Development of Fabrication Guidelines for Cold Bending of Plates

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In fabrication, plates are often bent to a radius in a press brake or die. Relatively thin plates may be roll formed to the desired profile. When conducted at room temperature, these processes are known collectively as "cold bending." To avoid cracking the plate during bending, it is necessary to adopt a suitable minimum inside bend radius, which typically varies with plate thickness and grade. However, because it appeared that current limits had not been developed on a consistent basis, the American Iron and Steel Institute (AISI) initiated a program to develop rational limits directly applicable to cold bending of plates. First a test program was conducted on several steel grades using small specimens. Then a study was made to review that information and develop suggested fabrication guidelines.

Two sources had generally been referred to for cold bending information. First, ASTM Specification A6 (ASTM, 1997) included a table giving bend diameter-to-thickness ratios for structural steel plate grades. This table was intended for material acceptance purposes rather than fabrication purposes; when the supplementary bend test in A6 was specified, specimens generally 1½ in. wide were bent to a specified diameter-to-thickness ratio to ensure that the material would not fracture under those test conditions. Second, the American Institute of Steel Construction (AISC) *Manual of Steel Construction* (AISC, 1989) included a table of recommended minimum radius-to-thickness ratios to be used in plate fabrication. The AISC limits were more conservative (greater bend radii) than the ASTM acceptance limits to allow for bending wider material and other conditions that may be present in fabrication.

EXPERIMENTAL WORK BY CTC

Concurrent Technologies Corporation (CTC) conducted an experimental program, augmented by inelastic finite element analysis, to investigate the forming characteristics of five plate steels (Holt, Semelsberger, Stawarz, and Chaudbury, 1997). The investigation, sponsored by AISI, included five steels: ASTM A36, A572 Grade 50, A588, A656 Grade 70, and A514. Rectangular specimens were marked with a grid (0.050 in. spacing) and cold bent in a forming die to a bend angle of 120°. If the specimen was not yet fractured it was then side pressed to fracture or to 180°. Strains were determined by measuring the grid spacing before and after testing so that the maximum strain reached or the strain at fracture could be determined. The tests were initially conducted on several hundred small plate specimens ¼, ⅜, and ½ in. thick, with bend line orientations both perpendicular and parallel to the rolling direction. Specimen width-to-thickness (*w*/*t*) ratios of 3:1, 5:1, and 10:1 were evaluated. All specimens had smooth edges to ensure that cracks did not emanate from the edges.

Plots were made showing the strain states and cracking conditions observed. Figure 1 shows the data for ½ -in.-thick ASTM A36 steel longitudinal specimens (bend line perpendicular to the rolling direction). The results for thinner plates were generally similar. The top sloping line is a fracture limit that divides specimens that did not crack from those that cracked or showed incipient cracking. The strain state

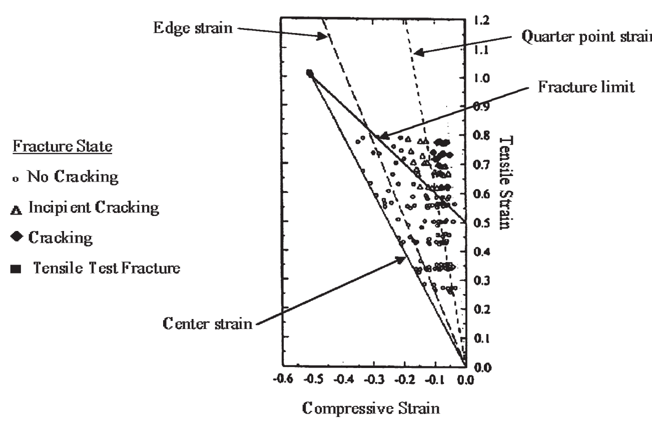

Fig. 1. Workability plot for ASTM A36 steel, ½-in.-thick plate, longitudinal orientation.

