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Artikel: From thick to thin or from thin to thick?

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From Thick to Thin or from Thin to Thick?

De l'épais au mince ou du mince à l'épais?

Von dick zu dünn oder von dünn zu dick?

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SUMMARY

Because thick-walled and thin-walled sections are not actually two different families, it should be aimed at having consistent rules which would apply to the whole range of sections. Based on a parametric study of uniaxial compression plates – the basic case – the authors suggest values of the parameters that are worthwhile being accounted for and they present a general format for plate buckling curves as well as the corresponding analytical expressions.

RÉSUMÉ

Il est nécessaire de disposer de règles de calcul homogènes qui couvriraient sans discontinuité tant les profils à parois épaisses que ceux à parois minces. Les auteurs ont procédé à une étude paramétrique du cas fondamental constitué par les plaques en compression uniaxiale. Sur cette base, ils proposent les paramètres à retenir et présentent une formulation générale des courbes de voilement ainsi que les expressions analytiques correspondantes.

ZUSAMMENFASSUNG

Es drängt sich immer mehr auf, über gleichwertige Berechnungsregeln zu verfügen, die kontinuierlich sowohl für dick- als auch für dünnwandige Profile gelten. Aufgrund des Studiums des grundlegenden Falles – einachsigem Druck ausgesetzte Platten – schlagen die Autoren die zu berücksichtigenden Parameter vor und geben eine allgemeine Formulierung der Beulkurven sowie die entsprechenden analytischen Ausdrücke an.

1. INTRODUCTION.

The codes and standards for steel construction have been first written with the hot-rolled sections in mind. At that time these sections can be called thick-walled because no local plate buckling can generally occur in the walls before the yield stress be reached there. That means that the wall slenderness is lower than a limiting value, beyond which local stability phenomena would prevail on yielding.

At a time when elastic design has been of regular use, the carrying capacity was supposed to be exhausted when the maximum stress, without account taken of any eventual residual stress, was reaching the yield stress. A section that is just able to comply with such a requirement is now called "semi compact". When the plastic design has been more in favour, yielding of the full cross-section became the collapse criterion of a section; a section that complies with such a condition is now called "compact". It has been then recognized that, at least in bending, the formation of a plastic hinge needed a large capacity of rotation. Thus a large amount of plastic deformation is required prior to the occurence of any plate buckling, with the consequence that the limiting value of the plate slenderness is lower for compact sections than for semi-compact ones. Usual hot-rolled sections made with the most common steel grades, i.e. Fe 360 and Fe 510, belong to compact sections.

On the opposite to heavy steel construction - structures made with hot-rolled sections belong to this range - the use of structural sheets and sections with very thin walls developped with view to special applications or as sheating (roofs, façades,...) of heavy constructions. These sections and sheets are most often cold formed. Specific design rules have been established especially for such structural components, that were produced using light gage steel. In this respect, most of the theoretical and experimental developments came from the United States and the first wide-spread book on the topics was the "Light Gage Cold-Formed Steel Design Manual" [1]. It is obvious that in the range of large plate slenderness values, plate buckling is elastic ; it benefits usually from an appreciable postcritical strength reserve and is only slightly affected by the now well-known detrimental effect of the geometrical - and structural imperfections. These imperfections consist mainly in an out-of-flatness of the plate elements and in residual stresses due to cold forming.

