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Torsional Rigidities of Open Stiffeners to Compression Flanges*

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ABSTRACT

A critical review of code provisions and other proposals concerning the requirements for torsional rigidities of flat stiffeners to compression flanges is made. The relevant rules are investigated by means of 65 tests on compressed, stiffened plates with various loading and supporting conditions. A new design rule for the determination of the dimensions of flat stiffeners, based on their ultimate stress and the ultimate stress of the stiffened plate, is proposed and relevant design charts are given.

INTRODUCTION

Theoretical and experimental research on axially loaded plates, stiffened on one side by open stiffeners have shown, that two modes of failure are possible (Fig. 1):

— plate failure, caused by plate buckling, where the deformations at failure consist of a global, overall deflection towards the stiffener and local buckles of the plate (Fig. 1(a));
— stiffener failure, caused by lateral torsional buckling of the stiffeners, where the deformations at failure consist of a global, overall deflection towards the plate and local buckles of the stiffeners (Fig. 1(b)).

The load carrying behaviour of these plates depends largely on the failure mechanism as experimental[1,2] and theoretical research[3] has shown. Plates with stiffener failure behave almost linearly up to failure, since only second-order effects are relevant, whereas their load-carrying capacity

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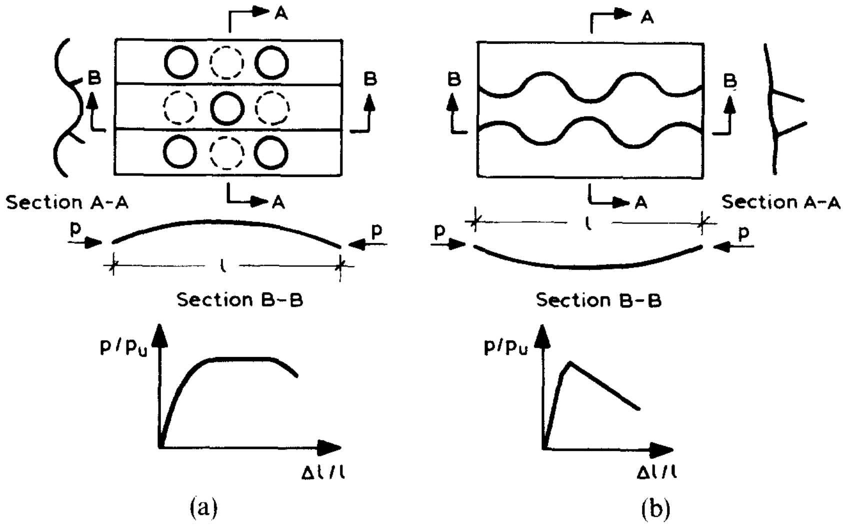


Fig. 1. Failure modes of axially compressed, stiffened plates. (a) Plate failure; (b) Stiffener failure.

rapidly decreases after failure (Fig. 1(b)). Plates with plate failure behave, before failure, largely nonlinearly because of plastic stress redistributions and second-order effects and they possess a high load-carrying capacity after failure (Fig. 1(a)).

It is, therefore, desirable (and several Codes do it) to prescribe minimum torsional rigidities of the stiffeners in order to avoid lateral torsional buckling, and consequently a stiffener mode of failure for the plate. In the present work the provisions for flat stiffeners of the Draft Code DIN 18 800 Part 3: 1989,[4] BS 5400 Part 3: 1982[5] and previous proposals made by Vayas[6] are examined through test results on compressed stiffened plates, and new rules that fit best to the tests are proposed.

REQUIREMENTS FOR FLAT STIFFENERS

In a uniformly compressed, stiffened plate the stress distribution in the cross-section is initially constant (Fig. 2(a)). This remains so as long as the stiffnesses of the plate between the stiffeners and those of the stiffeners are equal. At larger stresses (or strains) the stiffness of one of the two components is decreasing (in Fig. 2(b) the stiffness of the plate). This results in a downwards or upwards (as in Fig. 2) movement of the centroid S, so that the stiffened plate is no longer compressed centrically, but excentrically. Because of the excentrical compression the stiffened plate is deflected towards the stiffener or the plate and it fails by plate or stiffener

