International Specialty Conference on Cold-Formed Steel Structures

(1971) - 1st International Specialty Conference on Cold-Formed Steel Structures

Aug 20th, 12:00 AM

Crictical Shear Loading of Curved Panels of Corrugated Sheets with Restrained Edges

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CRITICAL SHEAR LOADING OF CURVED PANELS

OF CORRUGATED SHEETS WITH RESTRAINED EDGES

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INTRODUCTION

In long cylindrical shells made of corrugated sheets longitudinal stiffeners are arranged to take the flexural tension and compression while the shear is carried by the corrugated sheets. The shear buckling of these curved corrugated sheets is a prime factor in determining the ultimate load that can be carried by such shells. This critical shear loading was examined for the case in which the longitudinal stiffeners were flexible in the direction of the sheets (1). It was also noticed that the carrying capacity of the curved shear panels increased in the experiments when the stiffeners were replaced by flexurally rigid ones that could resist the displacement of the longitudinal edges in the direction of the sheets.

Herein, the curved shear panels of corrugated sheets are re-examined theoretically with the longitudinal edges forced to remain straight in the direction of the sheets. The panels are treated as orthotropic curved plates in which the mechanical properties are the average properties of the corrugated sheets (1). This approach is justified because the interest of this paper is in the overall buckling and not the local buckling.

BOUNDARY CONDITIONS

The boundary conditions imposed on the middle surface of a buckled simply supported curved panel are:

A - Deflection and Bending Conditions: The edges of the shear panel undergo no deflection and are free from moment lateral to the sheets, i.e.:

$$\text{along } x = 0 \text{ and } x = a \qquad w = \frac{\partial^2 w}{\partial x^2} = 0 \tag{1a,b}$$

$$\text{along } s = \pm b/_2 \qquad w = \frac{\partial^2 w}{\partial s^2} = 0 \tag{1c,d}$$

in which w = the displacement of the middle surface in the z- direction; x, s, and z being, respectively, the longitudinal, circumferential, and radial coordinates as shown in Fig. 1; a, b = length and width of the shear panel.

B - Conditions in the Plane of the Panel (Membrane Conditions): The edge members are assumed to be so rigid that the edges of the panel are prevented from any lateral displacement or longitudinal strain, i.e.:

$$\text{along } x = 0 \text{ and } x = a \qquad \frac{\partial u}{\partial s} = 0 \tag{2a}$$

$$\text{and } \varepsilon_s = n_s = 0 \tag{2b}$$

$$\text{along } s = \pm b/_2 \qquad \frac{\partial v}{\partial x} = 0 \tag{2c}$$

$$\text{and } \varepsilon_x = n_x = 0 \tag{2d}$$

in which u, v = displacement in the x-, and s- directions, respectively, ε_x, ε_s = axial strain of the middle surface in the x- and s- directions, respectively; n_x, n_s = axial force per unit length acting in the x- and s- directions, respectively.

The conditions 2b and 2d can be modified and expressed in terms of the displacement components u and v as follows:

Along $s = +\frac{b}{2}$ and $s = -\frac{b}{2}$ the differentiation of n_x with respect to x is equal to zero, i.e.:

$$\left(\frac{\partial n_x}{\partial x}\right)_{s = \pm\frac{b}{2}} = 0 \tag{3a}$$

The conditions of equilibrium in the s- and x- directions are:

$$\frac{\partial n_s}{\partial s} + \frac{\partial n_{xs}}{\partial x} = 0 \tag{3b}$$

$$\text{and} \qquad \frac{\partial n_x}{\partial x} + \frac{\partial n_{xs}}{\partial s} = 0 \tag{3c}$$

Substituting Eq. 3a in 3c leads to:

$$\left(\frac{\partial n_{xs}}{\partial s}\right)_{s = \pm\frac{b}{2}} = 0 \tag{3d}$$

Eq. 3d is differentiated with respect to x and substituted in Eq. 3b leading to:

$$\left(\frac{\partial^2 n_s}{\partial s^2}\right)_{s = \pm\frac{b}{2}} = 0 \tag{3e}$$

The relation between the membrane force n_s and the axial strain ε_s is (1):

$$n_s = \frac{1}{D_s}\varepsilon_s \tag{4a}$$

in which D_s = the axial rigidity in the s- direction. The geometric relation in the s- direction is given (4) by:

$$\varepsilon_s = \frac{\partial v}{\partial s} + \frac{w}{r} \tag{4b}$$

Applying Eq. 4b and 4a into Eq. 3e the boundary condition Eq. 2d, along $s = -\frac{b}{2}$ and $s = +\frac{b}{2}$, can be replaced by:

$$\frac{\partial^3 v}{\partial s^3} + \frac{1}{r}\frac{\partial^2 w}{\partial s^2} = 0 \tag{5a}$$