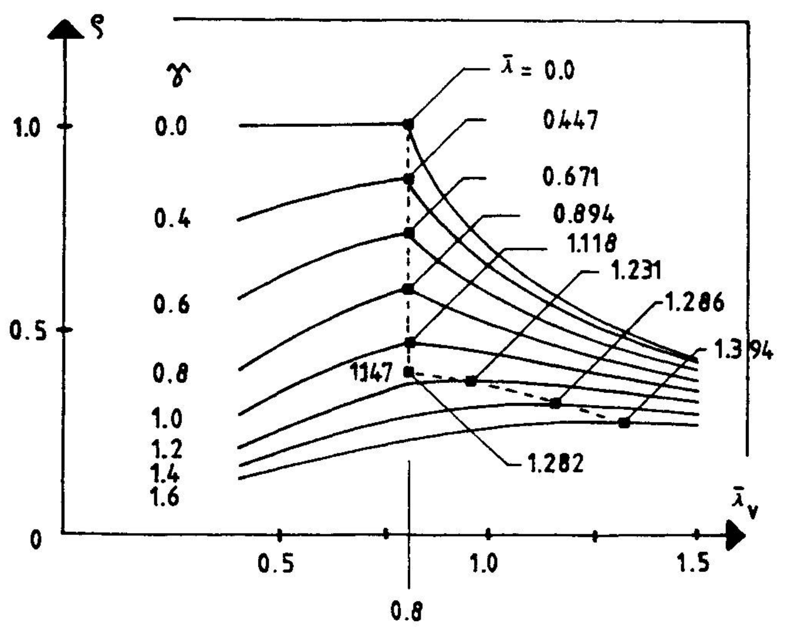

Figure 1 : Efficiency chart for square cold-formed hollow sections.

The attention has been drawn on the intermediate range of plate slenderness values, that lies between thick walls and thin walls, when a special effort was namely produced to promote slender sections, as most welded beams or thin walled hollow sections are. An investigation of square hollow sections that are currently used as columns or beam-columns, and have thus to sustain mainly compressive loads has been conducted by the authors [2]. For cold-formed sections, it yielded figure 1, that is an efficiency chart the original idea of which is due to USAMI and FUKUMOTO [3]. The efficiency ρ is measured by the ratio of the mean collapse stress σ to the material yield stress f_y, i.e. :

$$\rho = \frac{\sigma}{f_y} \tag{1}$$

The reduced plate slenderness $\bar{\lambda}_v$ of the walls of breadth b and thickness t is given by :

$$\bar{\lambda}_v = \frac{b}{1.9t}\sqrt{\frac{f_y}{E}} \tag{2}$$

The reduced column slenderness $\bar{\lambda}$ is defined as:

$$\bar{\lambda} = \lambda/\pi \sqrt{E/f_y} \tag{3.a}$$

and can be easily expressed in terms of the cross-sectional area A and of the length l as :

$$\bar{\lambda} = 2\sqrt{6}\ l/\pi \sqrt{EAb/tf_y} \tag{3.b}$$

Both above slenderness ratios may be connected according to :

$$\bar{\lambda} = \gamma/\sqrt{\bar{\lambda}_v} \tag{4}$$

where the dimensionless factor γ is equal to :

$$\gamma = 1.131\ (1/\sqrt{A})\ (f_y/E)^{0.75} \tag{5}$$

Interesting conclusions can be drawn from figure 1 :

- The optimum efficiency is never reached for a thick-walled tube, i.e. for $\bar{\lambda}_v < \bar{\lambda}_{vo}$, the limiting value $\bar{\lambda}_{vo}$ being chosen equal to 0.8 in accordance with the ECCS Recommendations [4];
- For small values of γ ($\gamma < 1.147$ in figure 1), the optimum efficiency corresponds to the limiting plate slenderness $\bar{\lambda}_v = \bar{\lambda}_{vo} = 0.8$;
- For larger values of γ, the optimum effciciency corresponds to thin walls, i.e. walls having $\bar{\lambda}_v$ larger than $\bar{\lambda}_{vo} = 0.8$.

For a specified wall breadth b, the efficiency ρ may be plotted against the wall thickness t for several values of the length l. The slope of the curves is larger in the region of thin walls than in that of thick walls ; in addition, all the curves are rather flat in the vicinity of the maximum efficiency. Figure 2 [5] illustrates the results for b = 100 mm and f_y = 360 MPa.