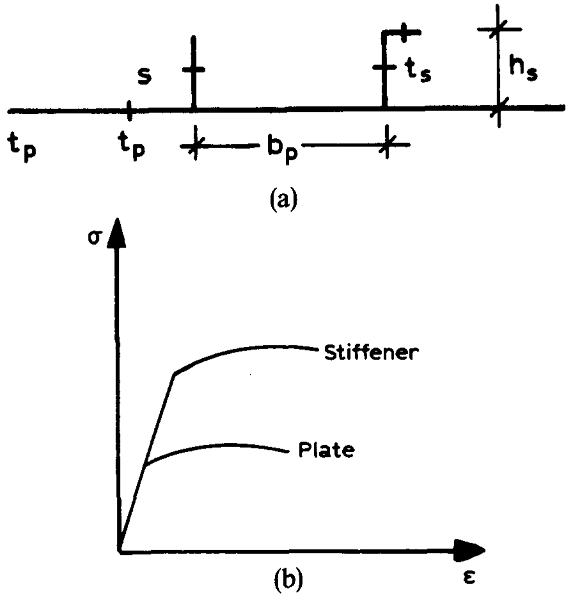


Fig. 2. Notation for and behaviour of, stiffened plates.

failure. The different Code provisions and proposals for torsional rigidition are derived from this background.

The provisions of the Draft Code DIN 18 800: Part 3: 1989[4] have been based on the assumption that the stiffness reduction of the plate or the stiffener is starting when the corresponding critical buckling stresses σ_{pi} and σ_{si} are reached. Taking into account the relevant safety factors against plate and column buckling of 1·5 and 1·7, respectively, this leads to the following condition:

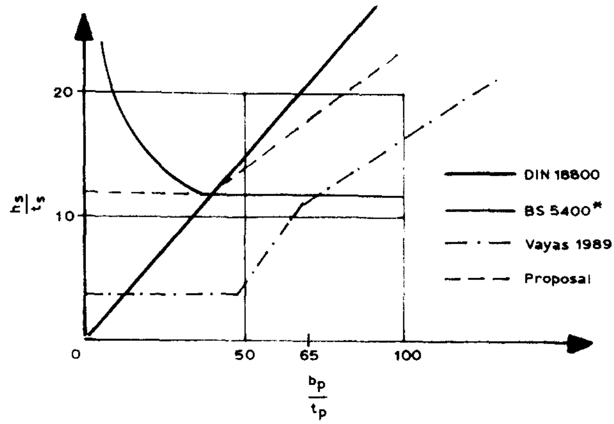
$$\sigma_{si} \leqslant \frac{1 \cdot 5}{1 \cdot 7} \sigma_{pi} \tag{1}$$

The proportions of the stiffeners with the notation of Fig. 2 should then be such that (Fig. 3):

$$\frac{h_s}{t_s} \leqslant \frac{1}{1 \cdot 3} \frac{b_p}{t_p} \tag{2}$$

The provisions of the Code BS 5400: Part 3: 1982[5] have been derived from the requirement that the slenderness of the stiffener $\bar{\lambda}_s = \sqrt{\sigma_{ys}/\sigma_{si}}$ is limited to 0·673, so that for the considered buckling curve:

$$\rho_s = \frac{1}{\bar{\lambda}_s} - \frac{0 \cdot 22}{\bar{\lambda}_s^2} \tag{3}$$



$$^{*}\frac{b_p t_p}{t_s^2}\sqrt{\frac{\sigma_{ys}}{355}}=20$$

Fig. 3. Provisions for flat stiffeners ($\sigma_y = 240$ MPa).

the ultimate stress σ_{us} is not reduced due to buckling, where

$$\sigma_{us} = \rho_s \sigma_{ys} \quad (\sigma_{ys} = \text{yield stress of the stiffener}) \tag{4}$$

The proportions of the stiffeners should be such that (Fig. 3):

$$\frac{h_s}{t_s}\frac{\sigma_{ys}}{355} \leqslant 10 \quad (\sigma_{ys} \text{ in MPa}) \tag{5}$$

For small values of the slenderness of the plate b_p/t_p the slenderness of the stiffeners can be increased due to a certain clamping effect of the plate, as shown in Fig. 3.

The provisions of the two codes are clearly contradicting. DIN 18 800 permits greater stiffener slenderness for greater plate slenderness due to the possible plate failure, whereas BS 5400 permits greater stiffener slenderness for lower plate slenderness, due to the clamping effects.

