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Inelastic Flexural Stability of Corrugations

Raymond L. Cary\*

SUMMARY

Empirically derived dimensional limits are presented for arc-and-tangent corrugated profiles to ensure local stability during inelastic bending, for example, during manufacture of culverts, storage bins and conveyer covers. An empirical relationship for corrugation moment capacity is also presented.

Twenty-four arc-and-tangent corrugated steel sheet specimens in eight profile and gage combinations were tested in flexure with uniform moment. Test parameter ranges were: arc inside radius/thickness ratios (3.7 to 27.7), tangent length/thickness ratios (4.4 to 23.6), material yield strengths (40 to 50 ksi (276 to 345 MPa)), and tangent length varied from .45 to 1.7 times arc inside radius.

\* Senior Staff Engineer, Structural Research, Armco, Inc., Middletown, Ohio  
45043

## INTRODUCTION

This study investigates the subject of local stability of arc-and-tangent corrugated profiles when subjected to inelastic bending. Corrugated sheets are frequently curved to form products such as culverts, storage bins and conveyer covers. The engineer must decide if the corrugated sheet can be satisfactorily curved without buckling. Certain structure installations may require the engineer to know the corrugation's critical flexural strain. Engineers have used experience and engineering judgment, based upon elastic behavior, in developing dimensional limits for such corrugated products. Geometric limits based on elastic behavior may be unconservative, however, when corrugations sustain large inelastic strains. The engineer's experience may also be lacking.

The only published research with some applicability to arc-and-tangent corrugated profiles deals with inelastic buckling of circular tubes. Sherman's(2) research is one example. Sherman conducted tests to determine the required outside diameter to thickness ratio (D/t) limit to prevent local buckling at fully developed plastic hinges. He concluded members with D/t of 35 or less can sustain sufficient rotations to fully develop plastic hinges and failure mechanisms where  $F_y = 44$  ksi (303 MPa). Maximum strains, however, were only about 2%. This is considerably less than many corrugated structures require to be successfully formed.

Sherman(2) also stated critical strain and other inelastic buckling characteristics appear to be related to  $\sqrt{F_y}$  rather than to  $F_y$  or to a buckling parameter of  $(t/D)^2 (F_y/E)$  rather than  $(t/D) (F_y/E)$ .

This current study presents empirically derived relationships from twenty-four flexural tests which relate critical corrugation dimensional limits to critical buckling strain, minimum curving radius and ultimate moment capacity.

## EXPERIMENTAL PROGRAM

Flexural tests of corrugated profiles and material tests to determine mechanical properties were conducted. Illustrated in Fig. 1 with key dimensions are the three commonly available corrugated profiles tested. Listed below are the corrugations and material gages tested. Thickness equivalents for these U.S. Standard sheet gages are shown in Table 1.

- 2-2/3 x 1/2 in 8, 14, and 20 ga.
- 3 x 1 in 8, 16, and 20 ga.
- 5 x 1 in 12 and 16 ga.

(Note: 5 x 1 are nominal dimensions. This is a metric corrugation - 125 x 25mm)

Arc inside radius/thickness ( $R_i/t$ ) ratios, tangent length/thickness ( $T_L/t$ ) ratios, and material yield strengths ( $F_y$ ) are the major parameters affecting corrugation local stability. The selected profiles and material gages test a broad parameter range of  $R_i/t$  (3.7 to 27.7) and  $T_L/t$  (4.4 to 23.6). Material gages were chosen to compare corrugation behavior when either of the dimensional parameters are nearly equal in different nominal profiles.

### Material Tests

Material samples were cut from a tangent portion of each corrugated sheet test specimen. Average tensile properties are shown in Table 2 for the eight profile and gage combinations. Yield strength varied from 40 to 50 ksi (276 to 345 MPa).

### Flexural Tests

#### Test Specimens

Triplicate specimens were cut for flexural testing from each corrugation profile and gage. Each was 36 in. (914 mm) long and three or five corrugations wide, determined by the test fixture width. Specimens were cut along the profile neutral axis to ensure the free edge is unstressed in flexure.

