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PLASTIC CAPACITY OF SEMI-COMPACT STEEL SECTIONS

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ABSTRACT

Semi-compact cross-sections are those that are defined as class 3 cross-sections in accordance with Eurocode 3 [1]. In the code, the cross-section capacity of class 3 sections is limited as purely elastic, resulting in a discontinuity at the border to the plastic resistance of class 2 sections. The present paper investigates the amount of the plastic cross-section capacity that can be developed by the semi-compact sections. Axial compression, major and minor axis bending as well as the combinations of them were investigated. Experimental and numerical tests were carried out. Based on the results design proposals were worked out, which have been statistically evaluated according to Eurocode EN 1990 [2].

1. INTRODUCTION

The design rules of Eurocode 3 (EC3) show a significant discontinuity in the definitions of the cross-section capacity at the transition point from plastic to elastic cross-sections. In EC3 "Class 2 - compact" cross-sections are specified to reach their full plastic section capacity until local buckling limits further rotations on the plastic level. However, "Class 3 - elastic" cross-sections are specified rather conservative to reach just the elastic capacity at limit state, regardless of their wall slenderness. Not only the pure moment capacities (M_y, M_z) are concerned here, but also the interaction between axial compression and bending have such abrupt discontinuity (Fig. 1). Considering the member capacity of Class 3 sections, such discontinuities connected with a sudden loss of capacity are similarly induced by the given design formulae of EC3.

These inconsistencies are physically not understandable, which means that a wide range of practical sections cannot be exploited by its real capacity so far by the code. Since sections come into the semi-compact range with increasing yield strength the given code design provision gets rather inefficient with the growing use of high strength steel grades.

Therefore, a European research project was started in order to solve this problem. In this paper results obtained by the research carried out at Graz University of Technology (TU Graz), Austria, University of Liège (ULg), Belgium and PSP Technologien im Bauwesen (PSP), Germany are presented.

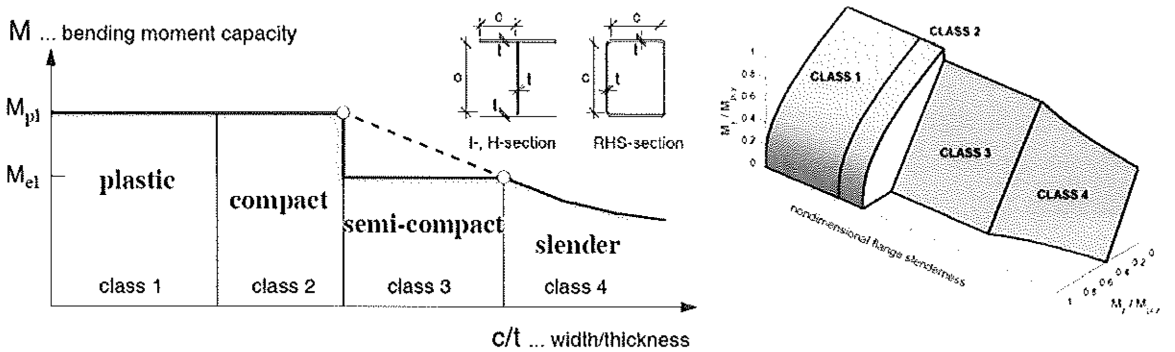

Figure 1: Discontinuity in Eurocode 3 cross-section capacity definitions

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2. RESEARCH APPROACH

The research covers several steps: experimental testing, finite element model development and calibration on test results, parametric study based on nominal values, parametric study based on random input variables (Monte-Carlo Method), design model development, statistical evaluation, final reporting and dissemination.

3. TEST PROGRAM

3.1. Overview

A test program was carried out in two different laboratories. In the Laboratory for Structural Testing at TU Graz (LKI), test series covering the cross-section behaviour of rolled and welded H-sections, and rectangular structural hollow sections (RHS) were performed. First test series were carried out in order to investigate biaxial bending without axial force. Second test series were performed in order to investigate the combined loading of N, M_y and M_z. All specimens were nominally classified as Class 3.

At ULg further test series were performed to investigate the member buckling behaviour. Class 3 - H-section and RHS were tested for member buckling. As loading, axial compression including monoaxial or biaxial bending was realized.

Due restricted size of this paper, these results will be presented in a separate publication.

3.2. Imperfection measurements

In the laboratories of TU Graz and ULg local and global imperfection measurements were performed. The increase in yield strength due to cold-working in the corner regions of cold-formed RHS was investigated. Residual stress measurements were carried out at ULg.