In a recent proposal, Vayas[6] derives stiffener proportions from the requirement that the ultimate stress of the stiffener σ_{us} is at least equal to the ultimate stress of the plate σ_{up}. The relevant condition is

$$\sigma_{us} = \rho_s \sigma_{ys} \leqslant \sigma_{up} = \rho_p \sigma_{yp} \quad (\sigma_{yp} = \text{yield stress of the plate}) \tag{6}$$

where the reduction factor ρ_s is determined from the European column buckling curve *c*, and the reduction factor ρ_p from the buckling curve:

$$\rho_p = 1{\cdot}13\left(\frac{1}{\bar{\lambda}_p} - \frac{0{\cdot}22}{\bar{\lambda}_p^2}\right) \tag{7}$$

The relevant requirement for the proportions of the stiffeners is shown in Fig. 3.

In the present paper the stiffener proportions are proposed to be derived from eqn (6), using as reduction factors for the stiffeners the Winter curve for simply supported plates on three edges:

$$\rho_s = \frac{0{\cdot}7}{\bar{\lambda}_s} \tag{8}$$

and, for the plate, the Winter curve for a plate supported on four edges (eqn (3), but with ρ_p, $\bar{\lambda}_p$ instead of ρ_s, $\bar{\lambda}_s$).

The above requirements lead approximately to the following condition for the proportions of the stiffeners (Fig. 3):

$$\frac{h_s}{t_s}\frac{\sigma_{yp}}{\sigma_{ys}} \leqslant \frac{1}{4{\cdot}6}\frac{b_p}{t_p} + 4{\cdot}0 \nless 12{\cdot}9\frac{\sigma_{ys}}{\sigma_{yp}} \tag{9}$$

TESTS AND TEST EVALUATION

In order to examine the different rules discussed in the previous section, the results of 65 tests on stiffened plates performed in the Institute of Steel Structures at the Technical University of Braunschweig, and reported by Barbré *et al.*[1] and Scheer and Vayas[2] are used.

The test programme is shown in Table 1. All plates were 7 mm thick (nominally) and were stiffened by four, equally spaced bulb stiffeners. The parameters of the tests were the plate slenderness b_p/t_p, the beam thickness l/i, the supporting conditions, the stress distribution and the imperfections. The A models were perfect, the B and D models had geometrical imperfections that led to plate failure (B without, D with residual stresses due to welding), and the C and E models had geometrical imperfections that led to stiffener failure (C without, E with residual stresses due to welding). In analogy to the deformations at failure, the imperfections consisted of a global deflection towards the plate (C and E) or the stiffener (B and D) and

TABLE 1
Test Programme

Ser.	Loading conditions	b/t \ l/i	A, D 20	A, D 70	A, D 100	B, E 20	B, E 70	B, E 100	C 20	C 70	C 100
II		25	×	×	×	×	×	×	×	×	×
		50	×	×	×	×	×	×	×	×	×
		75	×	×	×	×	×	×	×	×	×
III		50		×							
		75		×	×		×	×			
IV		50		×							
		75		×	×		×	×			

local stiffener (C, E) or plate (B, D) buckles. They all were four times larger than those prescribed by the Merrison rules.

All the test evaluations described in the following are based on the actual properties of the specimens (widths, thicknesses, yield strengths, imperfections, etc.). The bulb stiffeners have been considered as equivalent plates having the same critical stresses σ_{si}. In Fig. 4, the provisions of DIN 18 800: Part 3[4] are compared with the results of the tests. For each test, equivalent $(h_s/t_s)e$ and $(b_p/t_p)e$ ratios have been determined according to the following procedure. Due to the overall imperfection of the stiffened

