

COLD-BENDING OF THICK HIGH-STRENGTH STEEL PLATES

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ABSTRACT: The cold-bending behavior of thick high-strength steel plates is studied. Fifteen 1-in. (25.4-mm) and three 1.5-in. (38.1-mm) thick steel plates are cold-bent to angles up to 90°, with bend radii of 1.5, 2.5, 3.5, and 5.5 in. Quantities measured include maximum surface strain, load-displacement relationship, degree of springback, and residual stresses produced by the cold-bending. Selected equations for predicting maximum surface strain and degree of springback are reviewed, and the values predicted by these equations are compared to test results. The results of the residual stress measurements are presented in a companion paper.

INTRODUCTION

There is a strong motivation to reduce the amount of welding in fabricating structures from thick steel plates because high quality welding is a time-consuming and expensive process. Therefore, it may be cost-effective to fabricate heavy steel plate structures by cold-bending instead of by welding.

In order to achieve reasonably compact structural geometries, plates must be bent to very small radii of curvature, which induces large strains in the plates. Thus, a study on the maximum surface strain caused by cold-bending is necessary. In addition, the plates must be bent to a precisely specified shape; this process involves several problems, one of which, springback, is particularly critical. It is important to be able to predict the amount of springback before the actual design of the cold-bending operation is performed.

The present investigation involves cold-bending of 18 plates including 12 1-in. (25.4-mm) thick and three 1.5-in. (38.1-mm) thick HY-80 steel plates and three 1-in. thick HY-100 steel plates with bend radii of 1.5, 2.5, 3.5, and 5.5 in. The bending operation is carried out by using a punch and die device, as shown in Fig. 1. All plates are 18 in. square. Bend angles (θ) of 90°, 120°, and 150° are achieved as shown in Fig. 2.

The following topics were studied in this investigation.

1. Magnitude of maximum surface strain due to cold-bending.
2. Plate deformation as a function of applied load.
3. Amount of plate springback after unloading.
4. Residual stresses developed from the cold-bending operation (discussed in a companion paper).

Detailed results of this study are given in a report prepared by the writers (1984).

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LITERATURE REVIEW

Maximum Surface Strain Due to Cold-Bending

Sachs and Lubahn (1944) investigated the effect of plastic bending on aluminum alloys for use in military aircraft. This research showed that the tangential strain on the tension side is larger than that derived from the elementary bending theory, and that this difference increased with increasing curvature.

Kervick and Springborn (1966) presented results (based on the study by Sangdahl 1948) on the bending of rectangular bars. The maximum tangential strain was approximated by

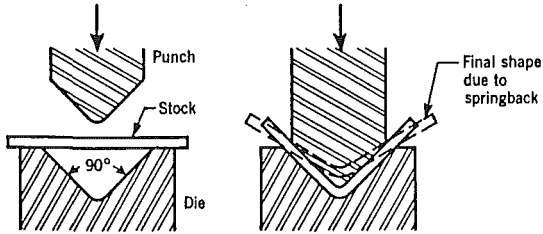


FIG. 1. Plate Bending Operation and Springback during Unloading

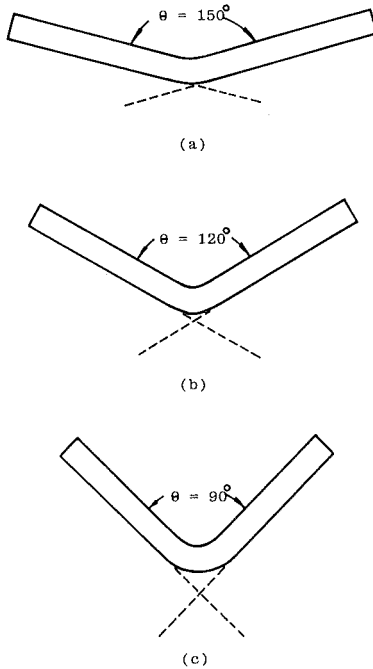


FIG. 2. Bend Angles of Steel Plates

$$\epsilon_{\max} = \frac{t}{2\bar{R}} \dots \dots \dots (1)$$

where t = bar thickness; and \bar{R} = bend radius to the neutral plane of the bar. It is assumed that the neutral surface remains at the center of the section and the thickness remains constant.

To account for the neutral surface shifting toward the compression side in severe plate bending, Cook (1966) introduced the following equation:

$$\epsilon_{\max} = \frac{1}{1.8 \frac{R}{t} + 0.82} \dots \dots \dots (2)$$

where R = the inside radius of bend. In this equation, the neutral surface is assumed to be offset about 5% toward the compression side.

