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A. K. Dhalla

G. Winter

DUCTILITY CRITERIA AND PERFORMANCE OF LOW DUCTILITY STEELS FOR COLD-FORMED MEMBERS

by A. K. Dhalla[1] and G. Winter[2], F.ASCE

INTRODUCTION

The cold-working of low carbon steel or the higher carbon contents in medium carbon steels increase the yield and the ultimate strengths while decreasing the elongation capability or ductility. The present investigation was undertaken to study the feasibility of effectively utilizing these high strength, low ductility steels in structural members.

The current Specification for the Design of Cold-Formed Steel Structural Members (1)[3] permits the use of any steel whose properties and suitability have been established by a recognized specification or appropriate tests. A problem exists, however, in defining what constitutes a suitable steel for cold-formed construction. The yield strength and tensile strength can be varied over a wide range, while the modulus of elasticity is nearly constant. In addition to these mechanical properties, ductility, formability and weldability are among the desirable performance attributes of a steel for cold-formed members.

An extensive investigation was carried out at Cornell University (Reference 2) to study the effects of ductility and of the spread between the yield and the ultimate tensile strength, on the behavior of thin cold-formed members and connections under essentially static loading. A limited study of performance attributes such as formability, and weldability of low ductility steels was also undertaken in the same investigation (2). In this paper only, the ductility parameters and the minimum ductility requirements for thin members are briefly reported.

Ductility is the ability of a material to undergo plastic deformations without fracture. It reduces the harmful effects of stress concentrations, and helps achieve uniform stress or load distribution in members or connections. A conventional measure of ductility, as per ASTM specifications (A370-68), is the elongation in a 2 inch gage length, ϵ_2, of a standard tension coupon. The minimum ϵ_2, specified for various grades and thicknesses of structural steel varies from 18 to 24%. Based on these specified minimum values and on ultimate tensile to yield strength ratios, σ_t/σ_y, established somewhat arbitrarily in the same ASTM specifications, some building codes presently impose restrictions or penalties on allowable design stresses for lower ductility steels. With the increased availability and use of higher strength steels possessing lower ductility and lower σ_t/σ_y ratios there is a need for more definitive information on such requirements.

Various standard tests which measure ductility of a material were evaluated from a survey of ths pertinent literature. There are a number of standard tests such as the tension test (9), bend test (14), or notch test (7), to measure the ductility of a material. The standard tension coupon test was chosen for investigation because it is widely used and has special significance to structural engineers. It supplies values of the yield and tensile strength, and indicates stress-strain characteristics of a material for static load conditions (9), (12).

<u>Significance of Ductility</u>. - There is an essential difference between the tensile strength of a structural member and the tensile strength of the material (5). This difference is associated with the presence of stress concentrations in the structure, e.g., at structural discontinuities, connections, holes, etc. The relative importance of stress concentrations for structural tensile strength depends strongly upon ductility. Qualitatively, the greater the ductility the greater the reduction of stress concentration from its elastic value. Because of the fact that stress concentrations provide a weak link in a structure, it appears that strains associated with a localized region of elastic stress concentrations may provide some meaningful estimate of the structural significance of ductility. Stowell (15) showed that the stress concentration factor in a tension member loaded into the plastic range decreases from its elastic value, while the strain concentration factor increases. Thus the strain concentration factor at impending complete plastification of a critical net section of a tension member can be correlated to the ductility requirements of the material.

In terms of the usual tension coupon test parameters, i.e. the elongation in a 2 inch G.L., ϵ_2, and the σ_t/σ_y ratio, the following criteria are suggested to distinguish roughly between low, medium and high ductility steels. That is:

Low ductility .... $\epsilon_2 \leq 10.0\%$ or $\sigma_t/\sigma_y \leq 1.1$

Medium ductility .... $10.0\% < \epsilon_2 \leq 25.0\%$ and $\sigma_t/\sigma_y > 1.1$

High ductility ...... $\epsilon_2 > 25.0\%$ and $\sigma_t/\sigma_y > 1.1$

The significance of the above differentiation of various ductility steels will become apparent in the section on "Uniform Ductility".