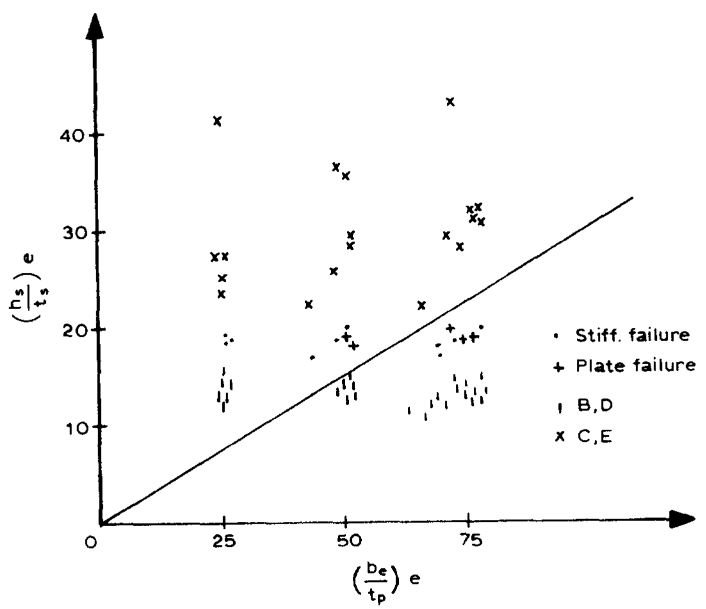


Fig. 4. Comparison of the provisions of DIN 18 800: Part 3 with the test results.

plate the initial stress distribution at the stiffeners is not uniform. For the actual stress distribution the critical stress σ_{si} has been determined and equated to the critical stress of a uniform compressed plate, simply supported on three edges having a slenderness of $(h_s/t_s)e$. The same procedure has been applied in order to determine $(b_p/t_p)e$ for test series IV where the stress distribution of the plate was not uniform.

In Fig. 4 a plate failure is expected to occur below the straight line and a stiffener failure above it. The test results show that in 12 tests in total the predicted mode of failure is incorrect. In eight tests the provisions of the Draft Code give conservative results, whereas in four tests with perfect models the rules for the stiffeners are not adequate.

In Fig. 5 the provisions of BS 5400, Part 3[5] are compared with the results of the tests. The evaluation of the equivalent width-to-thickness ratios has been done according to the same procedure described before. The test results show that in 21 tests in total the predicted mode of failure is incorrect, as stiffener failure is predicted whereas plate failure is actually taking place. In Fig. 6 the proposal of Vayas[6] is compared with the results of the tests. The stiffeners are considered as excentrically compressed bars fixed at the plate that fail under lateral torsional buckling. An equivalent slenderness λ_u is determined accordingly and the European buckling curve c is used for the evaluation of the ultimate stress σ_{us}. The test results show that in 22 tests the proposal is conservative and in one the dimensions of the stiffeners are not adequate.

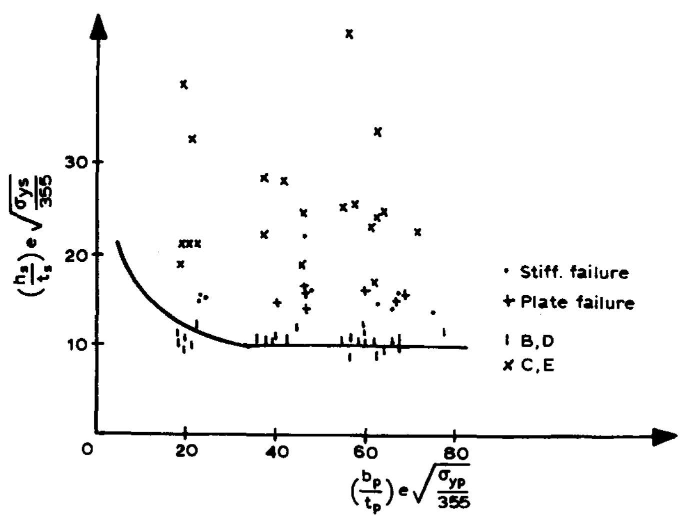


Fig. 5. Comparison of the provisions of BS 5400: Part 3 with the test results.

