

BUCKLING OF CORRUGATED SHEAR WEBS (TENTATIVE)

1. NOTATION

a, b	length and depth of web respectively	m	in
c	largest of d, e_1 or e_2	m	in
D_{11}	flexural rigidity of web for bending about y -axis, see Sketches 2.1 and 2.2, given by $D_{11} = \frac{Et^3}{12} \left\{ \frac{p}{e_1 + e_2 + 2d} \right\}$	N m	lbf in
D_{22}	flexural rigidity of web for bending about x -axis, see Sketches 2.1 and 2.2, given by $D_{22} = Et k_x^2 \left\{ \frac{e_1 + e_2 + 2d}{p} \right\}$	N m	lbf in
d, e_1, e_2	width of component flats of corrugations, see Sketches 2.1 and 2.2	m	in
E	modulus of elasticity of web material	N/m ²	lbf/in ²
E_t	tangent modulus of web material	N/m ²	lbf/in ²
f_n	stress at which $E_t = \frac{1}{2}E$	N/m ²	lbf/in ²
k_x	radius of gyration of web about x -axis	m	in
K_L	elastic local buckling coefficient defined by $q_e = K_L E \left(\frac{t}{c} \right)^2$		
M_x	stiffness of rotational restraint per unit length of web side parallel to x -axis, see Sketch 2.3	(N m/rad)/m	(lbf in/rad)/in
m	material characteristic (see Item No. 76016)		
$(N_{xy})_{cr}$	shear load per unit run	N/m	lbf/in
p	pitch of corrugations, see Sketches 2.1 and 2.2	m	in
q	shear stress in web flats at which local buckling occurs	N/m ²	lbf/in ²
q_e	elastic shear stress in web flats at which local buckling occurs	N/m ²	lbf/in ²

Issued October 1974
With Amendment A

t	thickness of web material	m	in
x, y	coordinate system as indicated in Sketches 2.1 and 2.2		
ε	coefficient of rotational restraint defined by $\varepsilon = M_x b / D_{22}$		
η	plasticity reduction factor for local buckling defined by $q = \eta q_e$		
θ	angle of corrugations, see Sketches 2.1 and 2.2	degree	degree
λ	half-wavelength in x -direction of buckle in overall mode, see Sketch 2.3	m	in

Both SI and British Units are quoted but any coherent system of units may be used.

2. NOTES

This Item presents a method for estimating the buckling of corrugated webs under shear, both overall instability of the whole web between the support members to which it is attached at its edges, and local buckling of the flat plates of which the web is composed. In Appendix A the available experimental data are set out and are compared with the theoretical predictions. In some instances agreement between theory and experiment is not good; accordingly, the Item is designated tentative*. Some factors that appear likely to affect the reliability of the theoretical estimates are reviewed in Section 3.

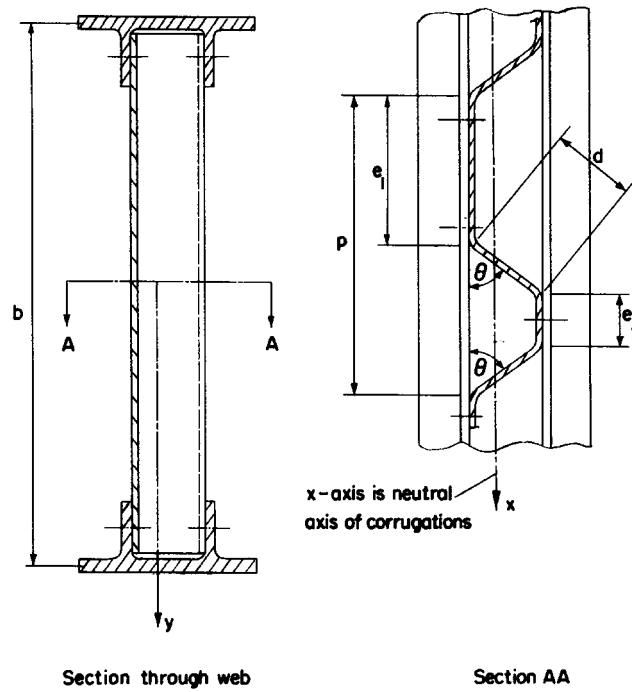
Sketch 2.1 illustrates a corrugated shear web with double-sided attachment and Sketch 2.2 shows one with single-sided attachment. Figure 1 gives the buckling shear flow, $(N_{xy})_{cr}$, and the associated half-wavelength of buckle, λ , in terms of the flexural stiffnesses along and across the corrugations, the web depth and the degree of rotational restraint provided by the support members along the corrugated edges. To facilitate use of Figure 1, Figures 2 to 5 provide $(D_{11} D_{22}^3)^{1/4} / E (td)^{3/2}$ in terms of the dimensions of the corrugations. Figure 6 gives the local buckling coefficient K_L for three common types of corrugations and Figure 7 provides plasticity reduction factors for correction of the elastic local buckling stress.