For this research three types of low carbon steels, designated X, Y, and Z, were made available by three different manufacturers. Steels X and Y were specially produced for the program; steel X was cold-reduced an average of 45% in the thickness direction, to produce 12 gage (0.106") and 16 gage (0.062") material and then annealed to arrive at the desired elongation requirements in 2 inches; while steel Y was cold reduced an average of 33% to obtain 7 gage (0.183") and 12 gage (0.106") material, and received no annealing treatment. Steel Z is an ASTM A446 Grade E commercial product which was obtained in 20 gage (0.038").

To distinguish between different types of steels used in this investigation, the following typical specimen designations will be used, (all "percent elongations" are nominal elongations in a 2 inch G.L. of a standard tension coupon test).

708Y - 7 gage Y steel, 8 percent elongation.

1205Y - 12 gage Y steel, 5 percent elongation.

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[1]Research Assistant, Department of Structural Engineering, Cornell University, Ithaca, N. Y.

[2]Professor of Engineering (Class of 1912 Chair), Cornell University, Ithaca, N. Y.

[3]Numerals in parentheses refer to the corresponding items in Appendix I. - References.

1205X - 12 gage X steel, 5 percent elongation.

1610X - 16 gage X steel, 10 percent elongation.

16FAX - 16 gage fully annealed X steel, 50 percent elongation.

2004Z - 20 gage Z steel, 4 percent elongation.

Specimens loaded perpendicular to the rolling direction (transverse) are designated by the letter "T"; those loaded parallel to the direction of rolling (longitudinal) by the letter "L"; the average material properties are designated by AV.

MATERIAL PROPERTIES

There are two basic aims in material testing:

(i) To distinguish and compare various deformations and strength characteristics of different materials.

(ii) To correlate the results of material tests with the structural behavior of members made from the subject material.

Compression members are not affected by lower steel ductility (e.g. Ref. 2, Chapter 6). Therefore in this paper, attention will be focused on the elongation capability of tension members or tension components of members.

Preliminary Tension Coupon Test Results and Observations. - Coupons for standard tension tests were prepared as per ASTM specifications A370-68. Load strain curves were plotted by an autographic recorder using a 2 inch G.L. exteneometer. Initial test speed was 0.005 in/min which was increased to 0.02 in/min at approximately 1% strain. The average mechanical properties of a few steels, as obtained from the coupon test, are reported in Table 1. All coupon specimens, except for 2004Z-T-AV1 material, were taken in a direction parallel to rolling (i.e. longitudinal). The mechanical properties of Z steel (2004Z-T-AV1) perpendicular to the rolling direction (transverse) have been included because this is the lowest ductility steel investigated in this project. To compare the stress-strain characteristics, typical complete stress-strain curves of a few low ductility steel specimens are plotted in Fig. 1.

The elongations in a 2 inch G.L. (ϵ_2) for longitudinal specimens 2004Z-L5, 1205Y-L2, 1205X-L2 and 1605X-L2 are about 4, 5, 6, and 7% respectively. Although the values of ϵ_2 for steels X, Y, and longitudinal Z are in the same range the shapes of the stress-strain curves are quite different. For example, longitudinal Z steel specimen shows a noticeable strain hardening capacity; indicated by the spread between the yield strength σ_y, and the ultimate strength σ_t. Furthermore, the major portion (73%) of the total strain in a 2 inch G.L. in 2004Z-L5 coupon is incurred before the ultimate load is reached, i.e. before necking. On the other hand the major portion of the strain in a 2 inch G.L. in X or Y steel occurs after the ultimate load is reached. That is, before the necking process starts, only a small amount of plastic strain is uniformly distributed over the length of the coupon, while the larger strains occur in the descending branch and are in effect localized at the neck in the eventual fracture zone.

