequently used in a statistical analysis following Annex D of EN 1990 as further developed in the RFCS project Safebrixtile. The statistical distributions of the steel properties recommended by Safebrixtile were adopted.

This paper presents the results of the statistical analysis and safety assessment of the strong axis bending-shear interaction design rule currently present in Eurocode 3. The parametric test group consists of HEA, HEM and IPE sections in the steel grades S235, S355 and S460: in total 180 numerical simulations with increasing amount of shear. A stress-strain model including strain hardening was used in the numerical simulations, since the influence of strain hardening is also largely present in the experimental test program. Based on strain hardening material behavior it is shown in this paper that the current partial factor is un-conservative for shear dominated beams and should be increased. Alternatively, the design rule should be modified.

Keywords: statistical evaluation, cross-sectional resistance, bending-shear interaction, I-section

1 INTRODUCTION

1.1 Bending-shear resistance

Clause 6.2 of EN 1993-1-1 [1] – known as Eurocode 3 part 1-1 - covers the cross-sectional resistance of steel sections. The bending-shear interaction is usually taken into account by reducing the yield stress for the presence of shear in the shear area, which consists of the web and part of the flanges. Subsequently, the reduced plastic bending moment resistance is calculated.

This paper presents the statistical evaluation and safety assessment of the strong axis bending-shear interaction design rule currently present in Eurocode 3, in continuation of a previous paper presented at the Eurosteel conference in Naples [2], where a preliminary experimental test series was presented. The code requirements, a recap of performed experimental and numerical research are presented first and followed by the parametric study. The parametric test group consists of

HEA, HEM and IPE sections in the steel grades S235, S355 and S460. In total 180 numerical simulations with increasing amount of shear expressed in the shear utilization ratio.

1.2 Code requirements

The text of [2] is partly repeated here for completeness. According to clause 6.2.8 of EN 1993-1-1 [1] the design bending moment M_{Ed} must not exceed the design value of the reduced resistance to bending allowing for the presence of a shear force $M_{V,Rd}$. The bending moment due to loading is denoted as M and the reduced resistance to bending moment allowing for the presence of shear force as M_V . For the sake of comparison of the different design rules all partial factors are ignored. The general method is to reduce the yield stress of the shear area of the section (A_v) by multiplication with the reduction factor $(1-\rho)$, as in Eq. (1). However, the influence of shear on the bending moment resistance can be ignored in case the acting shear force V is less than 50% of the plastic shear resistance V_{pl} .

$$f_{y,r} = (1 - \rho) f_y \quad (1)$$

where $f_{y,r}$ is the reduced yield stress of the shear area,
 ρ is the reduction factor to determine the reduced design values of the resistance to bending moments allowing for the presence of shear forces, see Eq. (2),
 f_y is the yield stress.

$$\rho = \left(\frac{2V}{V_{pl}} - 1 \right)^2 \quad (2)$$

where V is the shear force due to loading,
 V_{pl} is the plastic shear resistance.

$$V_{pl} = A_v f_y / \sqrt{3} \quad (3)$$

where A_v is the shear area, see Fig. 1a for the case of rolled I-shaped sections.

Fig. 1. a) Shear area EN 1993-1-1; b) Web area EN 1993-1-1; c) Shear area NEN 6770; d) Shear area DIN 18800; e) Reduced yield stress versus shear utilization ratio

In the case of rolled I-shaped sections Eurocode 3 gives an alternative design rule that can be used, which describes the reduced plastic bending moment allowing for shear force M_V , according to Eq. (4), for the case $V > \frac{1}{2} V_{pl}$.

$$M_V = \left[W_{pl} - \frac{\rho A_w^2}{4t_w} \right] f_y \quad (4)$$

where M_V is the reduced bending moment allowing for shear force,
 W_{pl} is the plastic section modulus,
 A_w is the web area, as shown in Fig. 1b, extending up to the flanges,
 t_w is the web thickness.