In the range of intermediate plate slenderness values, i.e.when $\bar{\lambda}_v$ is close to 1, plate buckling is elasto-plastic and because the critical plate buckling stress and the yield stress are close each other, the detrimental effect resulting from yielding-buckling interaction is there the most dependent on the magnitude of the structural and geometrical imperfections. That justifies the large scatter of the experimental results in this range and thus the discrepancy between the numerous proposals for plate buckling curves (fig. 3).

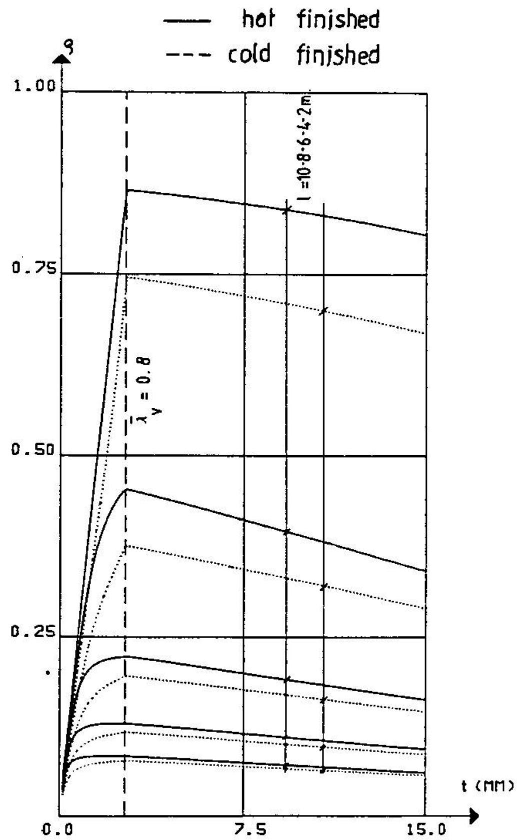

Figure 2 : Efficiency ρ against wall thickness t (f_y = 360 MPa, b = 100 mm)

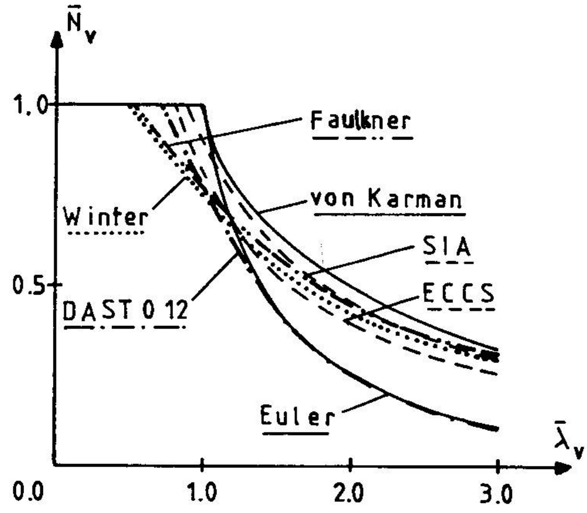

Figure 3 : Several proposals for plate buckling curves.

2. PARAMETRIC STUDY.

The authors are of the opinion that standardized European buckling curves for compression plates, ought to be suggested as it has been successfully done for the European column buckling curves. Such a goal is sensible to be reached by performing numerical simulations by means of a reliable computer program that takes account of initial structural and geometrical imperfections and allows for large deflections and plasticity. Therefore, such a study has been launched at the University of Liège with the so-called Live Energy Method, developed by LITTLE [6]. The displacements are approximated by finite series as in the RAYLEIGH-RITZ method ; each term of the series has to fulfil the boundary conditions. The axial shortening of the compression plate is successively incremented from the state of equilibrium that is known in displacements and stresses; the increments in the coefficients of the displacement series are determined by minimising the live energy according to a standard optimisation procedure. At each step strains and stresses are updated and the load is compared with that of the previous step in order to detect the maximum load, that will be the ultimate carrying capacity.