The above comparison suggests that the distribution of strain for nearly the same elongation in a 2 inch G.L. may be

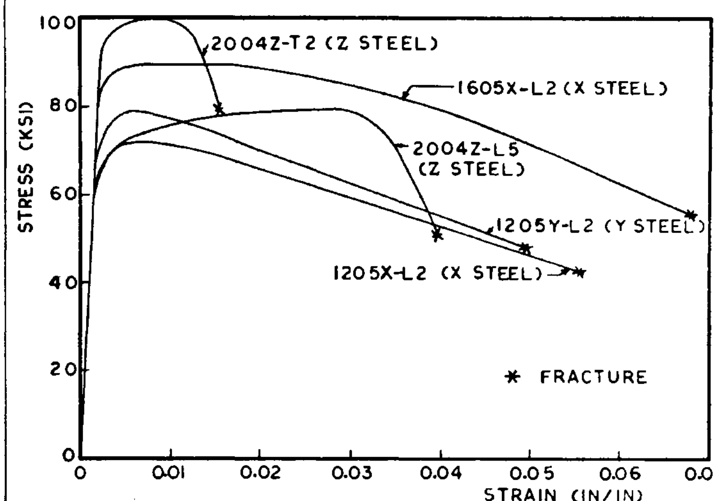


FIG. I. COMPLETE STRESS STRAIN CURVES OF X, Y AND Z STEELS (2" G.L.)

different for coupon specimens of different steels.

Thus the qualitative examination of stress-strain curves seems to indicate that it is essential to have at least two ductility parameters to describe the total elongation capability of a material. One would characterize the uniform straining in the strain hardening portion of the stress-strain curve, while the other that would identify the localized elongation in the neck, i.e. the downward branch of the stress-strain curve.

TABLE 1

AVERAGE MECHANICAL PROPERTIES OF STEELS X, Y AND Z, AS OBTAINED FROM STANDARD TENSION COUPON TESTS

Average Values of Various Steels	Thickness t (in)	0.2% Offset Yield Strength σ_y (ksi)	Tensile Strength σ_t (ksi)	Tensile Yield Ratio σ_t/σ_y	Elongation in a 2' G.L. ϵ_2 (%)	Reduction in Area (%)	Reduction in Thickness (%)
2004Z-L-AV1	0.039	75.5	81.7	1.08	4.38	56.1	55.8
2004Z-T-AV1	0.039	99.4	99.8	1.00	1.34	37.3	-
1205Y-L-AV2	0.106	78.3	79.2	1.01	5.20	65.2	61.0
1205X-L-AV1	0.106	72.2	72.2	1.00	6.00	71.4	67.6
1605X-1-AV1	0.062	88.7	88.9	1.00	5.30	60.9	57.4
1225X-L-AV1	0.108	36.6	50.0	1.37	36.50	79.2	70.2
1625X-L-AV1	0.065	38.5	49.1	1.28	39.20	81.9	74.0
16FAX-L-AV1	0.064	29.9	45.4	1.51	49.8	84.4	72.7

ELONGATION EQUATION

In a standard tension coupon test, at successive load increments, the change in length ΔL, is accompanied by a reduction of the cross-sectional area ΔA. MacGregor (10) showed that by measuring the reduction in area of a coupon at various stages of loading in a tension test, true uniform strain, and the true necking strain can be obtained in terms of the reduction in area. However, for thin rectangular coupon specimens it is difficult to measure accurately the reduction in area at fracture (2). Therefore an alternate method was sought to represent the longitudinal strain distribution along the length of the coupon.

In 1903, Unwin (17) suggested that the total elongation of a tension coupon of gage length L is made up of two parts: The first part is the uniform elongation along the bar and therefore proportional to the gage length: the second is due to local stretching and contraction in the neck which occurs at later stages of the tension test. To include size effects, Unwin used Barba's Law of Similarity and suggested the following equation for strain, ϵ_L, in gage length L,

$$\epsilon_L = \frac{c\sqrt{A}}{L} + b \tag{1}$$

where "b" and "c" are constants obtained from $[\epsilon_L - \frac{L}{\sqrt{A}}]$ plots, and A is the cross-sectional area of the specimen.