Johnson and Mellor (1980) gave an empirical relationship often used for plates when the width-to-thickness ratio exceeds 10 and the angle of bend is larger than 70°

$$\epsilon_{\max} = \frac{1}{1.8 \frac{R}{t} + 1} \dots \dots \dots (3)$$

Johnson and Mellor also noted that in achieving small bend radii, transverse contraction was observed on the tension side of the plate and thickening on the compression side. The net result is that the neutral surface of the plate moves from the original section centroid towards the compression side by as much as 5% of the plate thickness.

Springback after Cold-Bending

The springback in metal fabrication process has been investigated for many decades due to its practical importance in industrial production. Schoeder (1943) presented a theory for predicting the springback; Sachs (1945) gave a number of curves for various materials, but all were limited to a small range of springback. In 1957, Gardiner presented extensive test data and derived an equation based on the relation between radius of curvature before and after springback

$$\frac{\bar{R}}{r} = 4 \left(\frac{\bar{R}\sigma_y}{Et} \right)^3 - 3 \left(\frac{\bar{R}\sigma_y}{Et} \right) + 1 \dots \dots \dots (4)$$

where \bar{R} = bend radius to the neutral surface of the plate before springback, in.; r = bend radius to the neutral surface of the plate after springback, in.; σ_y = yield stress, ksi; and E = Young's modulus, ksi. However, Crandall (1957) pointed out that the equation proposed by Gardiner for calculating the springback of plates should be adjusted as follows

$$\frac{\bar{R}}{r} = 4 \left(\bar{R}\sigma_y \frac{1 - \mu^2}{Et} \right)^3 - 3 \left(\bar{R}\sigma_y \frac{1 - \mu^2}{Et} \right) + 1 \dots \dots \dots (5)$$

in which μ = Poisson's ratio. This adjustment is necessary because the member is bending as a plate rather than a beam and hence the plate stiffness should

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be used instead of the beam stiffness. For most metals, this correction is about 10%.

Alexander (1959) derived an expression for predicting springback

$$\frac{1}{\bar{R}} - \frac{1}{\bar{R}'} = \frac{3N(1 - \mu^2)}{2Ea^3} \dots\dots\dots (6)$$

in which \bar{R}' = radius to the neutral plane of the plate after springback; $a = t/2$; and N = bending moment. However, the equation is limited to moderate plate bending in which the outer fiber strain is less than 2%. Also, the bending moment, N , is not readily known and further calculation is required.

In 1967, Botros (1967) presented an analytical equation based on a geometrical approach that includes the shift of the neutral surface of the section toward the compression side by an average amount of 5% of the plate thickness. The following equation was introduced for predicting the springback in sheet metal forming after bending:

$$\frac{\theta_2 - \theta_1}{\theta_1 (\%)} = \frac{300\bar{R}\sigma_y(1 - \mu^2)}{Et} \left(\frac{180}{\theta_1} - 1 \right) \dots\dots\dots (7)$$

where θ_1 = angle of bend before springback, degrees; and θ_2 = angle of bend after springback, degrees. According to Botros's study, agreement between the analytical and experimental results [for plates up to $t = 0.25$ in. (6.35 mm)] was fairly close for different thicknesses and widths of specimens.

EXPERIMENTAL INVESTIGATION

Test Specimens

Table 1 provides the dimensions of the HY-80 and HY-100 steel plates and the combinations of bend radius and bend angle used for this investigation; W and L are the width of the plate parallel and perpendicular to the bend line, respectively. The reduction of the thickness, Δt , at the center of the bend portion of the plate is also shown in the table.

The material properties as obtained from the uniaxial tensile coupon tests are given in Table 2. The nominal stress-strain curves of HY-80 steel and HY-100 steel are shown in Fig. 3. The HY-80 steel has a yield stress of about 86 ksi, an ultimate strength of about 108 ksi, and a percentage of elongation in 2 in. (50.8 mm) gage length of 24%. Corresponding values for the HY-100 steel are 105 ksi (723 N/mm²), 119 ksi (820 N/mm²), and 19%. The Young's modulus and the Poisson's ratio for both steels may be taken as $E = 29,500$ ksi (203.25 kN/mm²) and $\mu = 0.28$.