Similarly, the condition Eq. 2b, along x = 0 and x = a, can be replaced by:

$$\frac{\partial^3 u}{\partial x^3} = 0 \tag{5b}$$

GOVERNING DIFFERENTIAL EQUATIONS

The differential equations governing the buckling of a shear panel are obtained by considering the orthotropic properties outlined in reference (1) together with the equilibrium conditions and geometric relationships of an infinitesimal element dx.ds of the buckled middle surface. Because the boundary conditions are all expressed in terms of the displacement components u, v and w, the differential equations are also developed to be in the displacement components. These are:

$$D_x\frac{\partial^4 u}{\partial x^4} + \frac{D_xD_s}{D_{xs}}\frac{\partial^4 u}{\partial x^2\partial s^2} + D_s\frac{\partial^4 u}{\partial s^4} = \frac{D_s}{r}\frac{\partial^3 w}{\partial s^2\partial x} \tag{6a}$$

$$D_x\frac{\partial^4 v}{\partial x^4} + \frac{D_xD_s}{D_{xs}}\frac{\partial^4 v}{\partial x^2\partial s^2} + D_s\frac{\partial^4 v}{\partial s^4} = -\frac{1}{r}\left[\frac{D_xD_s}{D_{xs}}\frac{\partial^3 w}{\partial s\partial x^2} + D_s\frac{\partial^3 w}{\partial s^3}\right] \tag{6b}$$

$$B_x\frac{\partial^4 w}{\partial x^4} + B_{xs}\frac{\partial^4 w}{\partial x^2\partial s^2} + B_s\frac{\partial^4 w}{\partial s^4} + \frac{D_s}{r}\left(\frac{\partial v}{\partial s} + \frac{w}{r}\right) + 2S\frac{\partial^2 w}{\partial x\partial s} = 0 \tag{6c}$$

in which D_x = the axial rigidity in the x- direction; D_{xs} = the shear rigidity; B_x, B_s = the bending rigidity in the xz- and sz- planes, respectively; B_{xs} = the torsional rigidity; r = the radius of curvature of the shear panel; and S = the buckling shear force per unit length and is considered:

$$S = k_s\left(\frac{\pi}{b}\right)^2\sqrt{B_xB_s} \tag{7}$$

in which k_s = a coefficient of shear buckling.

Note that Eq. 6b and Eq. 6c are independent of the displacement component u but they have to be solved simultaneously for w and v.

DISPLACEMENT FUNCTIONS

The following series expressions are used to present the displacement components w and v to any degree of accuracy:

$$w = \sum_{m=1,2,3}^{\infty}\sum_{n=1,3,5}^{\infty} A_{mn}\sin\frac{m\pi}{a}x\cos\frac{n\pi}{b}s + \sum_{m=1,2,3}^{\infty}\sum_{n=2,4,6}^{\infty} A_{mn}\sin\frac{m\pi}{a}x\sin\frac{n\pi}{b}s \tag{8a}$$

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$$v = \sum_{m=1,2,3}^{\infty} \sum_{n=1,3,5}^{\infty} V_{mn} \sin \frac{m\pi}{a} x \sin \frac{n\pi}{b} s$$

$$+ \sum_{m=1,2,3}^{\infty} \sum_{n=2,4,6}^{\infty} V_{mn} \sin \frac{m\pi}{a} x \cos \frac{n\pi}{b} s$$

$$+ \sum_{m=1,2,3}^{\infty} (Y_m^1 + Y_m^2) \sin \frac{n\pi}{a} x \qquad (8b)$$

Eq. 8a satisfies the deflection and bending boundary conditions, Eq. 1a to 1d. Y_m^1 and Y_m^2 are functions in y only, they are odd and even functions respectively and satisfy the homogeneous equation:

$$D_x \frac{\partial^4 v}{\partial x^4} + 2\left(\frac{D_x D_s}{2D_{xs}}\right) \frac{\partial^4 v}{\partial x^2 \partial s^2} + D_s \frac{\partial^4 v}{\partial s^4} = 0 \qquad (9)$$

For corrugated sheets, the ratio

$$\chi = \frac{\left(\frac{D_x D_s}{2D_{xs}}\right)}{\sqrt{D_x D_s}} \qquad (10)$$

is always greater than zero and less than one, therefore, Y_m^1 and Y_m^2 can be written as follows (3):

$$Y_m^1 = K_m^1 (\text{Cosh } g \alpha s \sin h \alpha s + B_m^1 \text{ Sinh } g \alpha s \cos h \alpha s) \qquad (11a)$$

$$Y_m^2 = K_m^2 (\text{Sinh } g \alpha s \sin h \alpha s + B_m^2 \text{ Cosh } g \alpha s \cos h \alpha s) \qquad (11b)$$

in which:

$$\alpha = \frac{m\pi}{a} \sqrt[4]{\frac{B_x}{B_s}} \qquad (12a)$$

$$g = \sqrt{\frac{1}{2} (1 + \chi)} \qquad (12b)$$

$$h = \sqrt{\frac{1}{2} (1 - \chi)} \qquad (12c)$$

K_m^1, K_m^2, B_m^1 and B_m^2 are integration constants which are calculated by satisfying the membrane boundary conditions along $s = \pm b/_2$ (i.e. Eq. 2c and Eq. 5a):

$$K_m^1 = \frac{1}{D_1} \sum_{n=1,3,5}^{\infty} (-1)^{\frac{n+1}{2}} V_{mn} \qquad (13a)$$

$$K_m^2 = \frac{-1}{D_2} \sum_{n=2,4,6}^{\infty} (-1)^{\frac{n}{2}} V_{mn} \qquad (13b)$$