Clause 6.2.1 of EN 1993-1-1 [1] gives the Von Mises yield criterion for a two-dimensional stress state. Reducing this criterion for combined normal and shear stress only and subsequently rewriting in the form of a reduced yield stress results in Eq. (5).

$$f_{y,r} = \sqrt{1 - \left(\frac{V}{V_{pl}} \right)^2} f_y \quad (5)$$

This formula is compared to Eqs. (1, 2) in Fig. 1e, showing that the Von Mises reduced yield stress is smaller than that according to Eqs. (1, 2) for $V/V_{pl} < 0.83$ and greater for values beyond 0.83. This may be explained by the definition of the upper bound M - V resistance function following Drucker [3]. His solution is independent of the yield strength, but based on the Tresca yield criterion with the shear localized in A_w . The bending resistance of the flange is added to the moment resistance of the web area. This results in a reduction of the moment resistance following Eq. 4, however in the definition of ρ the plastic shear resistance is based on the lower web area A_w and excludes the roots. According to DIN 18800 [4] the influence of a shear force on the bending resistance is taken into account if the shear force is greater than 33% of the plastic design shear resistance, which makes use of the shear area in Fig. 1d. The interaction design rule for bending and shear is:

$$0.88 \frac{M}{M_{pl}} + 0.37 \frac{V}{V_{pl}} \leq 1.0 \quad \text{if } V > 0.33V_{pl} \quad (6)$$

where M_{pl} is the plastic moment resistance ($W_{pl}f_y$).

Eq. (6) can be rewritten into:

$$M_V = \frac{W_{pl}f_y}{0.88} \left(1 - 0.37 \frac{V}{V_{pl}} \right) \quad (7)$$

The smaller shear area of Fig. 1d, extending to half way the flanges, results in a smaller value for the reduced bending moment allowing for shear force. The former Dutch code NEN 6770 [5] gives similar design rules as EN 1993-1-1. The only difference is the shear area of Fig. 1c being used consequently throughout the bending-shear interaction design rules, as in Eqs. (3, 4).

Fig. 2a shows the differences in reduction of the moment resistance of a HEA100 cross-section for the various design rules. The shear force V on the horizontal axis also indicates the influence of the different shear areas of Fig. 1. Fig. 2b compares the design rules in non-dimensional form, in this format the equation by Drucker and the current design rule – Eq. (4) – are similar, and would be equal for sections without roots. The differences in design rules are substantial and more obvious in the dimensional format.

Fig. 2. Bending-shear interaction diagram of HEA100 comparing code design rules and Drucker

1.3 Literature survey

For a brief survey of early literature [6, 7] on cross-sectional resistance to bending-shear interaction, the reader is referred to [2, 8]. The latter, [8], includes a survey of available test results on bending-

shear interaction, presenting very conservative test results when compared to the EN 1993-1-1 design rule. These tests were originally performed to investigate the cross-sectional classification instead of bending-shear interaction.

2 EXPERIMENTAL TEST RESULTS

In order to investigate bending-shear interaction, an experimental test program with strong axis 3-point bending tests was executed at Eindhoven University of Technology [8]. The preliminary experimental study [2] proved to be unusable, since the ultimate failure load was not reached. The final experimental program [8] mainly consisted of rolled I-shaped sections – 7x HEA280, 5x HEB240, 5x HEM180 and 7x IPE360 – in steel grade S355, in addition seven HEA280 sections were tested in steel grade S235 and three in S460. Bending-shear interaction around the weak axis was also investigated, by six HEA280 sections in steel grade S235, but will not be discussed in this paper.

All experiments have failed on moment-shear interaction, with the exception of two bending dominated beams, since limited deformation was possible within the test set-up, *Fig. 3d*. The results were all conservative except two shear dominated beams in IPE360, see *Fig. 3c*. The EN 1993-1-1 design rule allows for even more shear in the IPE360 section than tested, such beams would also result in un-conservative values.