The local imperfection measurement was performed either by

a. linear variable displacement transducers (LVDT's) on gridsize 40 x 80 mm (Fig. 2),
b. digital close-range photogrammetry producing a digital surface model (Fig. 3).

The high precision measurements were achieved in close cooperation with the laboratories and the Institute of Remote Sensing and Photogrammetry at TU Graz. The results indicate that the difference in the cross-section size and shape compared to the nominal size is larger than the local plate buckling imperfections. The observed plate buckling imperfections are in the range between b/150 and b/300.

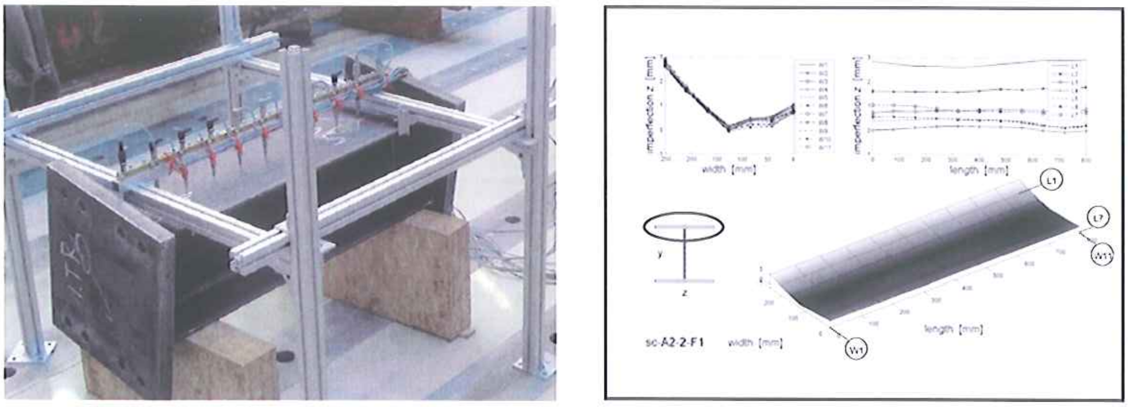

Figure 2: Local imperfection measurements via LVDT's and result, HEAA 260 (upper flange)

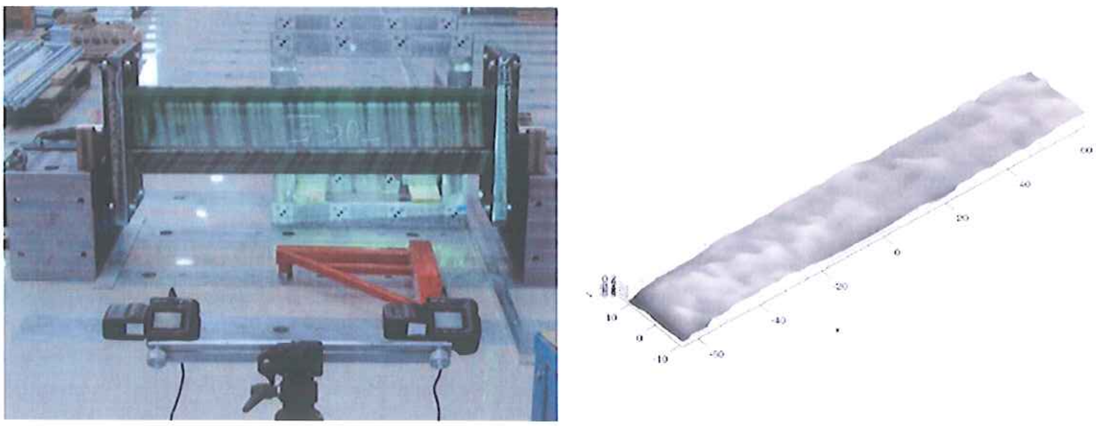

Figure 3: Digital surface model produced by digital close-range photogrammetry, HEAA 260

3.3. Bending without axial compression

At TU Graz there was a test programme to investigate the biaxial bending capacity of Class 3 sections [1]. The test series comprised 19 specimens: 12 rolled H-sections and 7 hot-finished RHS. On the experimental results a finite element model was developed and calibrated in order to perform reliable numerical studies. Figure 4 shows the test configuration. The bending moments were applied via horizontal lever arms into the horizontally placed specimens. The length of the specimens equals 4 resp. 5 times the width. Depending on load case the sections were connected with the end plates with different angles (0°, 30°, 45°, 60° and 90°). Support was provided by horizontal roller bearings.