$$B_m^1 = \frac{\nu - \zeta \text{ Tanh } G \tan H}{\zeta + \nu \text{ Tanh } G \tan H} \qquad (13c)$$

$$B_m^2 = \frac{\nu \text{ Tanh } G - \zeta \tan H}{\zeta \text{ Tanh } G + \nu \tan H} \qquad (13d)$$

in which

$$D_1 = \text{Cosh } G \sin H + B_m^1 \text{ Sinh } G \cos H \qquad (14a)$$

$$D_2 = \text{Sinh } G \sin H + B_m^2 \text{ Cosh } G \cos H \qquad (14b)$$

$$G = g \alpha \frac{b}{2} \qquad (14c)$$

$$H = h \alpha \frac{b}{2} \qquad (14d)$$

$$\nu = h^3 - 3 g^2 h \qquad (14e)$$

$$\zeta = g^3 - 3 h^2 g \qquad (14f)$$

Note that the membrane conditions along x = 0 and x = a, Eq. 2a and 5b, are not taken in consideration. They have no effect on the solution because the problem is simultaneous in w and v only while these conditions are in terms of the displacement component u.

By substituting Eqs. 8a and 8b into the differential Eq. 6b, the displacement coefficients V_{mn} are expressed as functions of the corresponding deflection coefficients A_{mn}:

$$V_{mn} = (-1)^n \frac{b}{r\pi} \phi_{mn} A_{mn} \qquad (15)$$

in which:

$$\phi_{mn} = \frac{\frac{D_x}{D_{xs}} n m^2 + \left(\frac{a}{b}\right)^2 n^3}{\frac{D_x}{D_s} m^4 \left(\frac{b}{a}\right)^2 + \frac{D_x}{D_{xs}} m^2 n^2 + n^4 \left(\frac{a}{b}\right)^2} \qquad (16)$$

Eq. 8a and Eq. 8b are substituted in Eq. 6c, then the displacement coefficients V_{mn} are substituted by the corresponding deflection coefficients A_{mn} as by Eq. 15. The resulting equation is multiplied by a single term of the deflection series, Eq. 7a (with $m = m_1$ and $n = n_1$) and is integrated from x = 0 to x = a and from $s = -b/_2$ to $s = +b/_2$. This Galerkin method of solution leads to the following equation which governs the buckling condition:

$$\frac{1}{k_s} Q_{m_1 n_1} A_{m_1 n_1} + \frac{1}{k_s} \cdot \sum_{n=1,2,3}^{\infty} L_{m_1 n} \phi_{m_1 n} A_{m_1 n}$$

$$+ \sum_{n=1,2,3}^{\infty} \sum_{n=1,2,3}^{\infty} K_{mm_1 nn_1} A_{mn} = 0 \qquad (17)$$

$$Q_{m_1 n_1} = \frac{\pi^2}{32} \left(\frac{b}{a}\right) [X_{m_1 n_1} + \sqrt{\frac{D_s}{D_x}} \left(\frac{a}{b}\right)^2 \theta^2 (1 - n_1 \phi_{m_1 n_1})] \qquad (18a)$$

$$X_{m_1 n_1} = \sqrt{\frac{B_s}{B_x}}\, n_1^4 \left(\frac{a}{b}\right)^2 + \frac{B_{xs}}{\sqrt{B_s B_x}} (n_1 m_1)^2 + \sqrt{\frac{B_x}{B_s}}\, m_1^4 \left(\frac{b}{a}\right)^2 \qquad (18b)$$

$$\theta = \frac{1}{\pi^2} \frac{b^2}{rt} \sqrt[4]{\frac{D_x D_s t^4}{B_x B_s}} \qquad (18c)$$

$$L_{m_1 n} = \frac{\pi a}{32} \theta^2 \alpha \sqrt{\frac{D_s}{D_x}} (-1)^{\frac{n-1}{2}} (C_1 + C_2) \qquad (19a)$$

$$C_1 = \frac{1}{D_1} [K_1 (h + g B_m^1) + K_3 (g - h B_m^1)] \qquad (19b)$$

$$C_2 = \frac{1}{D_2} [K_2 (h + g B_m^2) + K_4 (g - h B_m^2)] \qquad (19c)$$

$$K_{\substack{1\\3}} = \frac{1}{(g\alpha)^2 + \tau_1^2} [\tau_1 \sin \frac{\tau_1 b}{2} \text{ Cosh } G \pm g\alpha \cos \frac{\tau_1 b}{2} \text{ Sinh } G]$$

$$+ \frac{1}{(g\alpha)^2 + \tau_2^2} [\tau_2 \sin \frac{\tau_2 b}{2} \text{ Cosh } G \pm g\alpha \cos \frac{\tau_2 b}{2} \text{ Sinh } G] \qquad (19d)$$

$$K_{\substack{2\\4}} = \frac{1}{(g\alpha)^2 + \tau_1^2} [\pm \tau_1 \sin \frac{\tau_1 b}{2} \text{ Cosh } G - g\alpha \cos \frac{\tau_1 b}{2} \text{ Sinh } G]$$