Cold-Bending Operation

The cold-bending of the plate was accomplished with a 90° die and four 90° punches with different radii: 1.5 in. (38.1 mm), 2.5 in. (63.5 mm), 3.5 in. (88.9 mm), and 5.5 in. (139.7 mm). Bend angles of 90°, 120°, and 150° were achieved by using this device, with load being applied with a 400-kip (1,780 kN) capacity testing machine. The dimensions of the die and the punches are shown in Fig. 4. It is noted that the die functions as a "bottoming die" for 90° bends, and as an "air-bend die" for 120° and 150° bends. Four narrow grooves were machined on the surfaces of the die and punch

TABLE 1. Plate Dimensions and Maximum Applied Loads

Plate		θ^{ob}	L (in.)	W (in.)	t (in.)	Δt (in.)	P_{max} (kips)
Material (1)	R^a (in.) (2)						
HY-80 (t = 1 in.)	1.5	90 (A)	17-30/32	18-1/32	0.988	0.017	160
	1.5	90 (B)	17-28/32	18-0/32	1.002	0.026	157
	1.5	120	18-0/32	18-2/32	0.998	0.021	158
	1.5	150	17-30/32	18-0/32	1.015	0.010	156
	2.5	90 (A)	18-0/32	18-1/32	1.013	0.015	167
	2.5	90 (B)	17-30/32	18-1/32	1.008	0.016	159
	3.5	90	17-30/32	18-0/32	1.018	0.013	173
	3.5	120	17-30/32	18-0/32	1.007	0.010	160
	3.5	150	18-0/32	17-31/32	1.006	0.009	155
	5.5	90	17-31/32	18-0/32	1.008	0.009	220
	5.5	120	17-30/32	17-30/32	1.009	0.007	193
	5.5	150	17-28/32	18-1/32	1.008	0.006	156
HY-80 (t = 1.5 in.)	1.5	90 (A)	18-0/32	18-1/32	1.513	0.093	390
	1.5	90 (B)	18-1/32	18-2/32	1.514	0.096	391
	2.5	90	18-0/32	18-1/32	1.515	0.052	396
HY-100 (t = 1 in.)	1.5	90 (A)	17-30/32	18-0/32	1.001	0.028	178
	1.5	90 (B)	17-30/32	18-0/32	0.996	0.028	177
	3.5	90	18-0/32	18-1/32	0.998	0.012	195

^aRadius of punch.

^bSee Fig. 2 for definition of θ .

Note: 1 in. = 25.4 mm, 1 kip = 4.45 kN.

to accommodate two lines of strain gages on each side of the plate.

As the bending started, the plate was loaded with increments of 5 kips (22.25 kN) until the plate reached the desired bent shape. The "simple span" loading produces nonuniform bending in the plate, plus an undetermined amount of membrane tension. The maximum load applied to each plate is given in the last column of Table 1. The bending process concluded with removal of the load on the punch, and observation of springback.

Measurement of Surface Strains

Because of the large plastic strains developed during the cold-bending operation, EP-type high-elongation post-yield strain gages (made by Measurements Group Inc.) and Armstrong A-12 adhesive were used. The strain gages were mounted on the center portion of the plate surfaces, following the pro-

TABLE 2. Material Properties of Steel Plates

Steel (1)	σ_y (ksi) (2)	σ_u (ksi) (3)	E (10 ³ ksi) (4)	Elongation (%) in 2 in. (5)
HY-80 (1.0 in.)	86.1	107.1	29.6	24.1
HY-80 (1.5 in.)	86.4	108.1	29.3	23.5
HY-100 (1.0 in.)	104.6	118.5	29.5	18.6

Note: 1 in. = 25.4 mm, 1 ksi = 6.89 N/mm².

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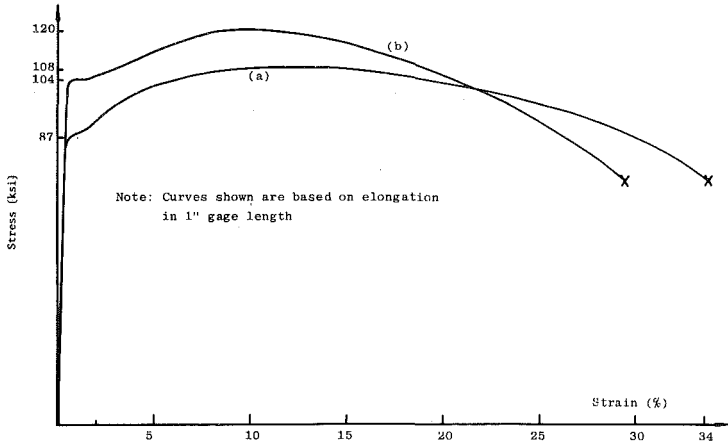


FIG. 3. Nominal Stress-Strain Curve: (a) HY-80; (b) HY-100m Steel (1 in. = 25.4 mm, 1 ksi = 6.89 N/mm²)

