Design of light weight steel structures

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IV 2

Design of light weight steel structures

Discussion

Zur Bemessung von Leichtbauten aus Stahl

Diskussion

Dimensionamento de estruturas ligeiras de aço

Discussão

Dimensionnement de charpentes légères en acier

Discussion

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The writer is gratified that his 1948 tests on post-buckling effective width continue to be of interest to the profession. He is intrigued by, but cannot entirely agree with Professor Stüssi's re-evaluation of these tests.

It is quite true that an ideally plane plate, ideally supported and loaded and, in the case of steel, possessing a straight stress strain curve up to the yield point, should not buckle before its theoretical elastic critical stress σ_{cr} is reached, provided that stress is smaller than the yield point σ_{yp}. Furthermore, it was shown by the early tests of L. Schuman and G. Back in 1930 [1] that compressed plates do not fail at σ_{cr} but develop postbuckling strength. Th. v. Karman's semi-empirical formula of 1932, which is identical with Prof. Stüssi's Eq. 3, expresses these facts in terms of an equivalent width b_e and reads

$$\frac{b_e}{b} = \sqrt{\frac{\sigma_{cr}}{\sigma_{yp}}} \qquad \text{(a)}$$

The sense of this equation can be understood as follows: A narrow, edgesupported, longitudinally compressed steel plate of thickness t with $\sigma_{cr} > \sigma_{yp}$ will fail by simple yielding at σ_{yp}. If t is kept constant and the width increased, the force F required to fail the plate increases proportional to the width b, but σ_{cr} correspondingly decreases until it becomes equal to σ_{yp}. For this particular width b' the ideal plate will simultaneously buckle and yield ($\sigma_{cr} = \sigma_{yp}$). If the width is further increased, the force necessary to fail the plate remains constant and independent of b. In fact, from Eq. (a) and since $\sigma_{cr} = K\,(t/b)^2$

$$F = \sigma_{yp}\, t\, b_e = t^2 \sqrt{K\, \sigma_{yp}} \neq f\,(b)$$

or

$$b_e = t \sqrt{\frac{K}{\sigma_{yp}}} \neq f\,(b)$$

where K is a known constant which depends on the material, and edge conditions of the plate.

Tests by E. E. Sechler in 1933 [2] as well as the writer's tests in 1946 [3] and 1948 [4] have shown that this picture is oversimplified in two respects: (1) Real, rather than ideal, plates develop buckling waves at stresses below σ_{cr} and, therefore, are not fully effective ($b_e < b$) even though $\sigma_{cr} \geqq \sigma_{yp}$, and (2) the effective width b_e for plates of width larger than b' does not remain constant but keeps increasing with increasing b' approaching the Karman value as an assymptote. The reason for the premature buckling, (1) above, is two-fold: (a) Real plates possess initial imperfections such as lack of flatness and/or eccentricity of loading which, as in columns, produce premature waving; this influence has been investigated by Hu, Lundquist and Batdorf [5] and was found to be sizeable, as is seen from Fig. 1. (b) While for steel E is assumed to be constant up to σ_{yp} and b_e is computed on this basis, in actuality residual stresses introduced by the sheet rolling process and by coldforming of sections produce a lowering of the effective proportional limit and therefore a decrease in the effective modulus for stresses larger than this proportional limit. This, in turn, reduces σ_{cr} and b_e. Since both these effects are irregular and accidental, they produce an irregular downward scattering. On the other hand, compression plates which are not isolated but are parts of structural sections, such as those tested by the writer, have some rotational restraint along their edges and for this reason their effective width tends to be larger than the usual expression for b_e for hinged edge support.

In view of the complexity of this situation, and the necessity of furnishing the light gage steel construction industry with a relatively simple and reliable design formula, the writer has developed his purposely conservative equation for b_e, based on his 1946 and 1948 tests as well as on those of Sechler, As early as 1949 [6] he gave a graphical presentation of these results whose form, except for the denominator 1.9 in the abscissas, is identical with that now given in Prof. Stüssi's figure. It is reproduced here unchanged as Fig. 1. This figure contains not only the 45 points of the writer's 1948 publication which have been used by Prof. Stüssi, but also the 26 points of his 1946 paper. It is seen that the v. Karman expression, represented by the inclined straight line and the horizontal line with ordinate 1.0, is close to an upper limit of the test results; the points which lie above that line are due to sizeable edge restraints of larger magnitude than is found in many shapes currently in use. On the other hand, the writer's curve is seen to be close to a lower limit of the test points, as is appropriate for a design determination which must be safe even for minimum edge restraint. Also shown is one calculated curve for an initial distortion of the plate equal to one-tenth of the plate thickness, i. e. of very small amount. It is seen that, according to Hu, Lundquist and Batdorf, even such a small amount reduces the equivalent width b_e noticeably. (These authors assumed the shape of initial distortion to be affine to that of the buckling surface; this will not usually be the case, which reduces the effect of initial distortion. On the other hand, in light gage steel constructions initial distortions of the order of t/2 and more are not uncommon, compared to t/10 for the curve on Fig. 1).