To extend the range of applicability Oliver (11) proposed the following modified form of Eq. 1:

$$\epsilon_L = K \left[\frac{L}{\sqrt{A}}\right]^{\alpha} \tag{2}$$

Eq. 2 is a straight line when plotted on a logarithmic scale; K is the value of strain when $L/\sqrt{A} = 1$, and α is the slope of the line.

Since Eq. 2 takes into account the length "L" as well as the cross-sectional area "A" of a coupon specimen, Oliver (11) indicated that the constants K and α are material constants independent of specimen shape. Furthermore the constants K and α, can be determined from a few extra observations (i.e. measuring elongations in 2 or 3 different gage lengths including the fractured portion) in any of the usual tension tests.

Thus, for the present investigation the relationship between percent elongation ϵ_L and $L/\sqrt{A}$ indicated by Eq. 2 offers a viable alternative in identification of ductility parameters instead of the measurement of reduction in area suggested by MacGregor (10).

To obtain the longitudinal strain distribution the central 3 inch length of tension coupons were scribed at 1/4 inch intervals (Fig. 2a). These gage lines were measured before and after the tension test under a travelling microscope (least count = 0.0001"). The longitudinal strain distribution along the length of a few low ductility steel specimens is shown in Fig. 2b. Fig. 3 gives a typical $[\epsilon_L - \frac{L}{\sqrt{A}}]$ plot for 16 gage X steel. For steels presented in Table 1, the constants K and α were obtained from similar $[\epsilon_L - \frac{L}{\sqrt{A}}]$ plots and are recorded in rows 3 and 7 respectively of Table 2.

<u>Comments</u> <u>on</u> <u>Elongation</u> <u>Equation</u>: - Rectangular coupons according to ASTM specifications A370-68 have a constant gage length (usually 2 or 8 inches) and 1/2 inch width. Thus the elongation equation (Eq. 2) can be rewritten as:

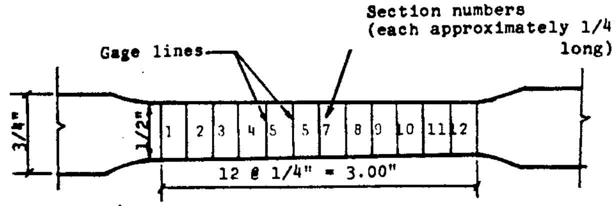


Fig. 2a. Sketch of a standard tension coupon.

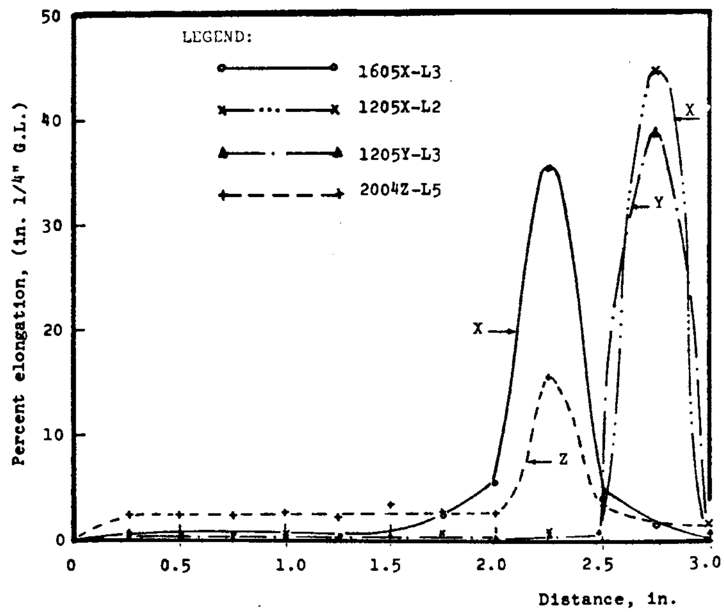


Fig. 2b. Distribution of longitudinal strain in tension coupon, (after fracture).