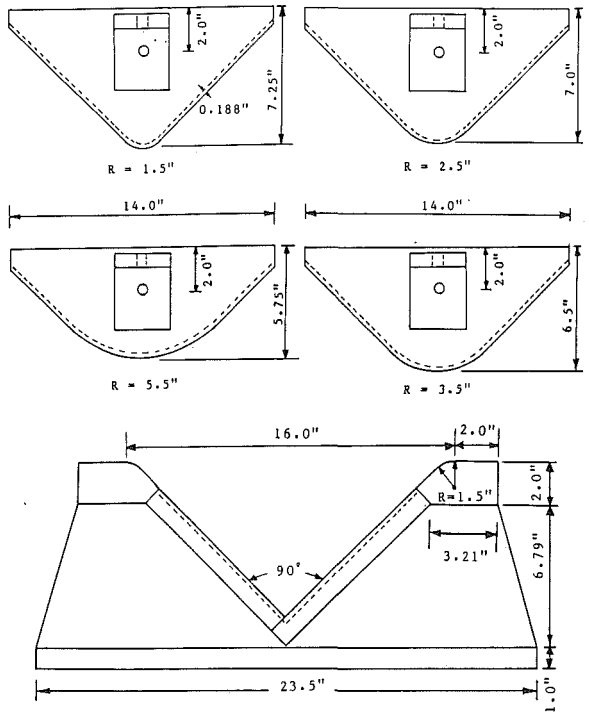


FIG. 4. Dimensions of Die and Punches

cedure suggested by R. T. Toth (1983).

For small bend radii of 1.5 (38.1 mm) and 2.5 in. (63.5 mm), however, the maximum surface strain on the cold-bent plate was too large to be measured with electric resistance strain gages. Therefore, a 6-in. (152.4-mm) long grid pattern with spacings of 0.1-in. (2.54-mm) was scribed on both sides of the plate, which is symmetric to the bend line of the plate. The distance between adjacent lines was measured with a microscope before and after bending, from which residual plastic strains on the tension side and compression side were calculated. The disadvantage of using mechanically scribed grids for strain measurement is that the load-strain relationship cannot be obtained. However, the grids provided a convenient and inexpensive way for measuring large residual plastic surface strains.

Measurement of Displacement and Springback

The displacement and the degree of springback of the cold-bent plate were determined by taking photos (slides) of the deformed shape of the plate at successive load levels. The slide image was then projected on to an 18-in. (457.2-mm) long piece of paper mounted on the wall, and the deformed shape of the plate was carefully traced on the paper to provide a full-size record of each bent plate shape. The displacements and bend angles were obtained by direct measurements from this drawing. The amount of springback is simply the difference between the bend angle measured before unloading and the bend angle measured after unloading.

EXPERIMENTAL RESULTS

Maximum Surface Strain

From the plate bending tests, the electric resistance strain gages were found to be good for measuring surface strains up to 16.0%. For plates bent to 90° with $R = 1.5$ in. (38.1 mm) and 2.5 in., the surface strains were determined by the grid technique. Table 3 gives the maximum surface strains measured at the center of the bent plates. The highest measured strain is 44.5% for the 1.5-in. (38.1-mm) thick plate bent to 90° with a 1.5-in. (38.1-mm) bend radius. It is observed that the measured strains on the tension side are larger than those on compression side, implying that the neutral surface of the section moved toward the compression side. The measured strains are plotted as a function of the bend angle, θ , and the R/t ratio, in Figs. 5(a) and (b), respectively.

In addition, the surface strains at the center of the bend line measured with the strain gages are plotted as a function of the applied load. Some typical load-strain curves are shown in Figs. 6(a-d). From these curves the variation of the surface strain through the entire loading history can be described.

Fig. 7 shows the distribution of residual surface strains along the tangential direction of a 1-in. (25.4-mm) thick plate bent to 90° with $R = 1.5$ in. (38.1 mm). These strains, measured with the grid technique, illustrate how the tangential strain decreases gradually along the bend from a peak value to zero. This means that the transition between the bent and the straight portions is not sharp, and the residual curvature of the bent portion is not uniform.

TABLE 3. Maximum Surface Strains Produced by Cold-Bending

Plate			Maximum Surface Strain (%)	
Material (1)	R (in.) (2)	θ° (3)	Tension side (4)	Compression side (5)
HY-80 ($t = 1$ in.)	1.5	90 (A)	No data measured	No data measured
	1.5	90 (B)	33.5 ^a	25.0 ^a
	1.5	120	23.0 ^a	No data measured
	1.5	150	9.5	8.9
	2.5	90 (A)	21.5 ^a	17.0 ^a
	2.5	90 (B)	20.5 ^a	16.5 ^a
	3.5	90	16.0	13.0
	3.5	120	14.3	11.7
	3.5	150	8.9	6.9
	5.5	90	9.6	9.1
	5.5	120	9.4	8.3
HY-80 ($t = 1.5$ in.)	1.5	90 (A)	44.5 ^a	No data measured
	1.5	90 (B)	42.0 ^a	26.5 ^a
	2.5	90	29.5 ^a	18.5 ^a
	3.5	90	15.5	13.5
HY-100 ($t = 1$ in.)	1.5	90 (A)	34.0 ^a	No data measured
	1.5	90 (B)	32.5 ^a	25.0 ^a

^aSurface strain measured by grid technique.