Calculations have been conducted with the aim of investigating the influence of the main parameters, which are :

- the aspect ratio of the buckled pattern, α ;
- the material steel grade, f_y ;
- the initial out-of-flatness f_o, measured as a portion of the breadth b, f_y ;

- the distribution and the amplitude of the residual stresses ;
- the membrane boundary conditions.

All the edges are assumed to be simply supported and the loaded edges are kept straight.

From the lot of numerical results, following conclusions have been drawn :

a) The ultimate load is slightly increasing with the aspect ratio α of the buckled pattern in the vicinity of $\alpha = 1$;

b) This increase is larger when the edges are constrained to remain straight, than when they are free to pull in ;

c) There is no significative difference between the results obtained for Fe 360 and Fe 510, so that dimensionless coordinates may be used within this range of material yield stresses ;

d) For a usual magnitude of initial out-of-flatness (from b/200 to b/400), the carrying capacity is increasing when the relative out-of-flatness is decreasing; this effect is only observed when the unloaded edges are free to pull in ;

e) A bi-triangular distribution of residual stresses is more favourable than a bi-rectangular one, the relative value of peak stresses at the edges being the same ;

f) Compressive residual stresses at the unloaded edges do not provide a significative drop of the carrying capacity of a similar plate that would be free from residual stresses ;

g) Tensile residual stresses at the unloaded edges have a detrimental effect, which is increasing with the amplitude of these stresses ; this evolution tends to become independent of this amplitude when the plate slenderness is increasing.

Consideration of these results incited the authors to adopt following data with view to define standardized plate buckling curves :

- an aspect ratio of 0.9 in order to comply with experimental evidence, on the one hand [7] [8],and with the actual kinematics of a long plate during plate buckling, on the other hand ;
- an initial out-of-flatness of b/200 in accordance with a previous statistical study on tolerances in steel plated structures [9] ;
- a bi-rectangular distribution of residual stresses, that is found to be safer and more in agreement with measurements ;
- residual stresses with peak tensile values at the edges equal to 0 and f_y, respectively.

Last, it is worth-while distinguishing between unloaded edges that are free to pull in and those that are kept straight.

The results of dimensionless plate buckling curves calculated in accordance with the aforementioned data are plotted in figures 4.a for unloaded edges free to pull in and in figure 4.b for unloaded edges that are kept straight.

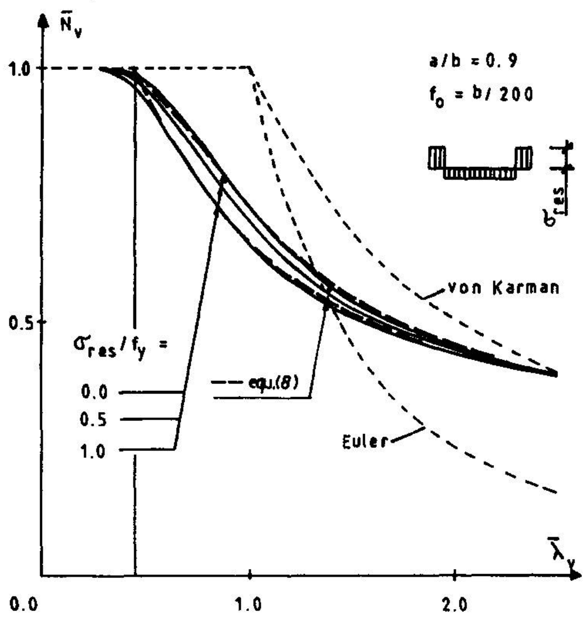

Figure 4.a.