Corrugations were measured across the entire width of each specimen and dimensions averaged to calculate appropriate design properties. Key buckling parameters  $R_i/t$  and  $T_L/t$  are listed in Table 3 as average measured values for triplicate specimens.

#### Flexural Test Procedure

The test set up is illustrated in Figures 2 through 4. Flexural specimens are subjected to a constant moment in the 3-1/2 in. (88.9 mm) long region between the two center rollers. The two support rollers, 19-1/2 in. (495 mm) apart, and two center rollers are steel rounds machined and lubricated at each end to roll freely as the specimen deflects during the test. An 1/8 in. (3.18 mm) thick neoprene cushion is bonded to each roller to distribute high local bearing pressures during the test over a portion of each arc. Figure 3 illustrates the fixture accommodating the large beam deflections necessary in this study.

A deflectionometer, illustrated in Figure 4 is placed in the valley of test specimen corrugations to measure specimen curvature in the center region of constant moment. The specimen's deflected shape in the constant moment region is conservatively assumed to be a circular arc. The deflectionometer consists of two pair of legs each spanning 3" (76.2 mm) and a linear displacement transducer (LVDT) centered between one pair of legs. The LVDT measures deflections to the nearest .0001 in. (.0025 mm) in the circular arc over a fixed chord length of 3 in. (76.2 mm) between legs. With mid chord

deflections and chord length known, the mean arc radius of curvature can be calculated by Equation 1.

$$R_C = (4b^2 + 9)/8b - d/2 \quad (1)$$

where  $R_C$  = Mean radius of curvature along the corrugated profile neutral axis

$b$  = LVDT deflection reading

$d$  = corrugation depth

With the arc radius of curvature determined the extreme fiber strain can be calculated by Equation 2.

$$\epsilon = (d + t)/2R_C \quad (2)$$

where  $\epsilon$  = extreme fiber strain

$t$  = material thickness

Equation 2 assumes no neutral axis shift which is not totally accurate. However, any inaccuracy in the calculated strain,  $\epsilon$ , is cancelled out whenever  $R_C$  is later back calculated using strains developed from Equation 2.

Initially, strain gages were also applied to test specimens to directly measure strains. Gage debonding problems as well as cost discouraged the further use of strain gages.

Loading was applied in deflection increments as recorded by the deflectometer at midspan and held steady at each increment until the load was stable for one minute. Usually, a four or five minute maximum hold stabilized loads at each increment.

A second LVDT measured fixture vertical displacement. This displacement plus deflectometer reading, applied load and panel rotations recorded by inclinometers enabled calculation of bending moments in the corrugated sheet. Bending moment equations are not shown due to length and complexities caused because loads and reactions through the fixture rollers are always normal to the curved specimen. The raw data were input to a computer program which calculated bending moment, bending radius, and strain at each loading increment.

#### Critical Buckling Strains

The author detected initial buckling by feel, running his fingers over the multiple corrugation surfaces at each deflection increment. When surface irregularities were felt, the affected corrugation, buckled component, and deflections were recorded. While this method is not sophisticated, it gave reasonably good replication of triplicate test results. Buckling always

initiated at one of the corrugations nearest the panel free edge. To eliminate influence of free edges, the test specimen was not considered buckled until an interior corrugation buckled.

After testing the 3x1 - 20 ga. specimens, it was obvious the arcs of corrugations in compression had deformed at center load lines due to large bearing pressures from the rollers. Round bar inserts the size of the arc radius were cut 3/4 in. (19 mm) long. A segment equal to the corrugation height was inserted between the center rollers at each corrugation to help distribute loads more uniformly into the flexural specimen (see Fig. 5). The same three 20 ga. specimens were retested by cutting off the previously failed center portion and reloading. All exhibited increased strain capacity before buckling. One 3x1 - 16 ga. specimen was retested in similar manner without a discernible difference in critical strain. Thus, the other two 3x1 - 16 ga. specimens were not retested. All specimens thereafter lighter than 8 ga. were tested with inserts.