Note: 1 in. = 25.4 mm.

Displacements of Plate

The displacements V and ΔH (shown in Fig. 8, $\Delta H = L - H$) of the plates were measured and plotted as a function of the applied load. Selected load-displacement curves are shown in Figs. 8(a-c). It is observed that there are relatively constant plateaus of load in Figs. 8(a) and (b) for plates bent to 90° with $R = 1.5$ in. (38.1 mm) and 2.5 in. (63.5 mm). However, the constant plateau does not occur for the plate bent with $R = 5.5$ in. (139.7

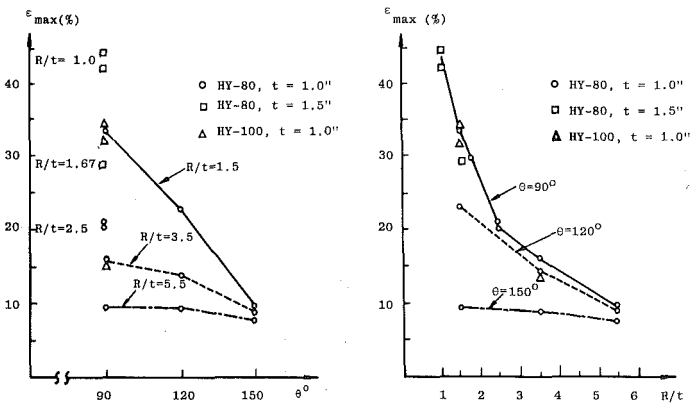


FIG. 5. Maximum Surface Strain: (a) Angle of Bend, θ ; (b) versus R/t Ratio

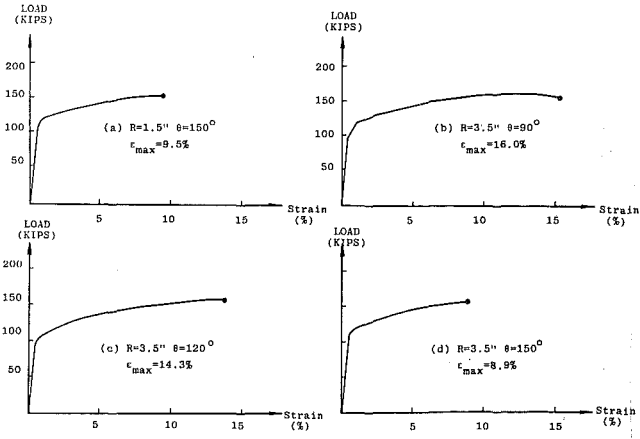


FIG. 6. Load-Strain Curves—HY-80 Steel, $t = 1.0$ in. (1 in. = 25.4 mm, 1 kip = 4.45 kN)

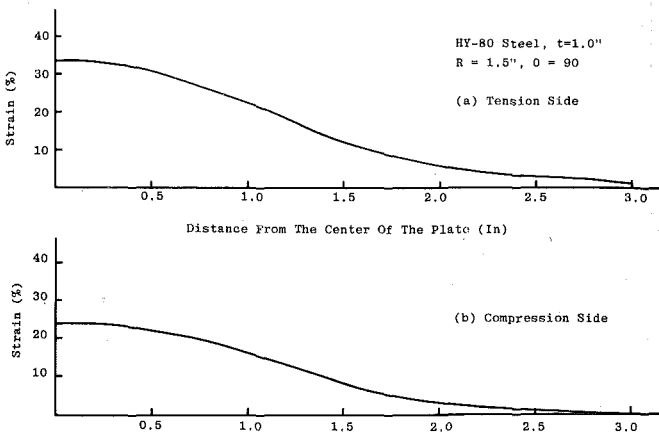


FIG. 7. Surface Strain Distribution along Tangential Direction Measured after Unloading (1 in. = 25.4 mm)

mm) in Fig. 8(c). This is because the center of the bend was fully plastic in the former cases, but not in the latter one.