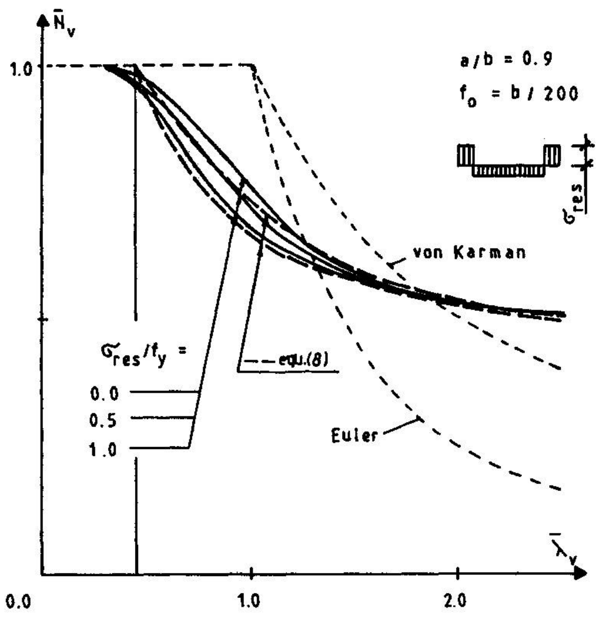

Figure 4.b.

3. PROPOSAL FOR COMPRESSION PLATE BUCKLING CURVES.

Considering that any plate buckling curve results from an interaction between the yield plateau $\bar{N}_v \equiv \sigma/f_y = 1$, for small plate slenderness ratios, and the buckling curve $\bar{N}_v = 1/\bar{\lambda}_v^{\gamma}$ of a perfect plate for large ones, a general format for plate buckling curves can be written as :

$$(1 - \bar{N}_v)\,(1 - \bar{N}_v\,\bar{\lambda}_v^{\gamma}) = \eta\,\bar{N}_v \qquad (6)$$

γ is depending mainly on the membrane boundary conditions.
$\underline{\eta}$ is an imperfection parameter that is depending on the plate slenderness ratio $\bar{\lambda}_v$, provided the latter be larger than a limiting value $\bar{\lambda}_{vo}$, that measures the length of the yield plateau $\bar{N}_v = 1$:

$$\eta = \beta\,(\bar{\lambda}_v - \bar{\lambda}_{vo}) \qquad (7)$$

β is characterizing a specified plate buckling curve.

The solution of (6) is written, account taken of (7) :

$$\bar{N}_v = \frac{1}{2\bar{\lambda}_v^{\gamma}}\,[1 + \beta(\bar{\lambda}_v - \bar{\lambda}_{vo}) + \bar{\lambda}_v^{\gamma}] - \frac{1}{2\bar{\lambda}_v^{\gamma}}\sqrt{[1 + \beta(\bar{\lambda}_v - \bar{\lambda}_{vo}) + \bar{\lambda}_v^{\gamma}]^2 - 4\,\bar{\lambda}_v^{\gamma}} \ngtr 1 \qquad (8)$$

To the authors' opinion, four plate buckling curves would be necessary but sufficient to describe the full set of conditions : unloaded edges free to pull in or constrained to remain straight, and, for each case, either zero residual stresses - covering cold formed edges - or tensile residual stresses with peak values $\sigma_{res}/f_y = 1$ at the unloaded edges - allowing for welded edges.

Experimental results and numerical simulations are comforting the idea that a same length $\bar{\lambda}_{vo}$ of the yield plateau can be reasonably accepted for both kinds of membrane boundary conditions along the unloaded edges.

By curve fitting to the results of the numerical simulation, following values of the parameters, that are describing the four aforementioned plate buckling curves, can be suggested :

Unloaded edges	$\bar{\lambda}_{vo}$	$\sigma_{res}/f_y = 0$ (cold formed edges or virgin edges)		$\sigma_{res}/f_y = 1$ (welded edges)	
		β	γ	β	γ
Free to pull in	0.45	0.19	0.75	0.34	0.45
Kept straight	0.45	0.20	0.25	0.28	0.00

The general format and the numerical values attached of the several plate buckling curves, as they are given hereabove, have only to be considered as a proposal.
It would be the task of an international working group to investigate further and to search for a general agreement on what could be called European plate buckling curves.

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