Fig. 3. Experimental test results in bending-shear interaction diagrams compared to code design rules for: a) HEA280 in S355; b) HEA280 in S460; c) IPE360 in S355; d) HEM180 in S355

The combination of the shear force and bending moment define the accuracy of the design rule. For almost every section the range of shear (up to V_{pl}) is reached, meaning utilization ratios n_v up to 1.0 and showing the validity of A_v . Only in the case of IPE360 (*Fig. 3c*), HEA280 in S460 (*Fig. 3b*) and the weak axis tests the upper limit of shear was not approached well enough. The HEB240 series reached a utilization ratio n_v of 0.94 with very conservative results, though still slightly less conservative than HEM180. The utilization ratios found by the experiments were fairly larger than the intended values based on the length and cross-sectional dimensions of each individual beam, possibly due to the positive effect of strain hardening. Strain measurements indicated that strain hardening was reached in the normative (mid) section. The results of HEA280 in steel grade S355

(Fig. 3a) are more conservative than those in S460 (Fig. 3b). A smaller f_y/f_u ratio negatively influences the resistance to bending-shear interaction, while the design rules only include f_y .

3 NUMERICAL MODEL VALIDATION

3.1 Finite element model

A numerical model [8] was made in the Abaqus FE Software 6.14. Geometrical and Material Nonlinear Analyses with Imperfections included (GMNIA) is performed using the arc length method (Riks). The numerical model was validated by the experimental test program [8], making use of the measured material properties and geometry as input. This resulted in overestimations of the experimental results by maximum 5% in most cases. However, the numerical model resulted in underestimations of the experimental values in case of HEA280 beams in S235 and S355, by maximum 5%. The influence of strain hardening was tested in the numerical models by comparing simulations with bilinear and strain hardening material properties. As the experimental strain suggested, strain hardening positively influences the cross-sectional resistance to bending-shear interaction. In bending dominated cases the benefits are minimal, however, in shear dominated cases with compact sections like HEM180 the benefits can increase up to 37%.

3.2 Strain hardening model

As mentioned earlier strain hardening is largely beneficial for bending-shear interaction. The strain hardening models of EN 1993-1-5 [9], BSK 99 [10] and NEN 6700 [11] (Fig. 5a) are used in GMNIA and compared with GMNIA using stress-strain diagrams measured by tensile coupons. Fig 5b shows the results of an HEM180 section with a span of 1020 mm and imperfection equal to 0.00005 b to introduce a perturbation. Note in the parametric study this imperfection is omitted, while it is almost negligible in shear dominated beams, which are the main focus of the investigation. In shear dominated cases the EN 1993-1-5 and NEN 6700 strain hardening model performed well and similar results were obtained, where the BSK 99 model always resulted in an overestimation. The EN 1993-1-5 model was chosen for further simulations, since the yield plateau length in the NEN 6700 model increases with an increase of yield strength, which is not in agreement with the observed material behavior.

Fig. 5. a) Strain hardening models for S355; b) Comparison of the effect of different strain hardening models for an HEM180 section in S355

4 PARAMETRIC STUDY

4.1 Definition of the parametric study

The bending shear resistance following EN 1993-1-1 [1] is calculated with nominal values, yet in daily practice imperfections are present, among others deviations of the actual stress-strain diagram, or actual cross-sectional geometry. These imperfections may result in both physically and geometrically non-linear behavior. A very large database would be required to include all variations in physical variables. However, a less extensive procedure may be used, which makes use of a database of simulations using nominal cross-sectional and yield strength and incorporates mean

values and the corresponding standard deviation of these properties into the statistical evaluation. A parametric study based on numerical results from Geometrical and Material Nonlinear Analysis (GMNA) is performed to define the influence of the individual parameters on the bending-shear resistance. In this research only deviations in the cross-section geometry and yield strength are taken into consideration.