$$\epsilon_L = K \left[\frac{L}{\sqrt{t/2}}\right]^{\alpha} \tag{3}$$

where t = thickness of the specimen

The conventional measure of ductility is the elongation in a 2 inch (or 8 inch) gage length. For example, to obtain the elongation in a 2 inch G.L. ϵ_2, for low ductility steel 1205X-L-AV1 (in Table 2), one can substitute K = 50.0, α = -1.0 and L = 2.0 in Eq. 3.

i.e. $$\epsilon_2 = \frac{50}{2\sqrt{2}} [\sqrt{t}] \tag{4}$$

Thus Eq. 4 shows that ϵ_2, which is one of the conventional measures of ductility, varies with the thickness of the material. For this reason the elongation in a fixed gage length of rectangular tension coupons is not a valid measure of ductility. In contrast, for circular cylindrical ASTM tension coupons of specified constant cross-sectional area A, the elongation in a constant G.L. "L" (usually 8 inches) would be the same for the coupons machined from different thickness materials.

Recognizing the above difficulty, in the German Code (8) DIN 50 125, the total elongation of a material is computed for a variable gage length which is proportional to the area of the rectangular specimen, instead of using a constant G.L. as is done in the ASTM specifications.

In addition, as will be noted in the next section even the elongation in one fixed gage length of cylindrical bar of fixed diameter, is not sufficient to differentiate between the local and the uniform elongation capabilities of the material.

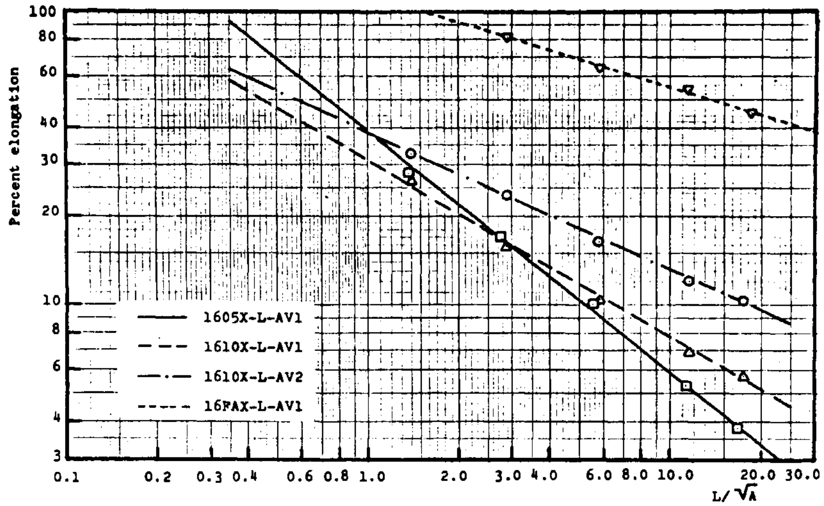


Fig. 3. Elongation - L/ √A curves for 16 gage X steel.