To account for effects from varying material yield strengths, specimen parameters  $R_i/t$  and  $T_L/t$  were normalized with respect to yield strength. Like Sherman(2) less scatter was evident when data were normalized with  $\sqrt{F_y}$  rather than  $F_y$ . Thus,  $R_i/t$  and  $T_L/t$  were normalized to use in design by multiplying by  $\sqrt{F_y}/33$ , where  $F_y$  is the tangent tensile yield strength and 33 ksi is the AISI(1) and AASHTO(3) design yield strength for buried corrugated steel structures. Normalized corrugation parameters are shown in Table 3 along with average measured values for comparison.

Careful observation of the failure modes, critical buckling strain values, and review of numerous plots of critical strain versus normalized  $R_i/t$  and  $T_L/t$ , separately and combined, led the author to conclude  $T_L/t$  does not significantly affect flexural buckling for the range of  $R_i$  to  $T_L$  relationships tested -  $.45 R_i < T_L \leq 1.7 R_i$ .  $R_i/t$  is the dominant factor. If  $T_L$  is greater than  $R_i$ , buckling will initiate in the tangents. If  $R_i$  is greater than or equal to  $T_L$ , buckling initiates in the corrugation arcs. However, regardless of buckling mode, critical buckling strain appears unaffected.

Figure 6 plots critical flexural strains versus  $R_i/t_n$ . The three curves represent three possible choices for lower bound predictions of critical strain. The first is a modified version of a lower bound for buckling of circular tubes suggested by Sherman(2). The coefficient has been modified to account for difference in design yield strengths. This curve is too conservative for predicting critical strains of arc and tangent corrugated profiles.

The second is a general curve for the range of  $R_i$  to  $T_L$  relationships represented by the test data. Although six specimens of 8 ga. material fall below the second curve, none of the six experienced buckling. They were simply limited by the fixture geometry which would not permit additional strain to be induced. It is quite probable that corrugations with  $R_i/t_n$

of 5.5 or less will be limited by material elongation capacity rather than buckling.

The third curve appears to reasonably predict critical strains for profiles where  $T_L$  is within 10% of  $R_i$  values, the approximate relationship of 2-2/3 x 1/2 profile.

#### Ultimate Moment Capacities

$T_L/t$  appears to be the most significant factor in determining the profile's maximum moment capacity for the range of  $R_i$  to  $T_L$  relationships tested.  $R_i/t$  factors are minor contributors. Two examples help support this conclusion. The first example compares 3x1 - 20 ga. and 5x1 - 12 ga. specimens.  $R_i/t_n$  factors are nearly equal, but  $T_L/t_n$  factors differ dramatically. See Table 3. The 3x1  $T_L/t_n$  factors are about 26, and moment capacity averaged 94% of its calculated plastic moment. The 5x1  $T_L/t_n$  factors are about 11, and moment capacity averaged 107% of its plastic moment. A second example compares the 5x1-12 ga. with 2-2/3 x 1/2 - 14 ga. Here,  $R_i/t_n$  factors are different, 18.4 vs. 11.5, but  $T_L/t_n$  factors for both are about 11. Both corrugations developed 107% of their calculated plastic moment capacity.

Figure 7 is a plot which compares maximum test moments to calculated plastic moments as a function of normalized  $T_L/t$ . Plastic moment capacity is calculated by multiplying the specimen's tangent tensile yield strength by its plastic modulus. The middle curve labeled " $M_{UC}$ " is the mean of the best fit generated by a curve fitting program. All data points are within +10% of the mean. The upper and lower curves are 95% confidence limits. For design, moment capacity " $M_{UC}$ " should not exceed the plastic moment " $M_p$ ." Thus, for  $T_L/t_n \leq 16$ , the moment capacity equals the plastic moment.

#### DESIGN RECOMMENDATIONS

The following recommendations are based on limited test data and should not be used beyond the parameter range of  $.45 R_i < T_L < 1.7 R_i$  without further testing. Recommendations should be considered only as guidelines for corrugation design and are not intended to replace product testing.