The load was simultaneously applied via two *MTS* - 1 MN hydraulic jacks and it was controlled by a *DMS plus* control unit. The loading rate was 2 mm/min in both actuators. Due to the significant rigid body motions, more than 20 measurement channels were used to collect the data needed for accurate evaluation of the load-displacement diagram in the critical section of the bent beam. In case of square structural hollow sections (SHS) the test rig was designed for in-plane deformations. However, out-of-plane motions had to be allowed for the test series of H-sections due to their different strong axis and weak axis bending stiffness.

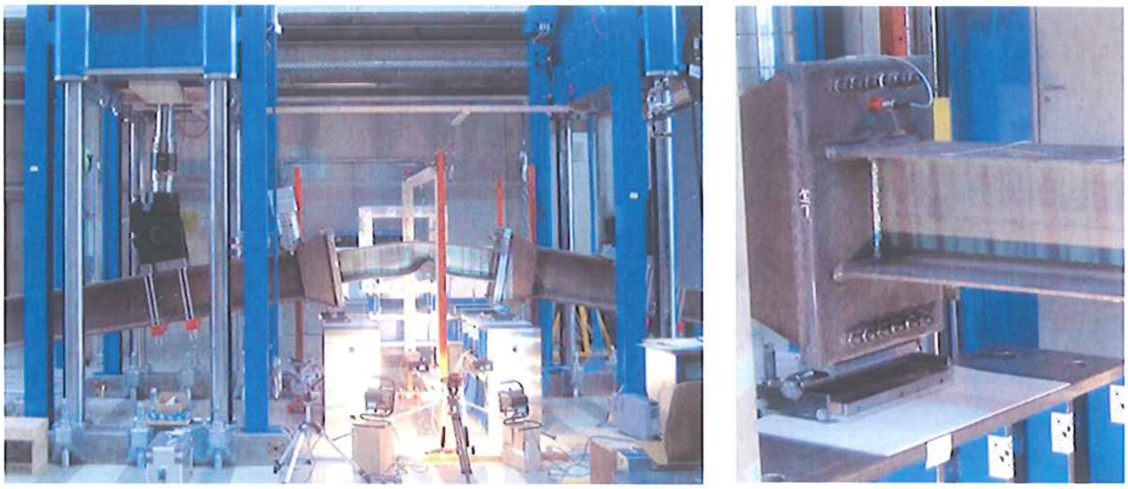

Figure 4: Test configuration and support detail of biaxial bending tests

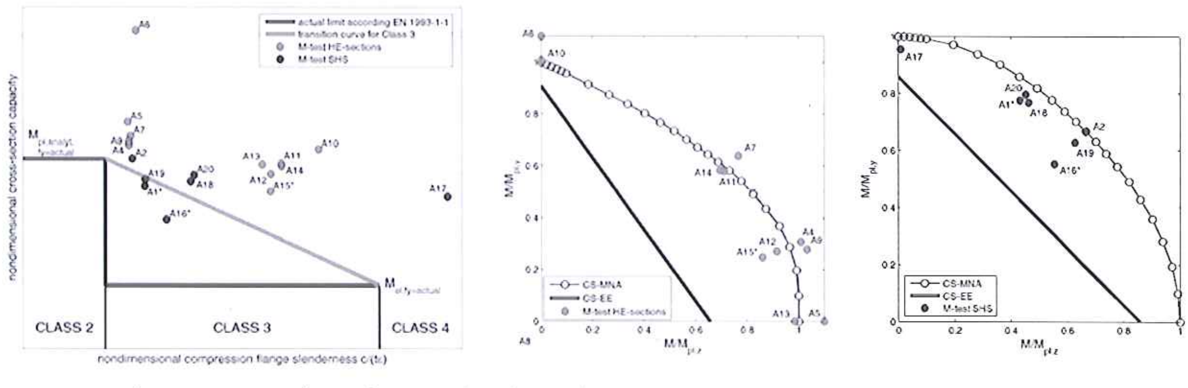

Figure 5: Comparison of test results with section capacity according EC3, M_y+M_z - loading

The results clearly indicate that Class 3 H-sections and SHS can develop partial plastic section capacity (Fig. 5). For H-sections the capacities are generally above a linear transition line. However, SHS specimens achieve lower capacity than expected in the range close to

Class 2. The comparisons are based on the actual values of geometric and material properties (Table 1). Axial force is not taken into account.