TABLE 2

COMPARISON OF DUCTILITY PARAMETERS*

Ductility Parameters	Low Ductility					Medium Ductility		High Ductility
	Z Steel 2004Z-L-AV1	Z Steel 2004Z-T-AV1	Y Steel 1205Y-L-AV2	X Steel 1205X-L-AV1	X Steel 1605X-L-AV1	X Steel 1225X-L-AV1	X Steel 1625X-L-AV1	X Steel 16FAX-L-AV1
Elongation in a 2" G.L.(incl. neck),(%)	4.4	1.3	5.2	6.0	5.3	36.5	39.1	49.8
Reduction in Area,(%)...	56.1	37.3	65.2	71.4	60.9	70.1	74.0	84.4
K, (%)...	22.0	10.0	44.0	50.0	39.0	80.0	88.0	114.0
Elongation in a ½" G.L.(incl.neck),(%)	9.9	4.2	20.5	23.6	17.0	60.0	59.9	78.1
Tensile-Yield Strength Ratio ...	1.08	1.00	1.01	1.00	1.00	1.37	1.28	1.51
Elongation in a 2½" G.L.(excl.neck),(%)	2.7	0.5	0.2	0.4	1.1	26.5	30.6	36.1
α , ...	-0.60	-0.78	-0.98	-0.97	-0.82	-0.36	-0.34	-0.32

* The values reported in this Table are the average values for different sheets of the corresponding steel reported in Table 1.

DUCTILITY PARAMETERS

An earlier comparison of different characteristics of the stress-strain curves of steels Y and longitudinal Z (in Fig. 1), had indicated that for the same elongation in a 2 inch G.L. Y steel had greater local elongation capability but less strain hardening ability than longitudinal Z steel specimen. In the next two sections the same two steels Y and longitudinal Z will be compared to show that K and α are local and uniform ductility parameters of a material.

Local Ductility. - In Table 2, it can be observed that the average values of percent reduction in area and of K (in rows 2 and 3 respectively), are greater for Y steel (1205Y-L-AV2) than for Z steel (2004Z-L-AV1). Reduction in area identifies the local elongation capability of the material. Hence, it is against the average specific elongation K in Fig. 4. The experimental points obtained from tension coupon test indicate that K increases with the increasing reduction in area. Because of scatter no attempt is made to fit a curve through the points plotted in Fig. 4. This scatter may very well be due to the inaccuracy in the measurement of final area after fracture in thin rectangular specimens.

Thus K and reduction area are local ductility parameters of a material. However, the evaluation of these quantities involve a considerable amount of work in routine practical application of tension test. Therefore, for simplicity the elongation measured in a 1/2 inch G.L. (row 4, Table 2), which includes the fractured portion, is suggested as a local ductility parameter. This 1/2 inch length is large enough to include the necked portion of various thicknesses and types of steel used, and is small enough to give valid comparison for different types of steels.

Uniform Ductility. - In Table 2, it can be observed that the average algebraic values of elongation ϵ_{un}, in a 2 1/2 inch G.L. excluding the neck (i.e. elongation in a 3 inch G.L. minus elongation in 1/2 inch of the necked portion), α, and the σ_t/σ_y ratio for Z steel (2004Z-L-AV1) are greater than those for Y steel (1205Y-L-AV2). Note that σ_t/σ_y identifies the strainhardening ability of a material and ϵ_{un} indicates the uniform elongation capability of a material excluding neck.

Hence it is construed that α, which is the slope of $[\epsilon_L - \frac{L}{\sqrt{A}}]$ plot on a lagarithmic scale, identifies the uniform ductility of the material. For example, in Fig. 3 (or in row 7 in Table 2) α increases from -0.82 for 1605X low ductility steel to -0.32 for 16FAX fully annealed steel, and their respective σ_t/σ_y ratios are 1.00 and 1.51 (row 5, Table 2).

For various project steels ϵ_{un} is plotted against α in Fig. 5. The equations of the linear least square fits for the experimental values are also plotted and are given by:

$$\epsilon_{un} = 10.8 + 10.8\ \alpha \qquad \text{for } \alpha \leq -0.46 \qquad (5)$$

and

$$\epsilon_{un} = 111.0 + 228.0\ \alpha \qquad \text{for } \alpha > -0.46 \qquad (6)$$

In Fig. 5 there is a distinct break at $\alpha = -0.46$ and $\epsilon_{un} = 5.8\%$. Furthermore, the overall experimental observations indicated that the uniform ductility parameters for the medium and high ductility X steels (i.e. for $\epsilon_2 > 10.0\%$, and $\sigma_t/\sigma_y > 1.1$), are $\epsilon_{un} > 5.8\%$ and $\alpha > -0.46$. In contrast, for low ductility steels X, Y, and Z (i.e. for $\epsilon_2 \leq 10.0\%$ or $\sigma_t/\sigma_y \leq 1.1$) the uniform ductility parameters are $\epsilon_{un} < 5.8\%$ and $\alpha < -0.46$. Therefore it is construed that the values of the uniform ductility parameters at the break in the ϵ_{un} versus α plot differentiate the low ductility steels from the higher ductility steels.