#### Critical Flexural Strain

Two equations can be used for predicting critical flexural strain in arc-and-tangent corrugated profiles. Equation 3 is for a specialized range of,

$$.9 R_i \leq T_L \leq 1.1 R_i$$

$$\epsilon_{cr} = 7.85/(R_i/t_n)^2 \quad (3)$$

where  $\epsilon_{cr}$  = critical flexural strain

$R_i/t_n$  =  $R_i/t$  normalized by multiplying

by  $\sqrt{F_y/33}$  ( $\sqrt{F_y/227}$ )

$F_y$  = Material yield strength in ksi (MPa)

Equation 4 is for a broader range of,

$$.45 R_i \leq T_L \leq 1.70 R_i$$

$$\epsilon_{cr} = 5.80/(R_i/t_n)^2 \quad (4)$$

In no case should  $\epsilon_{cr}$  exceed that given in Equation 5.

$$\epsilon_{cr} \leq \text{material elongation limit} \quad (5)$$

To achieve maximum flexural strain capacity, corrugations should be designed with  $R_i/t$  and  $T_L/t$  nearly equal and as small as possible. In addition, material should be close to the minimum yield strength of 33 ksi (227 MPa).

The minimum curving radius can be calculated using Equation 6 once critical flexural strain is known.

$$R_c = (d + t)/2\epsilon_{cr} \quad (6)$$

where  $R_c$  = Mean radius of curvature of the  
the corrugated profile

$d$  = corrugation depth

$t$  = material thickness

$\epsilon_{cr}$  = critical flexural strain

#### Ultimate Moment Capacity

Arc-and-tangent corrugation ultimate moment capacity can be calculated by Equation 7.



$$M_{uc} = [1.429 - .156 \ln (T_L/t_n)] M_p \leq M_p \quad (7)$$

where  $M_{uc}$  = ultimate moment capacity

$M_p$  = calculated plastic moment

$T_L/t_n = T_L/t$  normalized by multiplying by  
 $\sqrt{F_y/33 \text{ ksi}} \quad (\sqrt{F_y/227 \text{ MPa}})$

When  $T_L/t_n$  exceeds 16 the ultimate moment capacity will be less than the calculated plastic moment. See Figure 7 for illustration.

#### SUMMARY AND CONCLUSIONS

Triplicate steel specimens in eight arc-and-tangent corrugation and gage combinations were flexural tested to determine critical inelastic buckling strain levels and ultimate moment capacities. Specimens were 36 in. (914 mm) long and three or five corrugations wide. Key corrugation parameters were material yield strength ( $F_y$ ), arc inside radius/thickness ( $R_i/t$ ) and tangent length/thickness ( $T_L/t$ ) ratios.  $F_y$  varied from 40 to 50 ksi (276 to 345 MPa),  $R_i/t$  from 3.7 to 27.7 and  $T_L/t$  from 4.4 to 23.6. All specimens were subjected to pure bending in the critical regions. Conclusions for arc-and-tangent corrugated steel profiles are, where  $.45 R_i \leq T_L \leq 1.7 R_i$ :

1. Critical buckling strains are a function of  $1/(R_i/t)^2$ .  $T_L/t$  had little influence except in determining where buckling first initiates.
2. Corrugations with  $R_i/t_n$  (normalized to 33 ksi (227 MPa) yield strength) of 5.5 or less will probably be limited by material elongation rather than buckling.
3. Sherman's(2) equation for a lower bound of buckling in circular tubes is too conservative for corrugations.
4. Ultimate moment capacity is a function of the natural logarithm of  $T_L/t$ .  $T_L/t_n$  ratios (normalized to 33 ksi (227 MPa) yield strength) must be 16 or less before the full plastic moment can be developed.  $R_i/t$  did not significantly affect moment capacity.

#### APPENDIX -- REFERENCES

1. Handbook of Steel Drainage and Highway Construction Products, Third Edition, 1983, American Iron and Steel Institute, Washington, D.C.