2.1 Overall Buckling

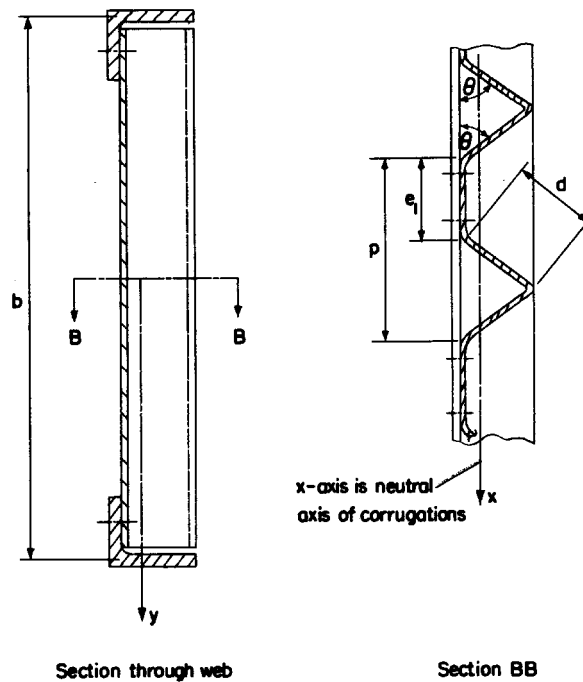
The data of Figure 1 are based upon representation of the corrugated web by an equivalent orthotropic plate, see Sketch 2.3. The deformation that occurs at buckling of corrugated webs is complex and is not always well represented by the simple orthotropic plate theory. Tables A4.2 and A4.3 of Appendix A show how the data derived from Figure 1 compare with experimental results.

Figure 1 is derived from Item No. 74005 "Buckling of long flat orthotropic plates in shear" which has been superseded by Item No. 80023 "Buckling of rectangular specially orthotropic plates". Only the flexural rigidities D_{11} and D_{22} have been taken into account in preparing Figure 1; the effect of all other terms in the flexural stiffness matrix (see Items Nos 94003 and 94004) have been neglected. The out-of-plane shear stiffnesses of the web in both the x - and y -directions have been taken to be sufficiently large for the associated deflections to be small in relation to bending deflections. The resistance to warping of the corrugations has also been neglected. The data are derived for long plates and are considered to be valid provided that a is sufficient to allow three complete half-waves to develop; with typical corrugated webs, for which D_{22} is usually very much greater than D_{11} , this limitation is usually met if a is greater than about 5λ .