In practice and for simplicity a conservative measure of uniform ductility can be obtained from a coupon test by measuring elongation in a 3 inch G.L. and subtracting from it the elongation in one inch G.L. This difference gives the percent elongation in a 2 inch G.L. not containing the fractured portion; hence it is a measure of the uniform ductility of a material.

MINIMUM DUCTILITY REQUIREMENTS

The establishment of minimum ductility requirements, for thin cold-formed members under static loading is part of the present study. In the subsequent sections the experimental and analytical results on member behavior will be discussed briefly and interpreted against the background of observations on materials behavior made on these low ductility project steels.

Summary of Experimental Investigation. - Elastic stress concentrations represent weak links in a structure. Therefore, to provide meaningful estimates of the structural significence of ductility, simple tension members were tested under static loading. Tests were made on rectangular plates with holes, followed by a detailed experimental investigation of the bolted and welded connections (Ref. 3).

From tension tests on perforated plates, it was concluded that, except for Z steel loaded transversely, all the project steels were able to develop the full tensile strength of the member $P_{ult} = \sigma_t A_{net}$ on the net cross-sectional area. Expressed differently, for all steels

$$\frac{\sigma_{tt}}{\sigma_t} \geq 1.0 \qquad (7)$$

where σ_{tt} = the average stress on the net area A_{net} at ultimate load,

and σ_t = material tensile strength determined from coupon test.

Eq. 7 indicates that the effect of the elastic stress concentration near the hole is wiped out and the material is able to redistribute stresses in the plastic range and develop the full tension capacity of the member. For the two tests on transverse Z steel specimens which failed in a semi-brittle manner the average σ_{tt}/σ_t was 0.94.

In bolted connections failure in low ductility steels X, Y and longitudinal Z occurred in a ductile manner. However, a few transverse Z steel specimens again failed in a semi-brittle manner. That is, the net section of transverse Z steel specimens developed an average of 75% of the predicted ultimate strength, and showed a transverse cleavage type fracture, rather than the inclined shear type of fracture observed in ductile failure of all other steels.

The ductile failure of connections made of steels X, Y, and longitudinal Z, which failed in tension tearing, was accompanied by localized plastic deformations. Furthermore these low ductility steel connection specimens showed considerable plastic deformations in bearing failure of bolted connections,