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Table 1. Forming Limits Based on Idealized Diagrams[a]				
Steel	Orientation[b]	Number of 1-in.-Thick Specimens	θ_{max}, deg.	$(R/t)_{min}$
A36	L T	3 4	80 50	0.25 0.40
A572 Gr. 50	L T	3 4	100 90	0.25 0.25
A588	L T	3 4	110 70	0.25 0.25
A656 Gr. 70	L T	3 4	100 90	0.25 0.25
A514	L T	4 7	40 30	0.75 0.75

[a] See Figure 4 for schematic diagram. Some values of $(R/t)_{min}$ listed here are more conservative than those initially recommended (Holt et al., 1997).
[b] *L* is for longitudinal specimen (bend line perpendicular to the rolling direction). *T* is for transverse specimen (bend line parallel to the rolling direction).

at the fracture limit corresponds to a particular bend angle and radius-to-thickness (*R*/*t*) ratio. Thus, a bending limit diagram could be constructed in terms of *R*/*t* and bend angle, with a line plotted to show combinations that were "safe" or "unsafe," that is, no-cracking or cracking conditions. Figure 2 shows such a diagram for ASTM A36 steel (bend line perpendicular to the rolling direction). Separate curves are shown for the three specimen *w*/*t* categories. Because the limit curves for *w*/*t* of 10:1 did not vary greatly from those for *w*/*t* of 5:1, it was assumed that the 10:1 results could be used for even wider plates with little error.

Subsequently, cold bending tests were made on a group of 1-in.-thick specimens of the five steels using a *w*/*t* of 10. This involved 39 specimens as detailed in Table 1. Specimens were selected to represent safe and unsafe conditions, so that the results could be plotted to evaluate the bending limit diagrams. Figure 3 shows the results for ASTM A36 steel (bend line perpendicular to the rolling direction). These tests suggested that some modifications should be made to the bending limit diagrams to better match the results for the thicker material.

Further examination of the bending limit diagrams suggested that they could be idealized as rectangular diagrams as illustrated in Figure 4. According to such a diagram, any *R*/*t* ratio could be used up to a specific bending angle, θ_{max}. For larger bend angles, the *R*/*t* must be greater than $(R/t)_{min}$ to avoid cracking. Table 1 gives values of θ_{max} and $(R/t)_{min}$ for each steel and for both orientations.

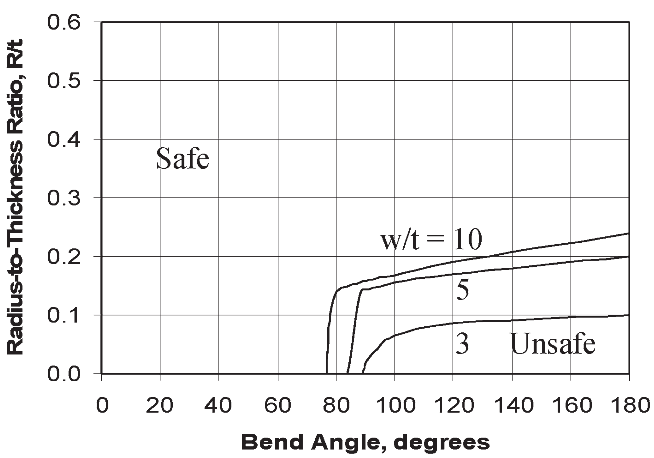

Fig. 2. Bending limit diagrams for ASTM A36 steel, longitudinal orientation.

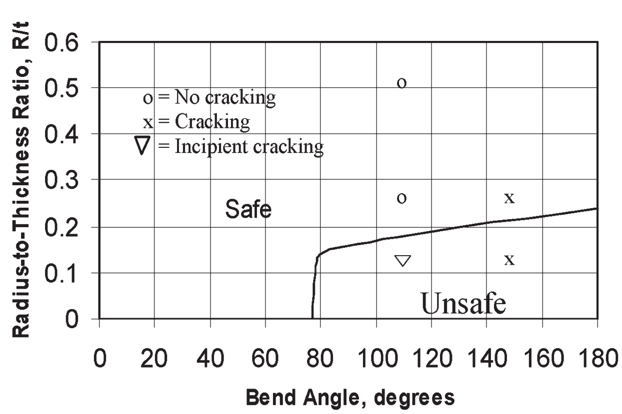

*Fig. 3. Bending limit diagram for ASTM A36 steel, width/thickness (*w/t*) of 10, longitudinal orientation, with data for 1-in.-thick plate.*