$$+ \frac{1}{(g\alpha)^2 + \tau_2^2} [\mp \tau_2 \sin \frac{\tau_2 b}{2} \text{ Cosh } G + g\alpha \cos \frac{\tau_1 b}{2} \text{ Sinh } G] \qquad (19e)$$

$$\tau_1 = h\alpha + \frac{n\pi}{b} \qquad (19f)$$

$$\tau_2 = h\alpha - \frac{n\pi}{b} \qquad (19g)$$

$1/_{k_s}$ is assumed:

$$\frac{1}{k_s} = (1 - \lambda) \qquad (20)$$

and Eq. 17 is written in a matrix form:

$$(A - \lambda B)\, X = 0 \qquad (21)$$

in which, A and B are square symmetric matrices and X is a vector of the deflection coefficients A_{mn}. Eq. 21 is multiplied by the inversion of the matrix B:

$$(A\, B^{-1} - \lambda\, I)\, X = 0 \qquad (22)$$

Eq. 22 represents a system of infinite number of simultaneous homogeneous equations. For calculating the eigenvalues λ only a limited number of the coefficients A_{mn} are considered, $n = 1,2,3 \ldots \bar{n}$ and $m = 1,2,3 \ldots \bar{m}$. This leads to $\bar{n} \cdot \bar{m}$ possible roots from which the minimum value of λ is considered since it leads to the minimum coefficient k_s. Either one of the IBM subroutines NROOT or ATEIG is applied to find the roots λ.

OBSERVATIONS

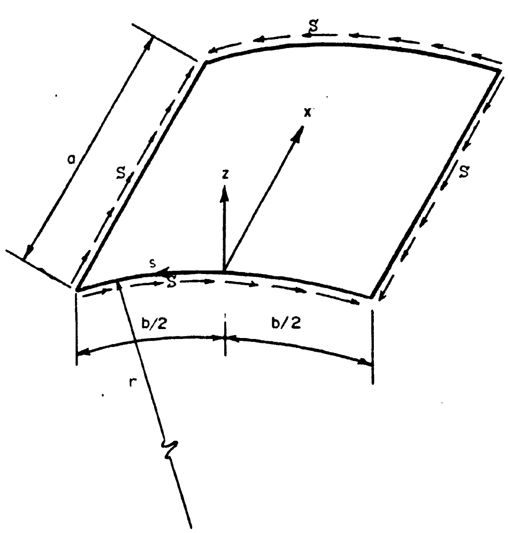
1 - The shear strength of the curved panels increases when the longitudinal edges are forced to remain straight rather than being free to move in the curved direction of the sheets. This increase is attributed to the membrane forces developed at the longitudinal edges acting in the curved direction and thus having components perpendicular to the sheets. However, restrained curved edges have no effect on the results since there is no curvature lateral to them, in the longitudinal direction. This explanation is apparent in the mathematical formulation of the problem in which Eqs. 6b and 6c are solved simultaneously for the displacement components w and v. The solution is independent of Eq. 6a which encounters the displacement component u that governs the membrane boundary conditions along the curved edges.

2 - The experiment reported in reference (1) for a shear panel with longitudinal edge members of angles 2-in. x 2-in. x 1/4 in. has a critical load of 150 lb/in. This buckling load is examined theoretically here and is found to be 180 lb/in. The deviation between the experimental and theoretical results is attributed to the theoretical assumption that the longitudinal edges are perfectly straight. This assumption cannot be exactly fulfilled in the experiments. On the other hand, the results obtained theoretically for the shear panels with free longitudinal edges (1) are less than those obtained experimentally although the experiments were arranged so that the longitudinal edges could move as free as possible.

Therefore, it is concluded that the theoretical assumption that the longitudinal edges are either completely free or completely restrained gives the lower or upper limit of the strength of practically used shear panels.

3 - The buckling shear stress, $S/_t$, is governed by the width of the panel, b, its thickness, t, its depth of corrugation, 2f, and the ratio $\frac{b}{r}$. The effect of each of these variables is shown in Figs. 2a to 2d when all but one variable are kept constant in each figure. These figures also compare the shear strength of the two cases of free and restrained longitudinal edges.

4 - The most commonly used patterns of standard corrugated sheets in Canada and the U.S.A. are those designated as standard 2-1/2 in. or 1-1/4 in. (2). Considering this type of corrugation and different values of θ and $a/_b$, the values of the shear coefficient, k_s, are calculated and presented in Figs. 3a to 3c and tables 1 to 3 for practical use of GA 26, 24 and 20.



The System of Coordinates of the Shear Panel

Figure 1

TABLE 1. - Coefficient of Buckling k_s for Sheets of GA 26 (t = 0.018 in.)