Like the experimental test program, simply supported 3-point bending tests were simulated with an actual stiffener at mid-span (attached by ties) and rigid bodies at the supports to simulate the stiffeners ($u_x = u_y = 0$), see *Fig. 4*. Longitudinal restraints with $u_x = 0$ (blue lines) were added to prevent lateral torsional buckling. Lastly the vertical line (yellow) at mid span was restrained in x- and z- direction. A pressure load was applied over the flange width x stiffener width ($t = 10$ mm grey area in *Fig. 4*). The arc length method (Riks) was used to determine the failure load.

Fig. 4. Boundary Conditions in FE model used for parametric study

In order to assess the entire scope of the bending-shear interaction design rules both small and large sections are considered for each section type in steel grades S235, S355 and S460. The dimensions are limited to IPE100, HEA100 and HEM100 for the small sections. For the large sections the IPE600, HEA600 and HEM600 are chosen, since an IPE600 is the maximum available rolled IPE section. In the numerical simulations different beam lengths were used in order to invoke different shear utilization ratios. Since the emphasis is on shear dominated beams, mainly short beams are regarded.

The numerical model makes use of C3D8i continuum elements in order to accurately describe the roots. *Table 1* presents the parameterized mesh, as a result of the mesh study, with 4 elements over the thickness of the flange and the web in almost all cases. In the longitudinal direction the mesh size varied, for the three areas “end”, “support” and “mid-section” as indicated in *Fig. 4*, from 20 to 2.5 mm for the ‘100’ series and from 40 to 5 mm for the ‘600’ series..

Table 1. Mesh size used in the parametric study: in the cross-section and in longitudinal direction

Section	Flange			Web			series	longitudinal		
	thickness	width	ratio	thickness	height	ratio		end	support	mid-section
HEA, IPE	$0.25 t_f$	$0.67 t_f$	3:8	$0.25 t_w$	t_w	1:4	‘100’	20 mm	20-2.5 mm	2.5 mm
HEM	$0.17 t_f$	$0.67 t_f$	1:4	$0.25 t_w$	t_w	1:4	‘600’	40 mm	40-5 mm	5mm

4.2 Database with numerical simulations

The parametric study resulted in a database of 180 numerical simulations with emphasis on shear dominated cases. *Fig. 6a, b* display the bending-shear interaction of an IPE100 section in steel grades S235 and S460. In the case of IPE100 all numerical results were very conservative, irrespectively of the amount of shear or steel grade. The DIN 18000-1-1 is most conservative and EN 1993-1-1 least conservative for shear dominated cases. The maximum amount of shear in simulations for S235 corresponds to the plastic shear force following NEN 6770. In the case of simulation for S460 the maximum amount of shear is just below the plastic shear force following EN 1993-1-1. All simulations result in high moment resistance values, though the cross-sectional resistance according to the EN 1993-1-1 decreases, like the f_y/f_u ratio, as visualized in *Fig. 6c*. For IPE100 the simulations could be scaled. Some simulations were aborted prematurely, these results are indicated with an arrow.

Fig. 6. Numerical GMNA simulations for IPE100: a) in S235; b) in S460; c) all steel grades with normalized axes

In the case of a larger section, for instance HEA600, the numerical simulations show un-conservative results for the shear dominated beams, as in Fig. 7. In the case of HEA600 all bending dominated cases resulted in conservative moment resistances, however, in shear dominated cases un-conservative results were observed. For shear dominated cases in higher steel grades, i.e. increase of f_y , the resistance deviates more from values described by EN 1993-1-1, see Fig. 7b, thus, simulations cannot be scaled. In general the DIN 18000-1-1 leads to conservative results, contrary to Eurocode 3 and NEN 6770 for shear dominated cases. The maximum amount of shear in simulations for S235 attains the plastic shear force following Eurocode 3. In the case of simulation for S460 the maximum amount of shear is just below the plastic shear force following DIN 18800-1-1. Similar to IPE100, the cross-sectional resistance of HEA600 decreases for higher amounts of shear, as illustrated by Fig. 7c. Resemblances with the experimental results from Fig. 3 are present.