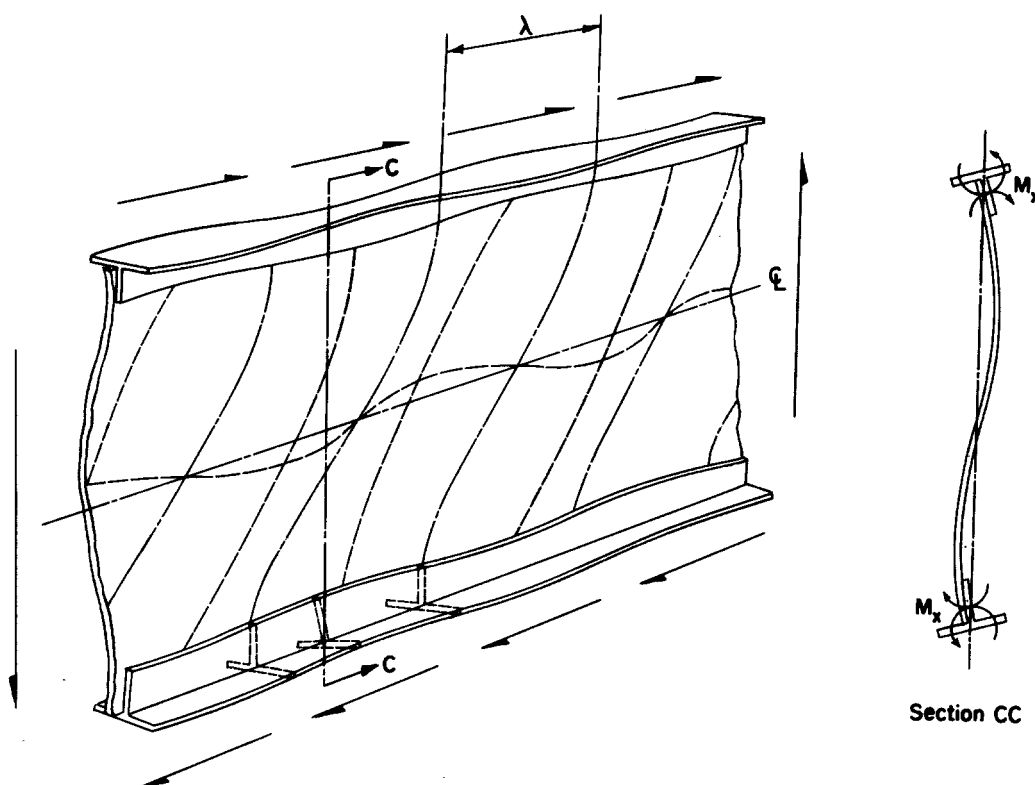
* Any further experimental data relating particularly to the factors discussed in Section 3 that you can communicate to ESDU may make it possible to revise and improve this Data Item.



Sketch 2.1 Web with double-sided attachment



Sketch 2.2 Web with single-sided attachment



Sketch 2.3 Mode of deformation of equivalent orthotropic plate

Calculation of ϵ must take full account of the probable form of deformation of the edge members. The edge restraint moment, M_x , shown in Sketch 2.3, changes sign every half-wavelength of buckle, λ . The calculation of M_x and hence ϵ , which determines λ , must therefore proceed by iteration so that M_x and λ can be matched. In most cases Item No. 73007 "Stiffness of loaded flat strips under sinusoidally distributed bending couples at their edges (for use in local buckling calculations)" may be used to estimate M_x . It should be noted that Item No. 73007 allows the influence of any direct loads acting in the support members to be taken into account when estimating M_x . Local deformations at the edge of the corrugations arising from, for example, attachment by rivets may significantly reduce ϵ and should therefore be assessed and allowed for if necessary. Typical calculations to estimate these factors are shown in the example.

2.2 Local Buckling

Figure 6 gives the local buckling coefficient for three types of corrugation. It is based upon the assumption that θ is sufficiently large for the junctions of the component flats to be nodal lines which remain straight on buckling. Curves are provided only for $0.3 \leq d/e_1 \leq 3.33$, since outside this range it is likely that overall buckling will occur at a lower load than local buckling. As noted on Figure 6, the particular case where $e_1 = e_2 = 0$ gives $K_L = 4.83$ which is the value for a long plate of width d .

Figure 7 provides the plasticity correction factor η for local buckling. This figure is identical to Figure 2 of Item No. 71005 "Buckling of flat plates in shear" and its application is illustrated in the example in this Item.

3. ACCURACY OF THE DATA

Appendix A provides the major details of 76 tests on corrugated shear webs and the data obtained from them may be used as a guide to the accuracy of the theoretical data provided. It should be noted that experimental data are only available for cases where $e_1 = 0$ and/or $e_1 = e_2$.

In general the prediction of local buckling using Figures 6 and 7 may be expected to be reasonably good. The assumption of straight nodal lines at the junctions of component flats of the corrugations appears to be satisfactory for $\theta = 35^\circ$ and above but must eventually break down at some lower value. Test data, for which failure by local buckling was predicted, are only available for $0.84 \leq d/e_1 \leq 1.67$ and $27 \leq c/t \leq 57$, except for test 2 of Table A4.3 and tests 34, 35 and 38 of Table A4.1.

It should be noted that attachment of the webs via only the parallel component flats results in a higher than average shear flow in those flats and a complex system of local stresses in the region where the load is diffused into the unattached flats. This is a detail design problem that must be considered since the associated stresses and deformations may lead to premature local instability. Attachment by a continuous weld improves the load distribution but residual stresses are likely to be present in the region of the weld and these may reduce the local buckling stress.