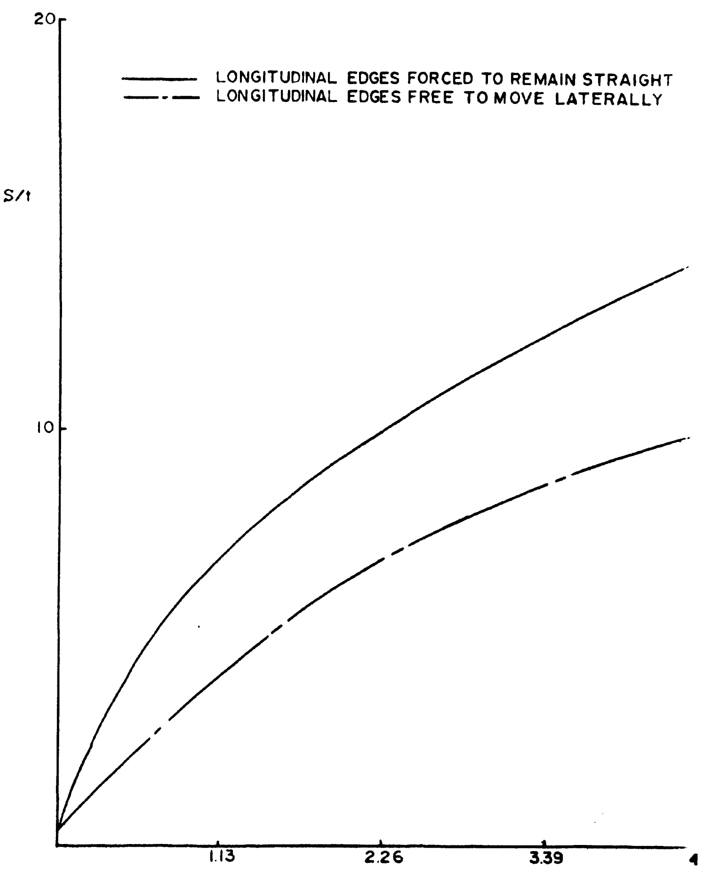
θ	a/b				
	0.5	0.75	1.0	2.0	3.0
(a) Corrugation in Curved Direction					
0	21.3	20.5	20.3	20.3	20.3
1.25	26.1	25.3	25.3	25.3	25.3
2.5	34.3	33.4	33.4	33.4	33.4
5	50.2	49.4	49.4	49.4	49.4
10	78.7	78.7	78.7	78.7	78.7
20	127.2	127.2	127.2	127.2	127.2
40	202.7	202.7	202.7	202.7	202.7
80	296.0	296.0	296.0	296.0	296.0
160	426.8	425.0	425.0	425.0	425.0
320	656.4	608.9	604.9	604.9	604.9
640	994.4	907.1	858.5	858.5	858.5
(b) Corrugation in Longitudinal Direction					
0	81.4	35.6	20.3	5.31	2.52
1.25	81.4	35.6	20.3	5.33	2.55
2.5	81.4	35.6	20.3	5.38	2.66
5	81.6	35.7	20.4	5.55	3.03
10	82.1	35.8	20.5	6.15	3.86
20	83.8	36.2	21.1	7.48	5.26
40	85.1	37.7	23.2	10.1	7.81
80	90.2	42.7	27.9	15.2	12.4
160	108.5	54.6	38.8	24.7	20.4
320	166.9	97.1	73.5	43.4	34.4
640	340.0	246.4	199.7	91.1	62.3

TABLE 2. - Coefficient of Buckling k_s for Sheets of GA 24 (t = 0.024 in.)

θ	a/b				
	0.50	0.75	1.0	2.0	3.0
(a) Corrugation in Curved Direction					
0	18.2	18.2	17.7	17.7	17.7
1.25	23.2	22.2	22.2	22.2	22.2
2.5	30.2	29.3	29.3	29.3	29.3
5	44.1	43.1	43.1	43.1	43.1
10	68.4	68.4	68.4	68.4	68.4
20	110.1	110.1	110.1	110.1	110.1
40	173.7	173.7	173.7	173.7	173.7
80	259.2	255.5	255.5	255.5	255.5
160	373.7	370.7	370.7	370.7	370.7
320	578.3	526.1	526.1	526.1	526.1
640	939.8	819.0	765.5	749.5	747.9
(b) Corrugation in Longitudinal Direction					
0	70.0	31.1	17.7	4.73	2.39
1.25	70.0	31.1	17.7	4.78	2.44
2.5	70.0	31.1	17.7	4.89	2.57
5	70.0	31.2	17.8	5.18	2.99
10	70.0	31.4	18.0	5.85	3.96
20	70.4	32.0	19.0	7.51	5.56
40	71.9	33.9	21.6	10.5	8.46
80	77.2	39.1	27.4	16.2	13.5
160	95.9	52.4	39.5	26.3	22.2
320	155.5	96.2	75.0	45.5	36.9
640	343.8	255.7	200.6	90.5	64.4