Fig. 8(a) shows a typical load-displacement relation during the cold-bending operating. When the test starts, the plate behaves elastically between points A and B. The region between points B and C indicates that the bent portion of the plate is partially plastic. As the load increases, the plastic zone penetrates farther toward the neutral surface of the plate, and the curve becomes flatter as shown between points C and D. Due to the extensive stretching on the tension side, a reduction of the thickness of the plate at the bent portion occurs, which results in a decrease of the applied loading due to the reduction of cross-sectional area of the plate. This is shown be-

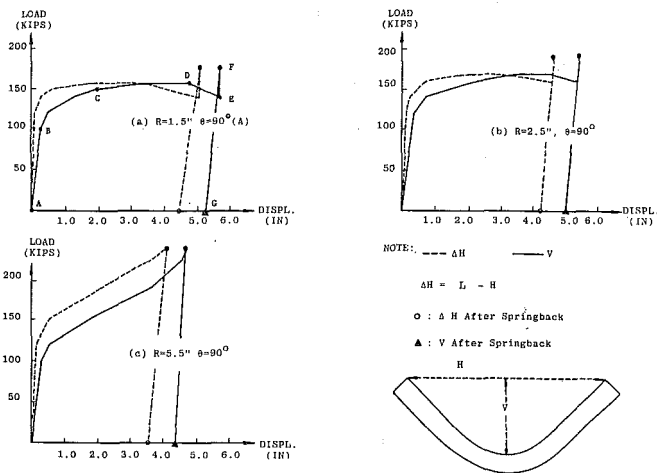


FIG. 8. Load-Displacement Curves—HY-80 Steel, $t = 1.0$ in. (1 in. = 25.4 mm, 1 kip = 4.45 kN)

tween points D and E. Then, the bottom surface of the plate contacts the surface of the die, which causes a rapid increase of the load, as shown between points E and F. Finally, the load is removed as indicated between points F and G.

Amount of Springback

The amount of springback is the difference between the angles of bend measured before and after unloading. Table 4 shows the springback, $\Delta\theta$, obtained from the tests of 18 plates. The highest measured value is 9.0° for the plate bent to 90° with $R = 5.5$ in. (139.7 mm), which is 10% of the original angle of bend. For the plate bent to 90° with the smallest radius of bend, $R = 1.5$ in. (38.1 mm), the springback is 5.5° and 6.5° for the 1-in. (25.4 mm) thick HY-80 and HY-100 steel plates, respectively.

As shown in Figs. 9(a) and (b), the percentage of springback is plotted as a function of θ and R/t . The results showed a clear tendency for the springback to increase as the angle of bend decreases, and to decrease as the R/t ratio decreases, except for plates bent to 150° , in which the effect of the bend radius on the springback is small.

In addition, it is also observed that the springback increases as the yield strength of the material increases. As shown in Figs. 9(a) and (b), for plates bent to the same radius and angle, the percentage of springback of HY-100 steel plate is higher than that of HY-80 steel plate.

Comparison between Test Results and Predicted Values

The equations reviewed previously are now used to predict the maximum surface strain and springback for the cold-bent plates. Comparisons are made between the test results and the predicted values.

Maximum Surface Strain Due to Cold-Bending

Table 5 gives a comparison between the measured maximum surface strains and the values predicted by Eqs. 1, 2, and 3. For plates bent to 90° , the

TABLE 4. Springback during Unloading

Plate			Springback $\Delta\theta^\circ$	Percentage of springback $\Delta\theta/\theta$ (%)
Material (1)	R (in.) (2)	θ° (3)		
HY-80 (<i>t</i> = 1 in.)	1.5	90 (A)	5.5	6.1
	1.5	90 (B)	5.5	6.1
	1.5	120	6.0	5.0
	1.5	150	5.8	3.9
	2.5	90 (A)	6.5	7.2
	2.5	90 (B)	7.0	7.8
	3.5	90	7.0	7.8
	3.5	120	6.2	5.2
	3.5	150	6.0	4.0
	5.5	90	9.0	10.0
	5.5	120	8.0	6.7
HY-80 (<i>t</i> = 1.5 in.)	1.5	90 (A)	4.0	4.4
	1.5	90 (B)	4.3	4.8
	2.5	90	5.0	5.6
HY-100 (<i>t</i> = 1 in.)	1.5	90 (A)	6.5	7.2
	1.5	90 (B)	7.0	7.8
	3.5	90	8.5	9.4

Note: 1 in. = 25.4 mm.

comparison shows that all the calculated values are smaller than the test results. It is noted that all these equations were derived based on the assumption that the plate is bent to a uniform curvature. However, for those plates bent to 90°, the experiment showed that the punch and the plate did not perfectly contact during the latter stage of the bending; a small gap was observed, as shown in Fig. 10 between points A and B. The existence of the gap results from the fact that the curvature of the bent portion of the