Test no.	Section	Length L (mm)	R_{eH} (N/mm²)	Angle α (°)	M_{Exp} (kNm)	M_{FE} (kNm)	M_{FE} / M_{Exp} (-)
TUG-A6		1000		0,0	190,4	173,7	0,91
TUG-A7		1000		29,1	126,5	121,3	0,96
TUG-A8	HEA 200 S 355	800	400,8	30,0	122,8	120,4	0,98
TUG-A4		1000		56,7	97,0	94,4	0,97
TUG-A9		800		59,9	96,0	96,7	1,01
TUG-A5		1000		90,0	88,5	84,9	0,96
TUG-A10		1300		0,0	222,2	216,5	0,97
TUG-A11		1300		28,8	146,1	145,0	0,99
TUG-A14	HEAA 260 S 235	1040	330,7	28,2	145,9	146,7	1,01
TUG-A12		1300		56,6	108,7	108,6	1,00
TUG-A15		1040		57,3	101,3	101,4	1,00
TUG-A13		1300		90,0	97,5	95,7	0,98
TUG-A17		900		0,5	88,5	86,4	0,98
TUG-A18	SHS 180/180/5 S 355	900	408,2	31,0	83,0	79,6	0,96
TUG-A20		720		29,5	84,8	82,9	0,98
TUG-A16		900		45,0	72,4	71,6	0,99
TUG-A19		720		45,0	77,8	78,5	1,01
TUG-A1	SHS 260/260/7,1 S355	1300	360,3	29,0	213,2	215,4	1,01
TUG-A2		1170		45,0	226,7	212,4	0,94
						Mean:	0,98

Table 1: Table of results of biaxial bending tests without axial force

3.4. Bending and axial compression

In the frame of *Semi-Comp* further tests on the cross-section capacity of Class 3 sections have been carried out at TU-Graz. The loading was bending and axial compression. Monoaxial and biaxial bending was produced by eccentric compression forces. The specimens were similar to those in 3.3. H-section specimens and RHS were investigted. However, only cold-formed RHS were used. The test configuration was modified (Fig. 6). The specimens were placed vertically in the test rig. The load was introduced by cantilever plates into the endplates of the specimens with different angles. The results are shown in Fig. 7 and Table 2.


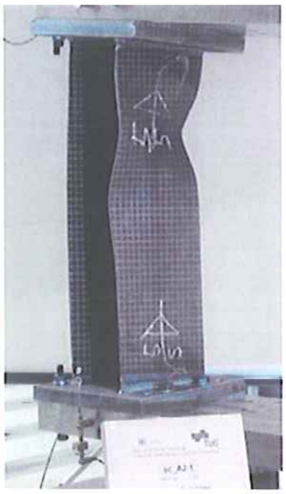


Figure 6: Test configuration and finite element model, deformed and undeformed specimens

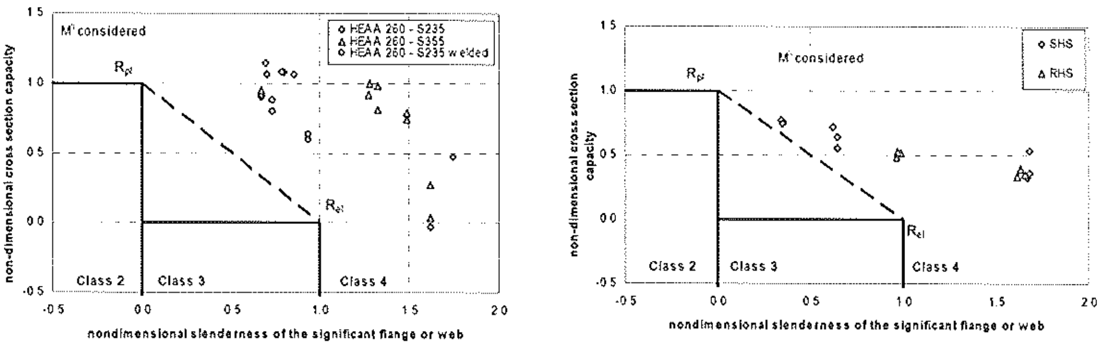

Figure 7: Comparison of test results with section capacity according EC3, N+M_y+M_z - loading