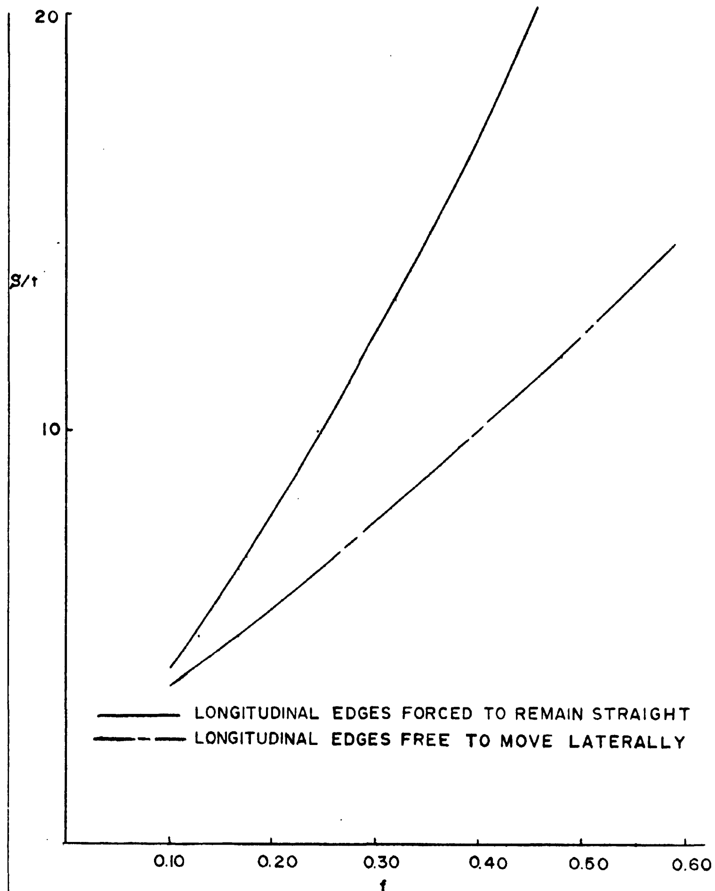
TABLE 3. - Coefficient of Buckling k_s for Sheets of GA 20 (t = 0.036 in.)

θ	a/b				
	0.5	0.75	1.0	2.0	3.0
	(a) Corrugation in Curved Direction				
0.0	16.0	15.1	14.7	14.7	14.7
1.25	19.6	18.7	18.3	18.3	18.3
2.5	25.8	24.3	23.9	23.9	23.9
5	36.8	35.5	35.0	35.0	35.0
10	56.4	55.4	55.3	55.3	55.3
20	90.0	89.1	89.1	89.1	89.1
40	140.0	140.0	140.0	140.0	140.0
80	209.8	208.1	208.1	208.1	208.1
160	324.3	302.6	300.1	300.1	300.1
320	494.6	451.7	428.3	428.3	428.3
640	830.4	686.6	657.4	605.6	605.6
	(b) Corrugation in Longitudinal Direction				
0.0	57.5	25.8	14.7	3.99	1.99
1.25	57.5	25.9	14.8	4.04	2.19
2.5	57.5	25.9	14.8	4.19	2.58
5	57.6	26.0	14.9	4.70	3.13
10	57.7	26.3	15.4	5.80	4.27
20	58.2	27.3	17.0	7.79	6.21
40	60.0	30.2	20.4	11.4	9.49
80	65.7	37.1	27.6	17.9	15.2
160	84.3	52.1	41.8	29.4	24.9
320	145.6	97.8	77.2	49.9	41.2
640	356.1	261.8	195.0	92.1	69.9



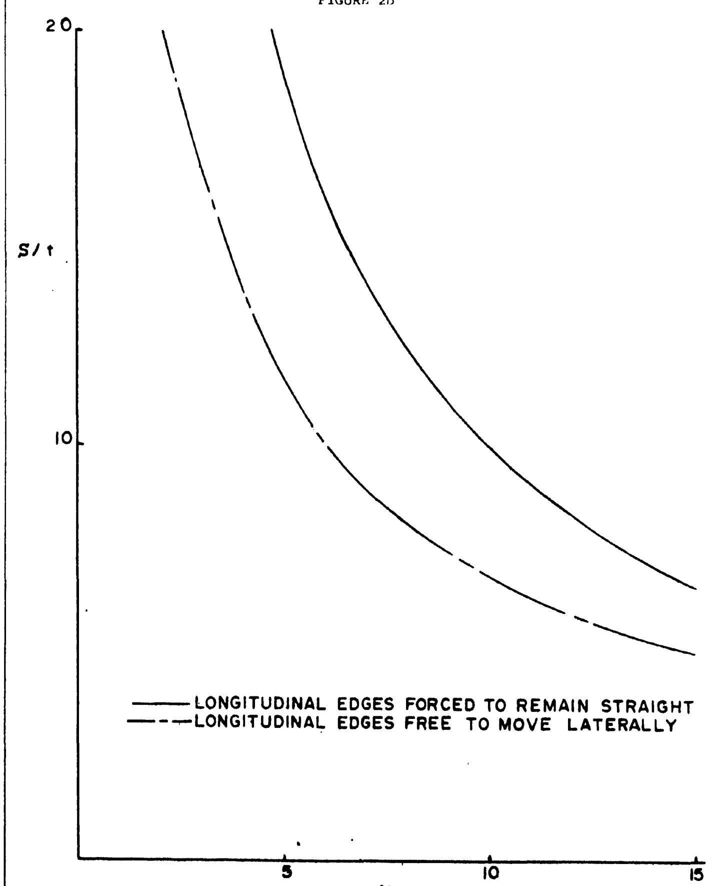
The Critical Shear Stress vs. The Ratio $b/_r$