Table 2. Comparison of Specified and Test Average Tensile Properties						
Steel	Specified or Test Avg.	Max. Thickness, in.	Min. Yield Stress, ksi	Min. Tensile Strength, ksi	% Elong. in 2 in.	% Elong. in 8 in.
A36	Specified	–	36	58	23	20
	Test Avg.		*44*	*65*	*34*	*25*
A572 Gr. 50	Specified	4	50	65	21	18
	Test Avg.		*61*	*77*	*38*	*25*
A588	Specified	4	50	70	21	18
	Specified	5	46	67	21	–
	Specified	8	42	63	21	–
	Test Avg.		*59*	*78*	*46*	*23*
A656 Gr. 70	Specified	1	70	80	17	14
	Test Avg.		*73*	*85*	*27*	–
A514	Specified	2.5	100	110	18	–
	Specified	6	90	110	16	–
	Test Avg.		*106*	*115*	*26*	–

METHOD FOR SETTING FABRICATION LIMITS

The Concept

The concept was to use the idealized bending limit diagrams to establish fabrication limits but to modify them with appropriate allowances for conditions in fabrication that differ from those in the tests. It was proposed that the fabrication limits for each steel be derived from the following relationship:

$$(R/t)_{fab} = F_1 F_2 F_3 (R/t)_{min} \geq 1.5 \qquad (1)$$

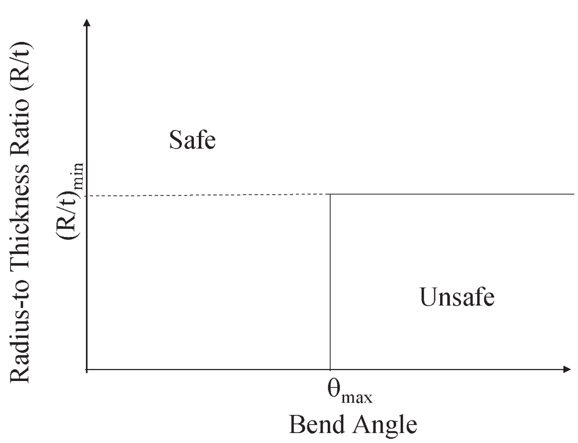

Fig. 4. Idealized bending limit diagram.

where

$(R/t)_{fab}$ = Minimum radius-to-thickness ratio to be used in fabrication for cold bending to any angle
$(R/t)_{min}$ = Minimum radius-to-thickness ratio from idealized bending limit diagram based on tests
F_1 = Factor to adjust for minimum properties
F_2 = Factor to adjust for thickness
F_3 = Factor to adjust for imperfections

The $(R/t)_{min}$ for longitudinal specimens could be used to develop limits for bend lines perpendicular to the rolling direction. Limits for bend lines parallel to the rolling direction could be taken as 1.5 times the limits for perpendicular bend lines. This ratio represents a compromise between (1) the traditional ratio of approximately two cited in the AISC *Manual of Steel Construction* (AISC, 1989) and (2) the nearly equal bend angles reached in tests of longitudinal and transverse specimens, as given in Table 1. The absolute lowest value of R/t = 1.5 was set as an arbitrary practical limit to avoid excessive strains. The adjustment factors for minimum properties, thickness, and imperfections are discussed in the following sections.

Factor for Minimum Properties, F_1

The CTC test specimens were taken from typical steel plate production. Thus, average material properties exceeded specification minimum values as detailed in Table 2. In a broad spectrum of fabrication operations, some material will likely approach specification minimum values, and a suitable

Table 3. Factor for Minimum Properties, F_1		
Steel	Ratio of Test Average to Specified Minimum % Elong. in 2 in.	F_1 (Rounded Values)
A36	1.48	1.5
A572 Gr. 50	1.81	2.0
A588	2.19	2.0
A656 Gr. 70	1.59	2.0
A514	1.44	1.5

Table 4. Ratio of *R*/*t* for Each Thickness to That for 1-in.-Thick Plate[a]

Steel	¾ in.	1 in.	2 in.	3 in.	4 in.	>4 in.
A36	0.50	1.0	2.5	3.0	3.0	3.0
A572 Gr. 50	0.67	1.0	2.0	2.3	2.7	–
A588	0.67	1.0	1.7	2.0	2.0	2.0
A514	1.00	1.0	1.5	2.0	2.0	–
Average	0.71	1.0	1.9	2.3	2.4	2.5