Test no.	Section	Length L (mm)	R_{eH}; $R_{p0.2}$ (N/mm²)	Eccentricity e (mm)	Angle α (°)	F_{Exp} (kN)	F_{FE} (kN)	F_{FE} / F_{Exp} (-)
sc-A1-2			318,6	303,6	-0,3	585,2	558,9	0,95
sc-A1-3			488,3	301,7	0,3	812,4	846,3	1,04
sc-A2-1				301,8	9,5	556,9	556,2	1,00
sc-A2-2	HEAA 260			298,1	11,0	554,3	551,7	1,00
sc-A3-1	S 235	900		299,9	40,9	404,5	392,6	0,97
sc-A3-2			318,6	298,2	39,6	396,6	399,3	1,01
sc-A4-1				98,9	90,1	826,8	834,4	1,01
sc-A4-2				97,8	90,4	824,8	841,6	1,02
sc-A10-2				95,8	89,6	853,4	864,5	1,01
sc-A7-1 [1]				299,2	-0,2	809,6	848,0	1,05
sc-A7-2				298,5	-0,3	772,3	848,0	1,10
sc-A1-1				300,2	-0,1	768,5	833,0	1,08
sc-A8-1	HEAA 260		488,5	298,8	10,5	790,7	834,0	1,05
sc-A8-2	S 355	900		298,6	11,4	769,9	803,0	1,04
sc-A9-1				299,4	39,7	559,1	585,0	1,05
sc-A9-2				299,1	39,8	602,4	575,0	0,95
sc-A10-1				99,3	89,7	1299,7	1290,0	0,99
sc-A10-3			501,4	99,4	90,1	1408,6	1334,9	0,95
sc-A22-1	HEAA 260		flange:	298,8	0,1	545,2	547,0	1,00
sc-A22-2	welded	900	319,3	298,3	0,4	543,7	552,0	1,02
sc-A23-1	S 235		web:	96,5	89,5	826,3	869,0	1,05
sc-A23-2			315,5	97,8	89,9	842,9	864,0	1,02
sc-A13-1				300,2	0,3	227,9	241,0	1,06
sc-A13-2				299,2	-0,2	245,6	240,0	0,98
sc-A13-3				300,2	-0,2	230,8	240,0	1,04
sc-A14-1	SHS		400,0	300,7	20,1	240,0	237,0	0,99
sc-A14-2	180/180/5	700		297,5	19,3	226,1	243,0	1,07
sc-A14-3	S 355		edges:	299,9	19,1	233,4	241,0	1,03
sc-A15-1			600,4	298,6	43,9	237,6	244,0	1,03
sc-A15-2				302,1	45,3	237,3	243,0	1,02
sc-A15-3				299,6	45,7	235,6	241,0	1,02
sc-A18-1				300,5	20,8	139,5	142,0	1,02
sc-A18-2	RHS		397,8	298,1	20,2	142,2	144,0	1,01
sc-A18-3	200/120/4	700		298,5	20,0	139,5	144,0	1,03
sc-A19-1	S 275		edges:	298,5	44,0	110,7	112,0	1,01
sc-A19-2			561,3	302,8	44,6	112,5	110,0	0,98
sc-A19-3				299,3	45,4	110,8	110,0	0,99
1) End plate rotations in test sc-A7-1 constrained							Mean:	1,02

Table 2: Table of results of biaxial bending tests with axial compression

The diagrams above show the amount of the plastic capacity (= R_{pl} - R_{el}) that could be developed. Due to higher yield strength some results belong to Class 4, nominally they are in

Class 3. The investigated Class 3 sections can develop a significant part of their plastic capacity for $N+M_y+M_z$ - loading which is not exploited so far by EC3.

4. NUMERICAL STUDIES

4.1. Calibration of FE-models

Finite element simulations were performed for each specimen. This was to develop a finite element model which can properly describe the load-carrying behaviour of such sections. Two different software packages (ABAQUS, FINELG) were used and the results of the two models have been compared intensively. The load-displacement behaviour of all experiments can be properly described with the FE-models. Minor differences occurred due to the assumption in model definitions (definitions of web-flange intersection, imperfection type). The achieved accuracy between the experimental results and the FE-model is 98 % and 102 % on average (Table 1 and 2).

4.2. FE-Parametric studies

Two sets of different simulations were performed for each of both, the cross-section and for the member buckling studies. First, nominal input quantities based on maximum imperfections according to the tolerance limits (EN 1090-2) were simulated for the Class 3 region. Second, the same set of sections was simulated for the different load cases, but all essential parameters have been applied by random distributions about their mean values, in particular the yield strength variation.