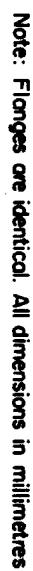
The prediction of overall buckling by means of Figure 1 may lead to significant errors. The experimental evidence of Appendix A shows that such errors appear to be conservative, predicting lower buckling loads than those that actually occur. In general the values for single-sided attachment may be expected to be closer to the actual buckling load than those for double-sided attachment.

4. DERIVATION

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|----|-------------------------------|--|
| 1. | PETERSON, J.P.
CARD, M.F. | Investigation of the buckling strength of corrugated webs in shear.
NACA tech. Note D-424, June 1960. |
| 2. | SIMHA, T.G.A.
ROTHWELL, A. | Unpublished work at Cranfield Institute of Technology, June 1974. |

5. EXAMPLE

It is required to estimate the local and overall buckling loads of the corrugated shear web shown in Sketch 5.1. The material properties of the web and edge members are identical and are $E = 72\,400 \text{ MN/m}^2$, $f_n = 339 \text{ MN/m}^2$, $m = 16$ and Poisson's ratio is 0.3. The overall length, a , of the web is 600 mm.



5.1 Estimation of Local Buckling Load

$$q_p = 6.04 \times 72\,400 \times (1.2/45)^2 = 311 \text{ MN/m}^2.$$

Then, correcting for plasticity, $q_e/f_n = 0.917$ and from Figure 7, at $m = 16$, $\eta = 0.64$ giving a local buckling stress of $q = 0.64 \times 311 = 199 \text{ MN/m}^2$, which is equivalent to a load per unit run of 239 kN/m.

5.2 Estimation of Overall Buckling Load

5.2.1 Equivalent orthotropic plate stiffnesses

The stiffness parameters are first calculated. Since $e_1/d = 2.81$ and $e_2 = 0$, then, from Figure 5 at $\theta = 40^\circ$,

$$(D_{11}D_{22}^3)^{1/4}/E(td)^{3/2} = 0.0525$$

so that

$$(D_{11}D_{22}^3)^{1/4} = 0.0525 \times 72\,400 \times 10^6 \times (1.2 \times 10^3 \times 16 \times 10^{-3})^{3/2} = 320 \text{ N m}.$$

Using the equation given in the notation

$$D_{11} = \frac{72\,400 \times (1.2 \times 10^{-3})^3}{12} \left\{ \frac{45 + 2 \times 16 \cos 40}{45 + 2 \times 16} \right\} \times \frac{10^{-3}}{10^{-3}} = 9.41 \text{ N m}.$$

$$\text{Thus, } \left\{ \frac{D_{11}}{D_{22}} \right\}^{1/4} = \left\{ \frac{D_{11}}{(D_{11}D_{22}^3)^{1/4}} \right\}^{1/3} = \left\{ \frac{9.41}{320} \right\}^{1/3} = 0.309$$

$$\text{and } D_{22} = (320^4/9.41)^{1/3} = 1040 \text{ N m}.$$

5.2.2 Calculation of rotational restraint coefficient, ε

Calculation of $(N_{xy})_{cr}$ and λ , which affects M_x , requires the web depth, b . This will be taken to be the distance between the intersection of the centre-lines of the three flanges A, B and C, which is $327 - 2 = 325 \text{ mm}$.

Figure 1 shows that for the majority of cases it is only necessary to obtain the correct order of ε for a reasonable estimate of the buckling load. Accordingly, the following calculations employ a relatively simple approach to demonstrate the size and effect of ε .

For this example the stiffness M_x may be considered as being composed of three separate parts. They are

- the bending of the flange A which transmits the restraint moment to the web from the junction of the flanges, A, B and C, termed $(M_x)_a$,
- the local deformation of the corrugations in the region of the web to flange attachments, termed $(M_x)_b$, and
- the twisting of the flange assembly, termed $(M_x)_c$.

The resultant M_x is given by

$$\frac{1}{M_x} = \frac{1}{(M_x)_a} + \frac{1}{(M_x)_b} + \frac{1}{(M_x)_c} \quad (5.1)$$

The stiffness $(M_x)_a$ may be estimated by assuming that the restraint moment transmitted by the flange A is