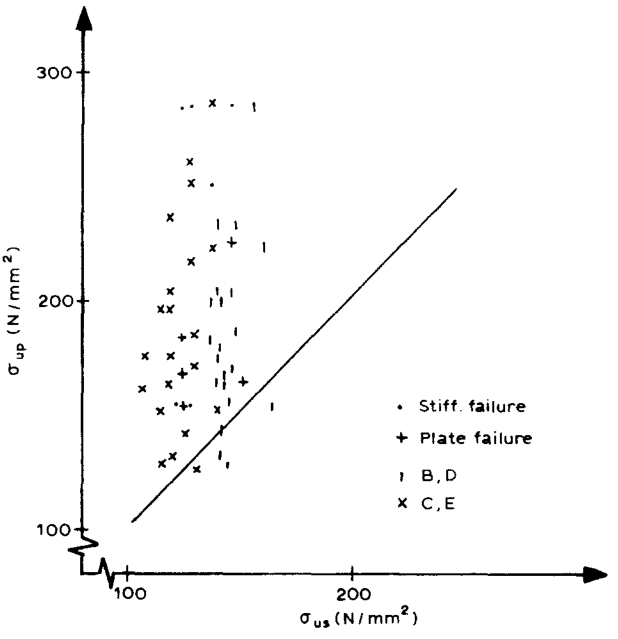


Fig. 6. Comparison of the Vayas proposal[6] with the test results.

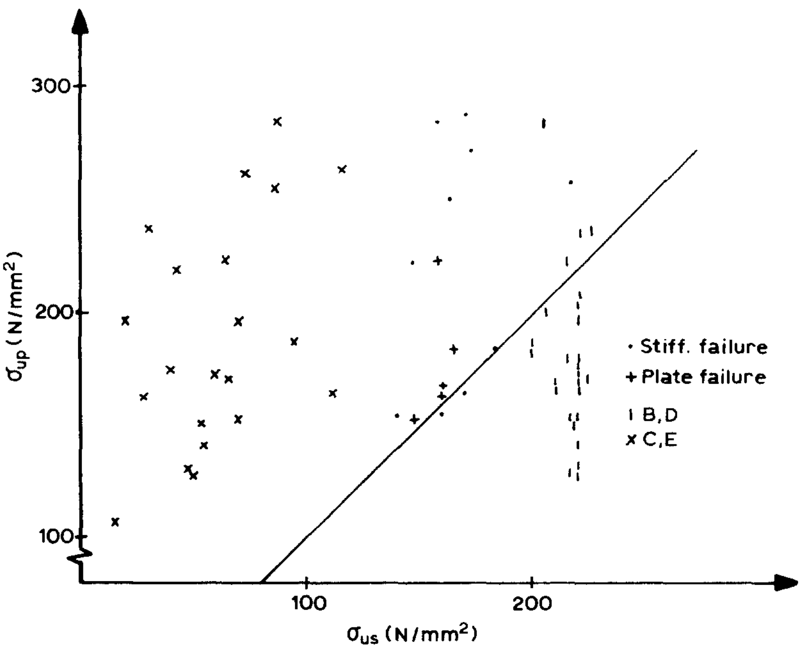


Fig. 7. Comparison of the present proposal with the test results.

In Fig. 7 the current proposal is compared with the results of the tests. In 11 tests in total the predicted mode of failure is incorrect and in two tests with perfect models the dimensions of the stiffeners are not adequate.

CONCLUSIONS

From the comparison of the considered 65 test results with the examined provisions for flat stiffeners to compressed plates the following conclusions can be drawn:

1. The test evaluation takes into account, as described before, only the global imperfections and not the local ones. The latter are so large (four times those of the Merrison rules) that they are not covered by any buckling curves. This explains the fact that the failure mechanism of so many tests is predicted incorrectly by the examined provisions.
2. The proposal of Vayas[6] is over-conservative for this type of stiffener, as it does not take into account their postbuckling strength.
3. The provisions of BS 5400: Part 3[5] are too conservative for great plate slendernesses, whereas those of DIN 18 800: Part 3[4] are too conservative for low plate slendernesses, but not safe enough for great ones.
4. The present proposal seems to fit best with the results. It leads in only two tests to unconservative results, both of which are very near to the stated criteria. It must, however, be stated that for greater slendernesses, a nonlinear behaviour of the stiffener is possible, which, according to the design method of BS 5400 should be excluded.
5. The comparison indicates that for low plate slenderness it is possible to take into account a certain clamping effect of the stiffeners to the plate, allowing thus even larger stiffeners slendernesses than proposed, but the number of tests considered does not allow for conclusive evidence.
6. For bulb stiffeners it is possible to use the same rules as for the flat stiffeners by determining an equivalent $(h_s/t_s)e$ ratio as described in the previous section.
7. Other types of open stiffeners are not expected to develop postbuckling strength so that the proposals of Vayas[6] can be used, which take into account the beneficial effects of warping.

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