FIGURE 2a



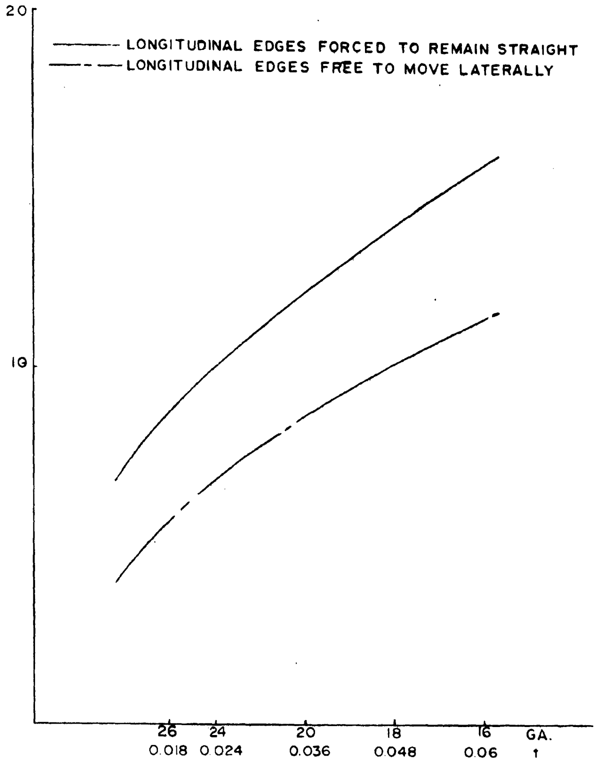
The Critical Shear Stress vs. Half The Depth of Corrugation

FIGURE 2b



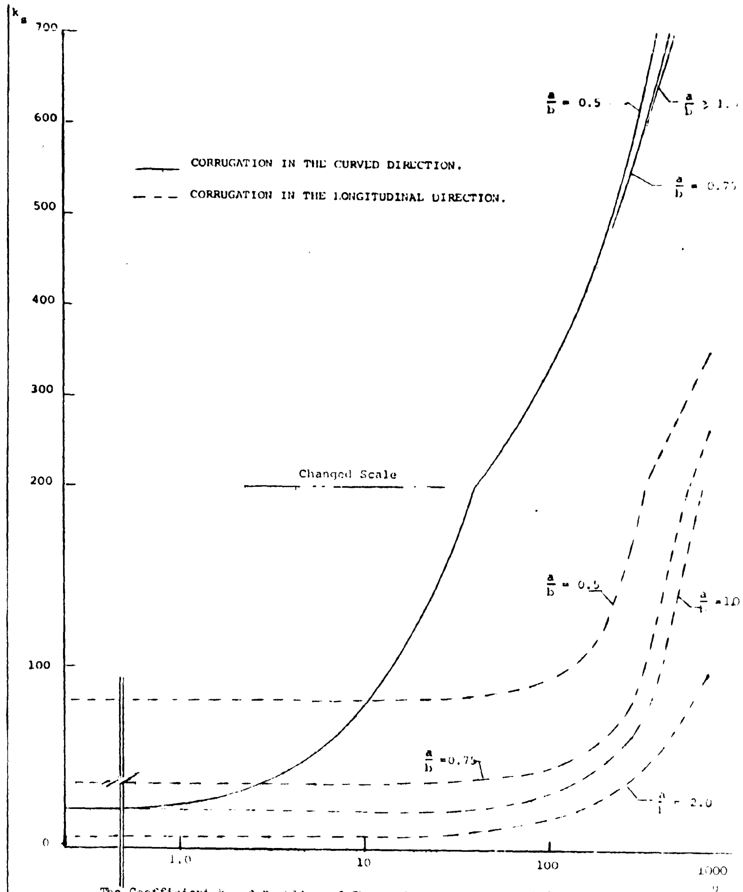
The Critical Shear Stress vs. The Width of The Panel

FIGURE 2c



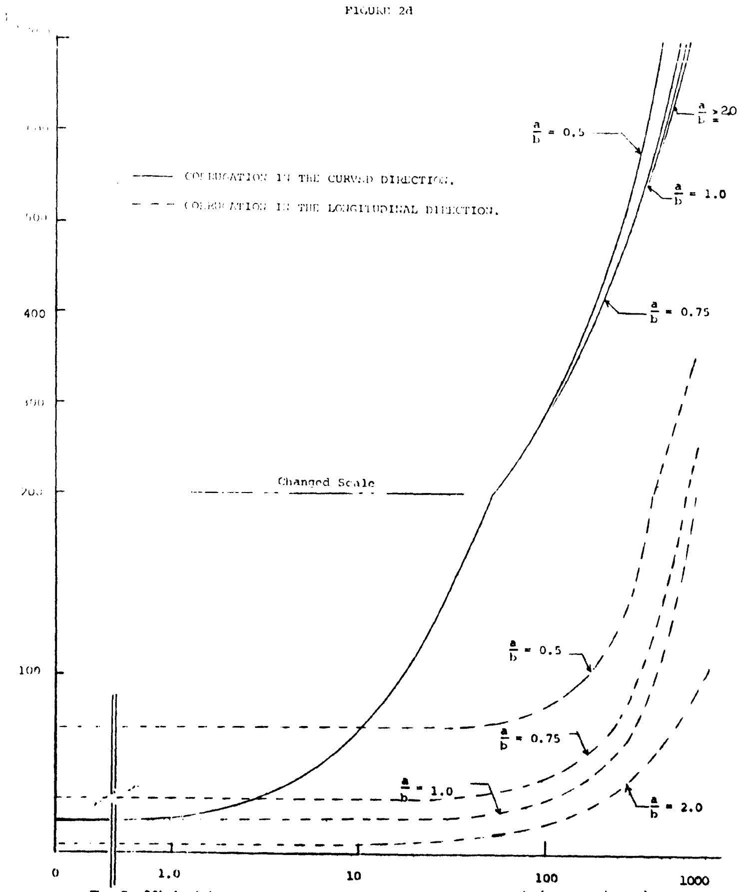
The Critical Shear Stress vs. The Thickness of The Sheet