The largest difference between test results and the writer's equation on the one hand, and v. Karman's (and Prof. Stüssi's) expression on the other, occurs in the region where the actual stress in the plate is about equal to σ_{cr}. While Eq. (a) indicates that $b_e = b$ if $\sigma_{cr} = \sigma_{yp}$, the tests definitely show that for such plates $b_e < b$ even though the actual plate stress is equal to or even smaller than σ_{cr}. This factor is more pronounced in the writer's 1946 tests with their relatively low b/t ratios i. e. relatively high σ_{cr}, than in his 1948 tests with their larger b/t and therefore much lower σ_{cr}. The fact that Prof. Stüssi analyzed only these latter tests may have mislead him somewhat.

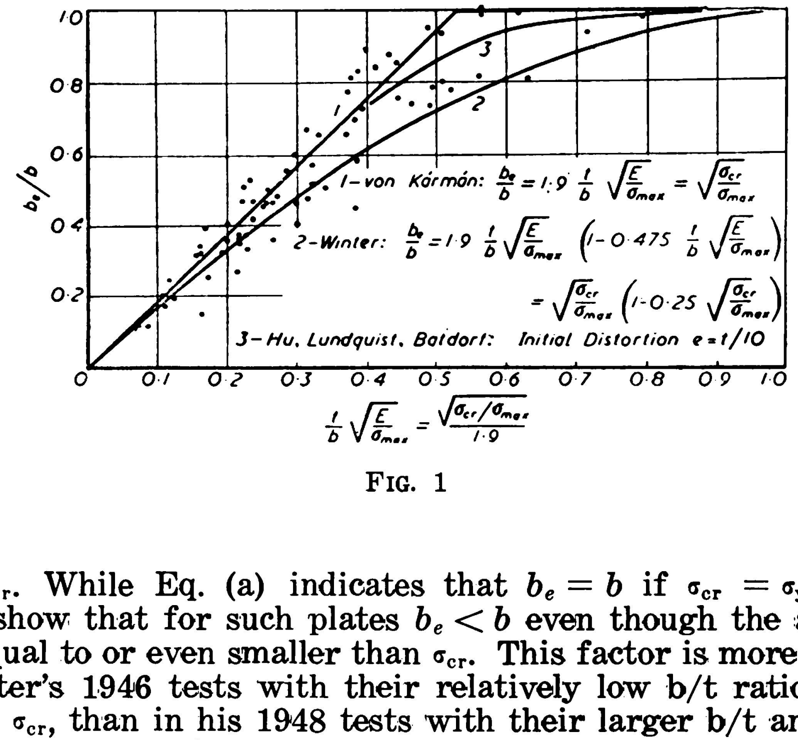

FIG. 1

It is not maintained that the writer's generalized expression

$$\frac{b_e}{b} = \sqrt{\frac{\sigma_{cr}}{\sigma_{max}}}\left(1 - 0.25\sqrt{\frac{\sigma_{cr}}{\sigma_{max}}}\right) \tag{b}$$

which holds not only for the yield point but for any plate stress σ_{max} provided $\sigma_{cr}/4 \leq \sigma_{max} \leq \sigma_{yp}$, is in any way theoretically rigorous. On the contrary, its aim is to represent reasonably well and somewhat conservatively the behavior of real compression plates which are part of real, light-gage, cold-formed steel members with all the random irregularities which this implies. It might be added that essentially this same expression has been officially in use in the U. S. A. light gage steel industry for about ten years, and that very numerous tests have been carried out by various companies to compare the performance (strength as well as deflections) of their own products with that predicted by this formula, with uniformly satisfactory results.

It should be stated at the same time that, even though the writer's formula is sometimes used in the aircraft industry, it was not originally meant to apply to non-ferrous metals with their lower E, their different stress-strain curve and residual stress properties and their artificially defined yield stress (Prof. Stüssi's σ_F). All these result in an effect of deviations from ideal conditions which is different from that which obtains in light-gage steel members as tested by the writer and reflected in his formula.