[a] Based on ASTM A6 (ASTM, 1997). A6 requirements were actually in terms of diameter-to-thickness values (d/t), but the ratios referenced to 1-in.-thick plate were the same. For example, for ASTM A36 steel, A6 listed d/t = ½ for ¾ in. and d/t = 1 for 1 in.; thus the normalized ratio is (½)/1 = 0.50 for ¾ in. Also, A6 did not give requirements for 1 in. or thicker plate for A656 Grade 70 steel.

allowance for this must be made. One measure of ability to deform is the percent elongation measured in a tensile test, particularly over a short gage length. Therefore, it was proposed to base the F_1 factor for each steel on the ratio of the average of the percent elongation in 2 in. of the test material to the specified minimum. Rounded values of F_1 vary from 1.5 to 2.0 as given in Table 3, and their use has the effect of increasing the minimum bend radius.

Factor for Thickness, F_2

The initial CTC tests were conducted on material from ¼ to ½ in. thick, and thickness had little effect. Subsequent CTC tests on 1-in.-thick material generally showed that somewhat larger R/t values should be used, and the idealized bending limit diagrams were adjusted to encompass 1-in.-thick plate. Since the fabrication limits could be applied to material with a thickness of 8 in. or more, depending on grade, a suitable allowance for plate thickness had to be made. As a guide for making this adjustment, the bend test requirements of ASTM A6 were examined. Although these requirements only applied to bend test specimens with smooth edges, the variation with thickness should be applicable here. The ASTM A6 requirements were normalized to the R/t limit for 1-in.-thick plate and the results averaged for each thickness, as given in Table 4. For individual grades, the normalized factor did not vary greatly from the average normalized factor for each thickness in most cases. Consequently, to adjust for thickness effects, these values were rounded to the F_2 values listed in Table 5. Application of these factors has the effect of increasing the minimum bend radius for plates over 1 in. thick and reducing it for ¾-in.-thick plate.

Factor for Imperfections, F_3

Plates to be cold bent during fabrication are likely to contain imperfections along their edges or on the surface. Imperfections with depths of ⅛ in. or more will cause significant local increases in strain, and this must be compensated for by increasing the minimum bend radius. Estimation of the worst likely imperfection is difficult. The AISC *Manual of Steel Construction* (AISC, 1989) gave the following guidance concerning plate edges: "Before bending, special attention should be paid to the condition of plate edges transverse to the bend lines. Flame-cut edges of hardenable steels should be machined or softened by heat treatment. Nicks should be ground out. Sharp corners should be rounded." No specific information was given on the depth of the imperfection or the radius to which it will be ground.

Table 5. Factor for Thickness, F_2	
Thickness, in.	F_2
0.75	0.75
1.00	1.00
2.00	2.00
3.00	2.50
over 3.00	2.50

Table 6. Calculated *R/t* Limits for Thicknesses 0.75 to 3.0 in.[a]

Steel	0.75 in.	1.0 in.	2.0 in.	3.0 in.
A36	0.56	0.75	1.50	1.88
A572 Gr. 50	0.75	1.00	2.00	2.50
A588	0.75	1.00	2.00	2.50
A656 Gr. 70	0.75	1.00	–	–
A514	1.69	2.25	4.50	5.62

[a] Disregarding absolute lower limit of 1.50.

Figure 5 illustrates a section of a plate with the top surface stressed in tension during cold bending. It was assumed that both the edge and the surface imperfection could be characterized by a shallow notch with depth *a* and radius *r*. The stress concentration factors, assumed to be similar to the strain concentration factors, may be calculated from knowledge of the stress intensity factors (Murakami, 1986) using the procedure described by Tada, Paris, and Irwin (1985).

Figure 6 shows the calculated stress concentration factors for surface and edge features for *a/r* ratios of 2 or less. For purposes of estimating the reduction factor, an *a/r* ratio of 0.8 was assumed for both surface and edge imperfections. In the case of an edge, this would be equivalent to a nick with a depth of 0.25 in., ground out leaving a radius of 5⁄16 in.; in other words, 0.25/0.3125 = 0.80. In the case of a surface, this could be a similar ground-out nick or a smaller untouched rolling imperfection that could be represented by an *a/r* of 0.8. Referring to Figure 6, the factor for the edge condition with *a/r* = 0.8 would be 3.0 and that for the surface condition with *a/r* = 0.8 about 2.15. However, the strain limit diagrams developed in the CTC study (Holt et al., 1997) showed that, because of the reduced constraint at the edges, the ratio of the tensile strain at fracture at the plate edge and at midwidth was about 3/2. Therefore, the factor for the edges was taken as ⅔ × 3 or 2.0. Consequently, a reduction factor of $F_3 = 2$ was adopted to characterize typical edge and surface fabrication imperfections for all cases.