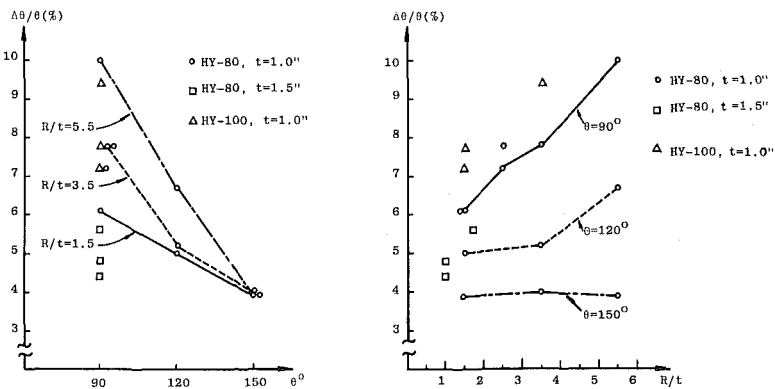


FIG. 9. Percentage of Springback: (a) versus Angle of Bend, θ ; (b) versus R/t Ratio (1 in. = 25.4 mm)

TABLE 5. Maximum Surface Strains: Test Results versus Predicted Values

Plate			Test result (%) (4)	Eq. 1 (%) (5)	Difference (%) (6)	Eq. 2 (%) (7)	Difference (%) (8)	Eq. 3 (%) (9)	Difference (%) (10)
Material (1)	R (in.) (2)	θ° (3)							
HY-80 ($t = 1$ in.)	1.5	90 (A)	No test data measured	25.0	No test data measured	28.4	No test data measured	27.0	No test data measured
	1.5	90 (B)	33.5	25.0	-25.4	28.4	-15.2	27.0	-19.4
	1.5	120	23.0	25.0	+8.7	28.4	+23.5	27.0	+17.4
	1.5	150	9.5	25.0	+163.2	28.4	+198.9	27.0	+184.2
	2.5	90 (A)	21.5	16.7	-22.3	18.8	-12.6	18.2	-15.3
	2.5	90 (B)	20.5	16.7	-18.5	18.8	-8.3	18.2	-11.2
	3.5	90	16.0	12.5	-21.9	14.1	-11.9	13.7	-14.4
	3.5	120	14.3	12.5	-12.6	14.1	-1.4	13.7	-4.2
	3.5	150	8.9	12.5	+40.4	14.1	+58.4	13.7	+53.9
	5.5	90	9.6	8.3	-13.5	9.3	-3.1	9.2	-4.2
	5.5	120	9.4	8.3	-11.7	9.3	-1.1	9.2	-2.1
	5.5	150	7.7	8.3	+7.8	9.3	+20.8	9.2	+19.5
HY-80 ($t = 1.5$ in.)	1.5	90 (A)	44.5	33.3	-25.2	38.2	-14.2	35.7	-19.8
	1.5	90 (B)	42.0	33.3	-20.7	38.2	-9.0	35.7	-15.0
	2.5	90	29.5	23.0	-22.0	26.1	-11.5	25.0	-15.3
HY-100 ($t = 1$ in.)	1.5	90 (A)	34.0	25.0	-26.5	28.4	-16.5	27.0	-20.6
	1.5	90 (B)	32.5	25.0	-23.1	28.4	-12.6	27.0	-16.9
	3.5	90	15.5	12.5	-19.4	14.1	-9.0	13.7	-11.6

Note: 1 in. = 25.4 mm.

plate is slightly larger than the curvature of the punch. This phenomenon explains why the maximum surface strains obtained from the tests for plates bent to 90° are higher than the predicted values.

For plates bent to the same R/t ratio, the test results given in Table 5 also shows that the maximum surface strain varies as the angle of bend changes. However, Eqs. 1, 2, and 3 indicate that the maximum surface strain is not affected by the change of the bend angle. Therefore, the consideration of not only the bend radius but also the effect of bend angle on the maximum surface strain is desirable in achieving a better equation for predicting the maximum surface strain. It is also suggested that the use of an empirical equation to account for the influence of the nonuniform curvature of the bent portion may be helpful.