1. L. SCHUMAN and G. BACK — *Strength of Rectangular Flat Plates under Edge Compression.* Nat. Adv. Comm. for Aeronautics, Report No 356, 1930.
2. E. E. SECHLER — *The Ultimate Strength of Thin Flat Sheet in Compression.* Guggenheim Aeronaut. Labr., Calif. Inst. of Techn., Publ. No. 27, 1933.
3. GEO. WINTER — *Strength of Thin Compression Flanges.* Trans. ASCE, vol. 112, p. 527, 1947, also Proc. ASCE vol. 72, No. 2, p. 199, 1946.
4. GEO. WINTER — *Performance of Thin Steel Compression Flanges.* 3rd Congress IABSE, Prelim. Publ., p. 137, Liège, 1948.
5. P. C. HU, E. E. LUNDQUIST, S. B. BATDORF — *Effect of Small Deviations from Flatness on Effective Width and Buckling of Plates in Compression.* Nat. Adv. Comm. for Aeronautics, Techn. Note No. 1124, 1946.
6. GEO. WINTER — *Performance of Compression Plates as Parts of Structural Members,* Research, Engineering Structures Supplement (Colston Papers, vol. II) p. 179, London, 1949.

SUMMARY

While v. Karman's semi-empirical post-buckling equation, which is identical with Prof. Stüssi's, is well justified for «ideal» conditions, compression plates which are parts of «real» steel structures show two types of imperfections: deviations from flatness and residual stresses caused by cold-forming which are equivalent to a lowered proportional limit. These reduce the post-buckling strength. On the basis not only of his 1948 tests but also of his 1946 tests and those of Sechler it is shown that the writer's formula for effective width, which has been in wide use in the U. S. A. for over ten years, represents conservatively and more realistically the behaviour of real, light-gage steel structures.

ZUSAMMENFASSUNG

Während v. Karmans Gleichung für überkritisches Beulen, welche mit derjenigen Prof. Stüssi identisch ist, gut gerechtfertigt ist für «ideale» Platten, so zeigen Druckplatten, welche Teile von wirklichen Stahlleichtbauten sind, zwei Arten von Unvollkommenheiten: Abweichung von der Ebenheit und Eigenspannungen die zu einer Erniedrigung der Proportionalitätsgrenze führen. Beide vermindern die überkritische Beulfestigkeit. An Hand nicht nur seiner 1948 Versuche, sondern auch derer

von 1946, sowie auch derjenigen von Sechler, ist gezeigt, dass des Verfassers Gleichung für die wirksame Breite, welche in den Vereinigten Staaten seit zehn Jahren weite Verwendung findet, das Verhalten wirklicher Stahlleichtbauten mehr konservativ und realistisch darstellt.

RESUMO

Ao passo que a utilização da equação semi-empírica de von Karman referente à encurvadura, e que é aliás idêntica à do Prof. Stüssi, se justifica em casos «ideais» de aplicação, o mesmo não acontece com placas comprimidas fazendo parte de estruturas de aço «reais» que apresentam imperfeições de dois tipos: empenos e tensões residuais provenientes da laminagem a frio que equivalem a um abaixamento do limite de proporcionalidade. Estas imperfeições reduzem a resistência da placa encurvada. Baseando-se não só nos ensaios que efectuou em 1948 e 1946, mas também nos de Sechler, o autor mostra que a sua fórmula de determinação da largura efectiva, já largamente utilizada nos E. U. A. há mais de dez anos, representa de maneira mais conservadora e realista o comportamento das estruturas de aço de pequena espessura.

RÉSUMÉ

Tandis que l'emploi de l'équation semi-empirique de von Karman, valable pour le stade post-flambage, et qui est d'ailleurs identique à celle du Prof. Stüssi, est justifié dans les cas «idéaux» d'application, il n'en est pas de même dans le cas de plaques comprimées faisant partie de charpentes «réelles» qui présentent deux types d'imperfections: des gauchissements et des contraintes résiduelles provenant du laminage à froid et qui équivalent à une diminution de la limite de proportionnalité. Ces imperfections réduisent la résistance de la plaque après le flambage. En se fondant, non seulement sur les essais qu'il a effectué en 1948 mais aussi sur ceux de 1946 et ceux de Sechler, l'auteur montre que sa formule de détermination de la largeur effective, couramment utilisée aux E. U. A. depuis plus de dix ans, représente d'une façon plus conservatrice et plus réaliste le comportement des charpentes en acier de faible épaisseur.