FIGURE 2d



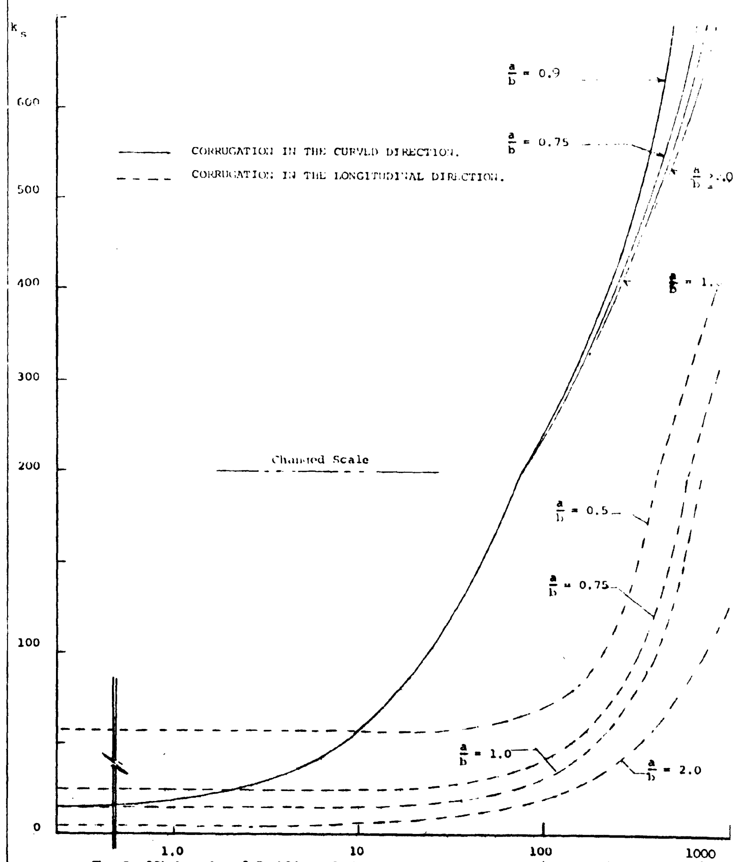
The Coefficient k_s of Buckling of Shear Diaphragms of GA 26 (t = 0.018 in.)

Figure 3a



The Coefficient k_s of Buckling of Shear Diaphragms of GA 24 (t = 0.024 in.)

Figure 3b



The Coefficient k_s of Buckling of Shear Diaphragms of GA 20 (t = 0.036 in.)

Figure 3c

CONCLUSION

This paper examines theoretically the buckling problem of curved shear panels with longitudinal edges forced to remain straight. This problem is encountered in the design of long shells of corrugated sheets with flexurally rigid longitudinal stiffeners. Curves and tables are given for the simple calculation of critical shear load. The results obtained here present an upper limit to the shear strength of such panels while the lower limit can be obtained from reference (1).

ACKNOWLEDGEMENT

Appreciation is expressed to the National Research Council of Canada for financial support for this work under Grant No. A-4350.

APPENDIX I - REFERENCES

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3 - Cornelius, H., "Die Berechnung der ebenen Flächentragwerke mit Hilfe der Theorie der orthogonal - anisotropen Platten", Der Stahlbau, Vol. 21, 1952, pp. 21, 43 and 60.

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APPENDIX II - NOTATION

The following symbols are used in this paper.

a	=	length of shear panel
b	=	width of shear panel
B_x, B_s	=	bending rigidity in the xz- and sz- planes respectively
B_{xs}	=	torsional rigidity
D_x, D_s	=	axial rigidity in the x- and s- directions respectively
D_{xs}	=	shear rigidity in the xs plane
E	=	modulus of elasticity of diaphragm material
f	=	half depth of corrugation
k_s	=	coefficient of shear buckling
n_x, n_s	=	axial force per unit length acting in the x- and s- directions respectively
n_{xs}	=	shear force per unit length acting in x-s plane
r	=	radius of curvature of shear panel
S	=	buckling shear force per unit length
t	=	average thickness of corrugated sheet
u, v, w	=	displacement in x-, s- and z- directions respectively
$\varepsilon_x, \varepsilon_s$	=	axial strain in x- and s- directions respectively
θ	=	$\frac{1}{\pi^2} \frac{b^2}{rt} \sqrt[4]{\frac{D_x D_s t^4}{B_x B_s}}$