Fig. 7. Numerical GMNA simulations for HEA600: a) in S235; b) in S460; c) all steel grades with normalized axes

Similar results were observed for the other cross-section types, meaning conservative values for the ‘100’ series and un-conservative values for shear dominated simulations in the ‘600’ series. Bending dominated cases always result in over conservative cross-sectional bending moment resistance when strain hardening is considered in 3-point bending tests.

5 STATISTICAL EVALUATION

5.1 Resistance function and statistical distributions

The database of 180 numerical results is used for the statistical evaluation of the Eurocode 3 design rule regarding bending moment-shear force interaction, following Annex D of EN 1990 as further developed in the RFCS project Safebrittile [12, 13]. The theoretical resistance function r_t is obtained from Eq. 4 in combination with all associated basic parameters. In the case of rolled I-shaped sections the geometry is defined by the width b , height h , flange thickness t_f , web thickness t_w , and root radius r . These parameters are not completely independent, due to standardized section typology. In addition to these geometric parameters the yield stress f_y is of influence. The theoretical resistance r_t is compared with the numerical resistance r_e originating from the database.

In case of an IPE100 section the Eurocode design rule does not comply with the numerical results. Though, the decrease of bending resistance at higher amounts of shear force in S235 conform

Eurocode 3 equals that of the numerical results, as illustrated in *Fig. 8a* where the numerical results are positioned on a virtual straight line parallel to the dashed line, which resembles the design rule. However in steel grade S460 the bending resistance decreases faster than prescribed by EN 1993-1-1 at higher n_V , see *Fig. 8b*. *Fig. 8c* illustrates the inaccuracy of the EN 1993-1-1 design rule for M - V interaction by comparing the ratio of experimental over theoretical resistance (vertical axis) at different amounts of shear (horizontal axis).

In case of a HEA600 section the Eurocode design rule is not accurate and fails to describe the decrease of resistance at higher amounts of shear, as illustrated by *Fig. 9a, b*. In *Fig. 9c* a similar shape as the curves in *Fig. 7c* may be recognized.

Fig. 8. Experimental versus theoretical resistance for IPE100: a) in S235; b) in S460; c) for all steel grades with the normalized amount of shear on the horizontal axis

Fig. 9. Experimental versus theoretical resistance for HEA600: a) in S235; b) in S460; c) for all steel grades with the normalized amount of shear on the horizontal axis

Similar results were observed for the other cross-section types, meaning numerical simulations more or less parallel to the Eurocode design rule in the $r_e - r_t$ graphs for the most of the ‘100’ series, while the numerical results for the ‘600’ series are more vertically directed.

As mentioned earlier the variation of geometrical properties, and yield strength is taken into account by means of mean values μ , standard deviations σ , and coefficients of variation V . *Table 2* gives the ratio mean to nominal (nom.) values and coefficient of variation for each parameter [13]. These parameters are used in the statistical assessment of the bending moment-shear force interaction design rule as described in Eurocode 3.

Table 2. Statistical distributions used for evaluation of bending-shear interaction

parameters	b	h	t_f	t_w	$f_y, S235$	$f_y, S355$	$f_y, S460$
$\mu / \text{nom.}$	1.000	1.000	0.975	1.000	1.250	1.200	1.150
V	0.9%	0.9%	2.5%	2.5%	5.5%	5.0%	4.5%

5.2 Results statistical evaluation

The statistic evaluation is performed on all 180 numerical test results and once on a set of all test results with a bending moment resistance lower than M_{pl} . The latter set contained 55 numerical

simulations, for a large number of simulations resulted in higher resistance to bending moment due to strain hardening, e.g. the complete set of IPE100 and HEM100 sections was excluded. *Table 3* presents the results of the statistical evaluation for the different steel grades, the second to fourth column give the results for all simulations and the last three columns only include simulations with $M < M_{pl}$.