Fabrication Limits for Five Steels

Using Equation 1 and the adjustment factors discussed above, but disregarding the lower limit of 1.5, *R/t* limits for each steel and thickness category were calculated as shown in Table 6. For example, the limit for 3-in.-thick ASTM A36 steel plate was calculated as follows. From Table 3: $F_1 = 1.5$; from Table 5, $F_2 = 2.5$; for all cases, $F_3 = 2.0$; and from Table 1, $(R/t)_{min} = 0.25$. Substitution in Equation 1 gives

$$\begin{aligned}(R/t)_{fab} &= F_1 F_2 F_3 (R/t)_{min} \\ &= (1.5)(2.5)(2.0)(0.25) \\ &= 1.88\end{aligned}$$

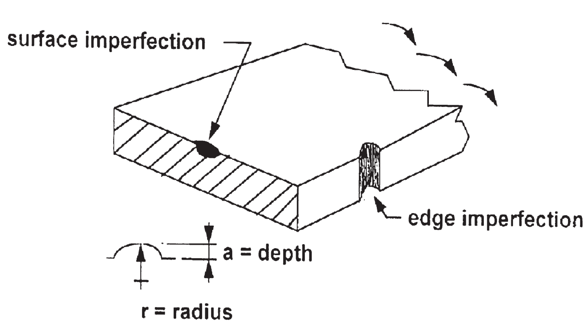

Fig. 5. Characterization of edge and surface imperfections.

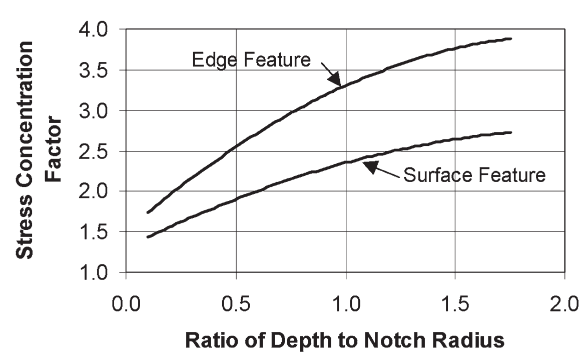

Fig. 6. Stress concentration factors for edge and surface imperfections.

Table 7. Suggested Minimum Inside Bend Radii for Cold Forming Five Steels[a]				
	Thickness, t, in.			
Steel	Up to ¾	Over ¾ to 1, incl.	Over 1 to 2, incl.	Over 2
A36	1.5t	1.5t	1.5t	2.0t
A572 Gr. 50	1.5t	1.5t	2.0t	2.5t
A588	1.5t	1.5t	2.0t	2.5t
A656 Gr. 70	1.5t	1.5t	–	–
A514	1.75t	2.25t	4.5t	5.5t

[a] Values are for bend lines perpendicular to direction of final rolling. If bend lines are parallel to final rolling direction, multiply values by 1.5.

Table 8. Comparison of Bend Radii (R/t) for Thicknesses 0.25 to 2.0 in.							
Steel	Limit[a]	¼ in.	½ in.	¾ in.	1 in.	1½ in.	2 in.
A36	AISC	1.5	1.5	–	2.0	3.0	4.0
	Present	1.5	1.5	1.5	1.5	1.75	2.0
A572 Gr. 50	AISC	2.5	2.5	–	4.0	–	–
	Present	1.5	1.5	1.5	1.5	1.75	2.0
A588	AISC	2.0	3.0	–	5.0	–	–
	Present	1.5	1.5	1.5	1.5	1.75	2.0
A514	AISC	2.0	2.0	–	2.0	3.0	3.0
	Present	1.75	1.75	1.75	2.25	3.38	4.5

[a] Comparision is to previous AISC limits (AISC, 1989); hot forming was recommended for thicknesses greater than those shown.