2. Sherman, D. R. "Tests of Circular Steel Tubes in Bending," ASCE Structural Div. Journal, ST11, American Society of Civil Engineers, Inc., New York, November 1976.
3. Standard Specification for Zinc-Coated (Galvanized) Steel Sheets for Culverts and Underdrains, AASHTO Designation: M218-82, American Association of State Highway and Transportation Officials, Washington, D.C.

## APPENDIX -- NOTATION

D	Outside diameter
E	Young's Modulus
$F_y$	Material yield strength
$M_p$	Calculated plastic moment
$M_{uc}$	Ultimate moment capacity
$R_c$	Mean curvature radius of corrugated profile
$R_i$	Corrugation arc inside radius
$T_L$	Corrugation tangent length
b	Deflectometer deflection reading
d	Corrugation depth not including material thickness
n	Subscript noting that corrugation parameter is normalized
t	Specimen material thickness
$\epsilon$	Flexural strain
$\epsilon_{cr}$	Critical flexural strain

Table 1. Abridged Table of Thickness Equivalents for U.S. Standard Sheet Gages

<u>Gage No.</u>	<u>U.S. Standard Gage for Uncoated Sheet</u>	
	<u>Customary Units (in.)</u>	<u>SI Units (mm)</u>
8	.1644	4.176
12	.1046	2.657
14	.0747	1.897
16	.0598	1.519
20	.0359	.912

Table 2. Material Properties<sup>1</sup>

<u>Corrugation</u>	<u>Gage</u>	<u>Yield Str. (ksi)</u>	<u>Ult. Tensile Str. (ksi)</u>	<u>% Elong. in 2 in.</u>
3 x 1	8	43.5	55.4	30.8
3 x 1	16	47.7	59.0	30.6
3 x 1	20	41.5	55.2	32.2
5 x 1	12	48.5	60.1	25.8
5 x 1	16	43.3	56.7	27.6
2-2/3 x 1/2	8	48.7	60.0	25.3
2-2/3 x 1/2	14	43.9	55.1	27.6
2-2/3 x 1/2	20	42.3	54.2	29.1

<sup>1</sup> Average of six tensile tests for each gage. Properties were determined from measured base metal thicknesses for coated materials.

SI Conversions: 1 in. = 25.4 mm  
1 ksi = 6.89 MPa

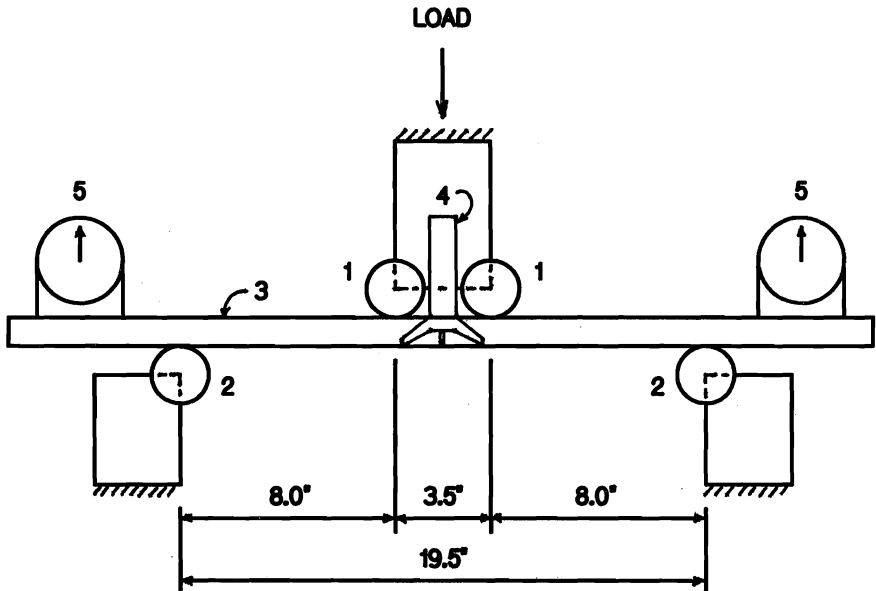
Table 3. Measured and Normalized Corrugation Buckling Parameters