From Table 5, it is seen that the values predicted by Eq. 2 give the best estimation to the test results for plates bent to 90° , in which the differences

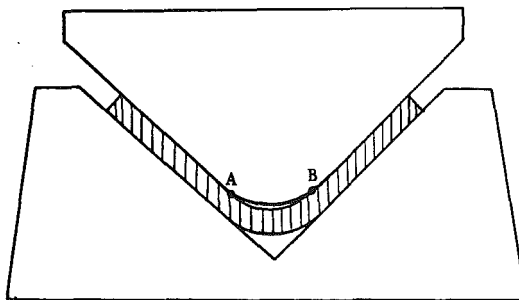


FIG. 10. Gap between Punch and Cold-Bent Plate

TABLE 6. Springback: Test Results versus Predicted Values

Material (1)	Plate		Percentage of Springback		Ratio: test/predicted (6)
	R (in.) (2)	θ° (3)	Test (%) (4)	Predicted (%) ^a (5)	
HY-80 (<i>t</i> = 1.0 in.)	1.5	90 (A)	6.1	1.61	3.79
	1.5	90 (B)	6.1	1.61	3.79
	1.5	120	5.0	0.80	6.25
	1.5	150	3.9	0.32	12.18
	2.5	90 (A)	7.2	2.41	2.99
	2.5	90 (B)	7.8	2.41	3.24
	3.5	90	7.8	3.22	2.42
	3.5	120	5.2	1.61	3.23
	3.5	150	4.0	0.64	6.22
	5.5	90	10.0	4.82	2.07
	5.5	120	6.7	2.41	2.78
5.5	150	3.9	0.97	4.02	
HY-80 (<i>t</i> = 1.5 in.)	1.5	90 (A)	4.4	1.22	3.60
	1.5	90 (B)	4.8	1.22	3.93
	2.5	90	5.6	1.77	3.16
HY-100 (<i>t</i> = 1.0 in.)	1.5	90 (A)	7.2	1.96	3.67
	1.5	90 (B)	7.8	1.96	3.98
	3.5	90	9.4	3.92	2.40

^aValues predicted by using Eq. 7.

Note: 1 in. = 25.4 mm.

ranged between 3% and 17%. However, it is noted that the surface strains measured by the grid technique are not the actual maximum strains that the plate experienced during the bending; the grid values are residual strains that exist after springback. Consequently, the differences between the predicted values and the actual maximum strains can be larger than those given in the table.

Amount of Springback

The results of the measured springback values and the values predicted by Eq. 7 are compared in Table 6. The comparison shows that the differences between the test results and predicted values are large, generally by a factor larger than 2. It is noted that Eq. 7 was derived by assuming that the material is perfectly elastic-plastic, and the plate was bent to a uniform curvature under a pure bending condition. However, the materials used in the present investigation show an effect of strain hardening, and the bent portion of the plate is not a perfect circular arc. The springback includes a lot of elastic energy recovery from large areas of the plate that were slightly stressed, which is probably the main reason why the predicted and the measured springbacks differed so much. If the entire plate had been bent to the same circular curvature as that experienced in the critical section, the springback would have been smaller.

Nevertheless, Eq. 7 does take into account the effects of bend radius and bend angle on springback. For further study on the prediction of springback, the effects of strain hardening as well as the nonuniform curvature of the

bent plate should be taken into account. Since the curvature of the bent plate is not uniform, it is impractical to compare the curvature predicted by Eqs. 4, 5, and 6 to that of the bent plate. Large-deformation, nonlinear finite element codes may provide the best approach to predicting the geometries of severely bent plates.

SUMMARY AND CONCLUSIONS

The results of cold-bending 18 thick steel plates are presented, including maximum surface strain, load-displacement relationship, and springback.

The test results showed that a maximum surface strain of 44.5% was observed for a 1.5-in. (38.1-mm) thick HY-80 steel plate bent to 90° with a 1.5-in. (38.1-mm) bend radius. The highest measured degree of springback is 9.0° for a HY-80 steel plate bent to 90° with a 5.5-in. (39.7 mm) bend radius. In general, the more severe the bend, the smaller the percentage of the springback of the cold-bent plate.

In addition, the experimental results were compared to the values predicted by various equations. Some discrepancies were observed because: (1) These equations were derived based on idealized assumptions that are not appropriate for this investigation; and (2) the cold-bending operation did not produce uniform bending in the entire plate. To provide a better prediction of the behavior of the severely cold-bent thick steel plates, the effect of strain hardening as well as the nonuniform curvature of the bent plate should be taken into account in any further theoretical investigations.

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

- E = Young's modulus;
- H = relative horizontal displacement;
- L = width of plate perpendicular to bend line;
- N = applied bending moment;
- P = applied loading;
- \bar{R} = bend radius to inside surface of plate;
- \bar{R} = bend radius of neutral surface of plate;
- r = bend radius to neutral surface of plate after springback;
- t = plate thickness;
- V = vertical displacement of plate;
- W = width of plate parallel to bend line;
- θ = angle of bend before springback;
- ϵ_{\max} = maximum surface strain;
- μ = Poisson's ratio;
- σ_y = yield stress of material; and
- σ_u = tensile strength of material.