As expected the Eurocode design rule does not comply with the results from the numerical simulations, see partial factor γ_M^* in *Table 3*. Some other subsets do result in acceptable results. The acceptance diagram in *Fig. 10* gives all subsets by means of $\gamma_M^* / \gamma_{M,target}$ to the coefficient of variation V_r . The dashed line represents the acceptance limit, markers below this line are accepted, markers above that need a higher value for $\gamma_{M,target}$. Only for IPE100 and HEM100 and 5 other subsets a $\gamma_{M,target} = 1.0$ suffices, *Fig. 10a*. Overall $\gamma_{M,target} = 1.45$ is required. When only simulations with low M are regarded, the scatter decreases and a few more subsets are accepted with $\gamma_{M,target} = 1.0$ even though these sets are punished for having a small number of results. For this case $\gamma_{M,target} = 1.2$ is required. The large variation in numerical results and high deviation from Eurocode 3 result in the need for a high $\gamma_{M,target}$. In general it should be concluded that the Eurocode 3 design rule for bending moment-shear interaction is not adequate.

Table 3. Results statistical evaluation for M - V interaction in 3 point bending tests

Set	<i>all simulations</i>			<i>simulations $M < M_{pl}$</i>		
	#	V_r	γ_M^*	#	V_r	γ_M^*
<i>S235</i>	68	0.2571	1.703	16	0.1295	1.333
<i>S355</i>	49	0.1964	1.647	19	0.1180	1.323
<i>S460</i>	63	0.1428	1.355	20	0.1174	1.337
<i>S235-S460</i>	180	0.2224	1.666	55	0.1207	1.307

Fig. 10. Acceptance diagram for partial factor: a) all simulations; b) limited group of simulations (55) with $M < M_{pl}$

6 CONCLUSIONS

The purpose of the present research is to investigate the influence of shear on the bending resistance for I-shaped steel cross-sections with as result a possible reconsideration of the Eurocode design rules. A short summary of the experimental program was given, followed by validation of the numerical model. Subsequently the parametric study was defined, which was used to perform the assessment of the Eurocode 3 design rule. The conclusions are as follows:

- Experimental results displayed high moment resistances in the presence of shear, due to a positive effect of strain hardening (confirmed by the finite element model).
- A smaller f_y/f_u ratio negatively influences the resistance to bending-shear interaction, while the design rules only include f_y .
- The EN 1993-1-5 [9] strain hardening model gives better results than that of BSK 99 [10]. The NEN 6700 [11] model performs like EN 1993-1-5, but is inconsistent in its description of the yield plateau at different yield strengths. Therefore the EN 1993-1-5 model is used.

- Numerical simulations of IPE100 and HEM100 are very conservative in comparison with Eurocode 3. In these cases the maximum shear force is larger than V_{pl} following EN 1993-1-1, IPE100 in S460 is an exception with a value slightly smaller than V_{pl} .
- Numerical simulation of the '600' series result in un-conservative values for shear dominated cases. In these cases the maximum shear is slightly smaller than V_{pl} of Eurocode 3 in S235, while for S460 this value is even smaller than V_{pl} following DIN 18800-1-1 [4].
- Numerical simulations cannot be scaled based on the yield strength or ratio f_y/f_u .
- The current moment-shear interaction design rule of clause 6.2.8 of EN 1993-1-1 [1] has a recommended partial factor of 1.0, while this study shows that overall 1.45 (all simulations) or 1.20 (55 simulations) is required.
- The current partial factor is un-conservative and should be increased. Alternatively, the $M-V$ design rule should be modified.

More research should substantiate these findings and the current design rules should be changed in order to better approach the decrease in moment resistance for high amounts of shear.

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