<u>Corrugation</u>	<u>Gage</u>	Measured <sup>1</sup>		Normalized <sup>2</sup>	
		$R_i/t$	$T_L/t$	$R_i/t_n$	$T_L/t_n$
3 x 1	8	3.8	4.5	4.3	5.2
3 x 1	16	10.8	15.1	12.9	18.2
3 x 1	20	17.0	23.5	19.1	26.3
5 x 1	12	15.1	9.0	18.4	10.9
5 x 1	16	26.5	15.4	30.4	17.7
2-2/3 x 1/2	8	4.3	4.4	5.2	5.4
2-2/3 x 1/2	14	10.0	9.7	11.5	11.2
2-2/3 x 1/2	20	18.2	20.0	20.6	22.7

Average corrugation parameters for three specimens.

Normalized to design  $F_y = 33$  ksi (227 MPa) by multiplying  $R_i/t$  and  $T_L/t$  by  $\sqrt{F_y/33}$  ( $\sqrt{F_y/227}$ )

FIGURE 2. FLEXURAL TEST SET-UP

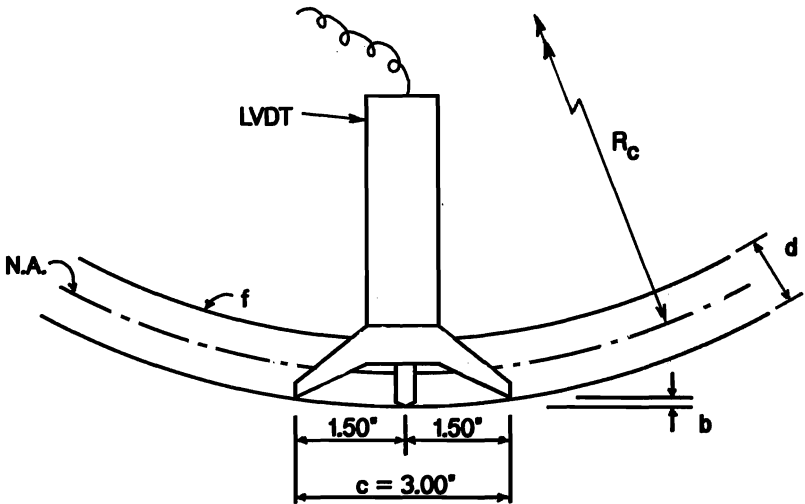


## ITEM DESCRIPTION:

1. 1.75 IN. DIAMETER STEEL LOAD ROLLERS COVERED WITH .125 IN THICK NEOPRENE.
2. 1.75 IN. DIA. STEEL SUPPORT ROLLERS COVERED WITH .125 IN. THICK NEOPRENE.
3. CORRUGATED FLEXURAL TEST SPECIMEN.
4. DEFLECTOMETER TO MEASURE MIDSPAN CURVATURE.
5. MAGNETIC BASE INCLINOMETER TO MEASURE ANGULAR CHANGE OF ENDS.

SI CONVERSIONS: 1 IN. = 25.4MM

FIGURE 4. DEFLECTOMETER



## ITEM DESCRIPTION:

**b** = DEFLECTOMETER DEFLECTION READING

**c** = CHORD LENGTH OR DISTANCE BETWEEN DEFLECTOMETER LEGS

**d** = DEPTH OF CORRUGATED SPECIMEN

**f** = ASSUMED CIRCULAR ARC DEFLECTED SHAPE OF FLEXURAL SPECIMEN

LVDT = LINEAR DISPLACEMENT TRANSDUCER

N.A. = SPECIMEN NEUTRAL AXIS ASSUMED AT MIDDEPTH FOR ALL STRAIN LEVELS

$R_c$  = MEAN RADIUS OF CURVATURE

SI CONVERSIONS: 1 IN. = 25.4MM