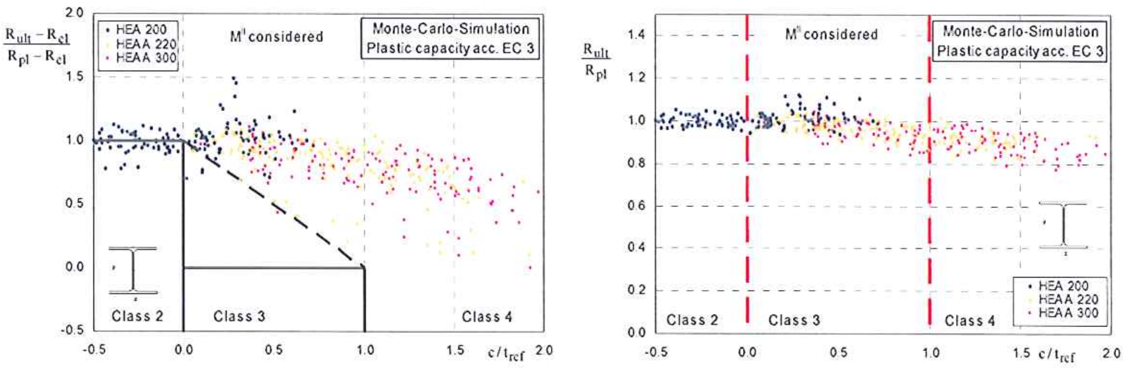

Figure 8: Results of statistical analysis using random input parameter variation

The coefficients of variation resp. lower and upper limits have been the following: depth (0.05), width (0.01), flange/web thickness (0.05), yield strength S235/275/355/460 ($f_{y,mean}$=285/325/400/520, V_x=0.06/0.05/0.04/0.04), local imperfection (between B/300 and B/150). The parameters were assumed to be normal distributed, except for yield strength which was assumed to be log-normal distributed.

The numerical results confirm the existence of a partial plastic behaviour for semi-compact sections (Fig. 8).

5. DESIGN PROPOSAL

To conclude, the following design proposal based on the given investigations shows that parts of the plastic capacity can be exploited for Class 3 sections. It describes a continuous transition from the Class 2 to the Class 4. The formulae are in line with the EC3 Class 2 cross-section formulae in principle and approach the elastic section capacity at the Class 3/Class 4 limit.

Proposal for I-sections:

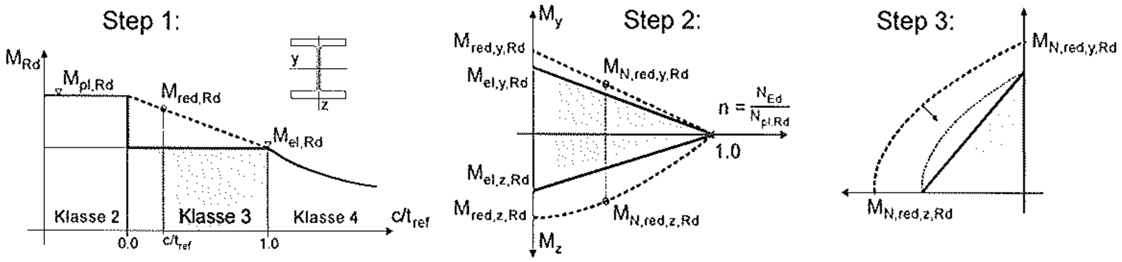

Figure 9: Design proposal for Class 3 H-sections

$$c/t_{ref,y} = \max\left[\frac{(c/t_f - \beta_{2,y,f})}{(\beta_{3,y,f} - \beta_{2,y,f})};\frac{(c/t_w - \beta_{2,y,w})}{(\beta_{3,y,w} - \beta_{2,y,w})}\right] \qquad c/t_{ref,z} = \frac{(c/t_f - \beta_{2,z})}{(\beta_{3,z} - \beta_{2,z})}$$

$$M_{red,(y,z),Rd} = M_{pl,(y,z),Rd} - \left(M_{pl,(y,z),Rd} - M_{el,(y,z),Rd}\right)\cdot c/t_{ref,(y,z)}$$

$$M_{N,red,y,Rd} = M_{red,y,Rd}\cdot(1-n) \qquad M_{N,red,z,Rd} = M_{red,z,Rd}\cdot\left(1-n^2\right)$$

$$\left[\frac{M_{y,Ed}}{M_{N,red,y,Rd}}\right]^{\alpha} + \left[\frac{M_{z,Ed}}{M_{N,red,z,Rd}}\right]^{\beta} \le 1 \qquad \alpha = 2;\quad \beta = 5n \ge 1$$

The statistical evaluation according to EN 1990 verifies the proposal for H-sections with

$$\gamma_M^* = 1{,}075$$

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