Table 9. Group Designations for Cold Bending		
Group Designation	Range of Specified Minimum Elongation in 2 in., % (inclusive)	Steel Specifications and Grades[b]
A	30–26	A 283-A, A 283-B
B	25–23	A 36, A 283-C, A 283-D, A 572-42, A 573-58, A 573-65, A 656-60, A 633, A 709-36, A 945-50, A 945-65
C	22–21	A 242, A 529-50, A 529-55, A 572-50, A 573-70, A 588, A 678-A, A 678-B, A 690, A 709-50, A 709-50W, A 808
D	20–19	A 572-55, A 656-60, A 678-C, A 678-D, A 709-70W, A 709-HPS70W, A 852
E	18–17	A 572-60, A 572-65, A 656-70, A 871-60, A 871-65
F[a]	–	A514, A 656-80, A 709-100, A 709-100W, A 710

[a] Group F includes all steels with a ratio of specified minimum tensile strength to specified minimum yield strength of 1.15 or less.
[b] The grade designation follows the dash; where no grade is shown, all grades and/or classes are included.

Table 10. Suggested Minimum Inside Radii for Cold Bending for ASTM A6[a]				
Group Designation[b]	Thickness (t), in.			
	Up to ¾	Over ¾ to 1, incl.	Over 1 to 2, incl.	Over 2
A	1.5t	1.5t	1.5t	1.5t
B	1.5t	1.5t	1.5t	2.0t
C	1.5t	1.5t	2.0t	2.5t
D	1.5t	1.5t	2.5t	3.0t
E	1.5t	1.5t	3.0t	3.5t
F	1.75t	2.25t	4.5t	5.5t

[a] Values are for bend lines perpendicular to direction of final rolling. If bend lines are parallel to final rolling direction, multiply values by 1.5.
[b] Steels specifications included in the group designations may not include the entire thickness range shown in this table.

Applying the lower limit of R/t = 1.5 and rounding a few values, the final set of suggested values was developed as shown in Table 7.

In Table 8, the suggested values are compared to fabrication guidelines for cold bending that were in the AISC *Manual of Steel Construction* (AISC, 1989). It is apparent that the values suggested are generally more liberal (allow tighter bends) than the AISC values. Exceptions include ASTM A36 steel in thicknesses of ½ in. or less and ASTM A514 steel in thicknesses of 1 in. or more. Thus, adoption of the suggested values provides greater flexibility in fabrication in most cases.

GUIDELINES FOR ASTM A6

Based on the preceding method, a set of guidelines was developed for minimum cold bend radii suitable for typical fabrication, encompassing all steel plate specifications referenced in ASTM A6. To accomplish this, the steels were divided into six groups as shown in Table 9. The steels were arranged in Groups A through E according to their value of specified minimum elongation in 2 in., which was considered to be the dominant factor in distinguishing between different levels of formability. However, Group F was set up to include all steels with a ratio of specified minimum tensile strength to specified minimum yield strength of 1.15 or less. This was done because the CTC tests had indicated that a greater bend radius was required for ASTM A514 steel, which has a tensile-yield ratio of 1.10.

Table 10 shows the guidelines for cold bending for each group. Cold bending requires more generous radii when progressing from Group A to Group F, particularly in the greater thickness ranges, but formability of steels within a group is considered to be about the same. Groups B through F each include at least one steel that was studied experimentally, and the minimum bend radii developed for that steel can be reasonably assumed to be applicable to the other steels in that group. Limited extrapolations were made where necessary based on engineering judgment and considering trends between grades in ASTM A6.

These guidelines were subsequently adopted in ASTM A6 as suggested minimum inside bend radii for cold forming in typical shop fabrication. The AISC Manual (AISC, 2001) no longer provides a separate set of guidelines. Similar guidelines for pressure vessel steels were developed and adopted in ASTM A20 subsequently.

CONCLUSIONS

Radius-to-thickness limits from idealized bending limit diagrams developed from specimen tests can be used to establish fabrication limits if appropriate allowances are made for conditions in fabrication that differ from those in the tests. This includes adjustments to account for plate properties that approach minimum specified values rather than the typical properties of the test material, thicknesses greater than those tested, and edge or surface imperfections that may be present in typical fabrication. After making such adjustments, a table of suggested limits was developed and subsequently adopted in ASTM A6 as suggested minimum radii for typical shop fabrication. The adopted values are generally more liberal (allow tighter bends) than those that had been given in the AISC *Manual of Steel Construction*, thus providing greater flexibility in fabrication in most cases.

ACKNOWLEDGMENT

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