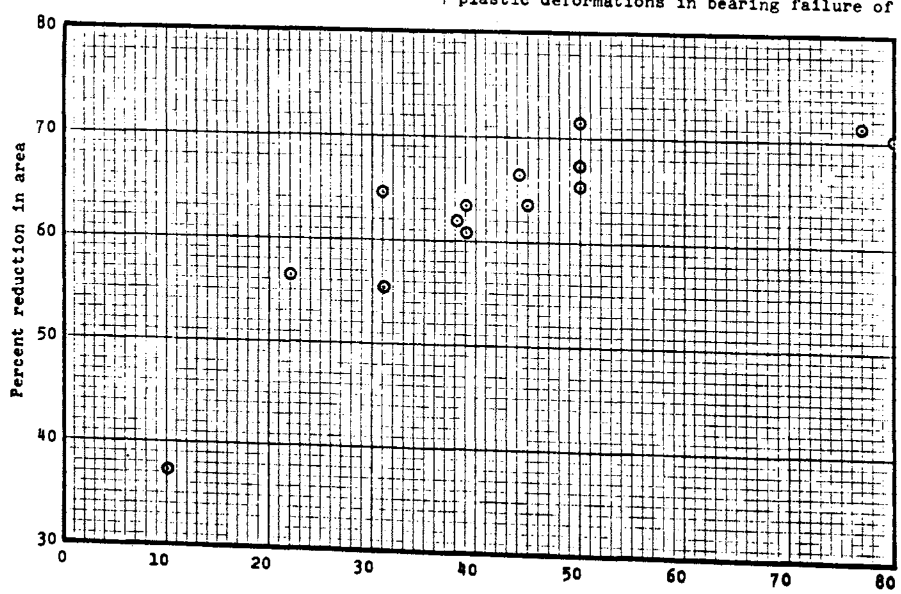


Fig. 4. Percent reduction in area plotted against elongation equation parameter K.

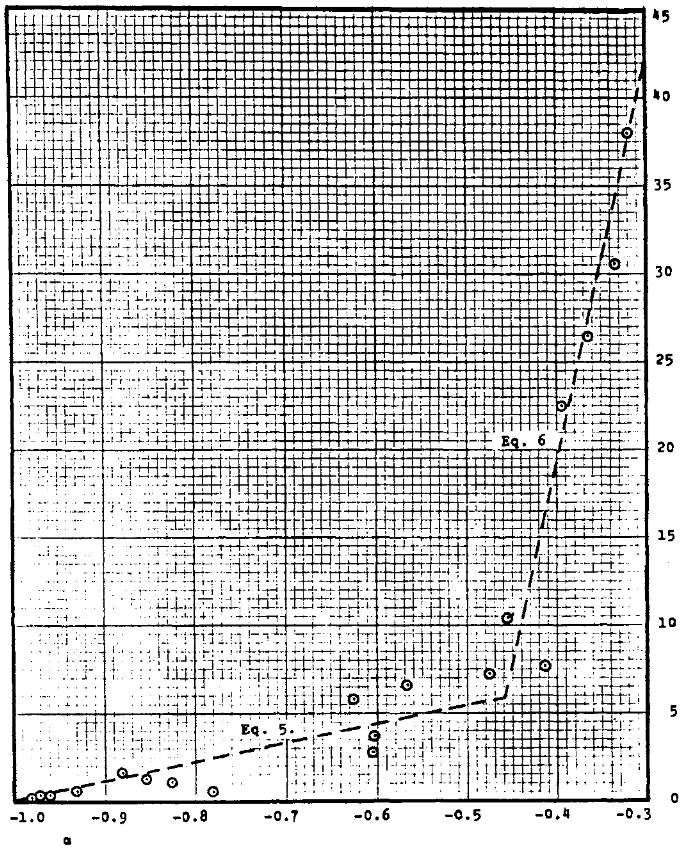


Fig. 5. Relationship between uniform strain ϵ_{un}, and α for steels X, Y and Z.

and in weld shear failure in fillet weld connections. These two failure modes were similar to those obtained for high ductility steels (2). Therefore the experimental observations suggest that steels X, Y, and longitudinal Z, in spite of their conventionally low ductility had sufficient ductility to prevent premature brittle fracture at elastic stress concentrations in perforated plates and in connections. The significance of the above observations will be evaluated in the section "Evaluation of Experimental and Analytical Results".

Summary of Analytical Results. - Ductility requirements should ensure that for a steel with ductilities greater than the required minimum a ductile fracture will occur when such a steel is used as a conventional structural member under static loading. To complement the experimental results and to help in establishing minimum ductility requirements, perforated and notched plates were analyzed in the elastic-plastic range utilizing a finite element computer program (13). In order to develop the full tensile strength of a member with a stress raiser, and to avoid premature brittle fracture it is necessary to achieve full plastification of a "critical" section. For example, in the case of a perforated plate (Fig. 6a), when the plastic zones initiated at the points of elastic stress concentration (A) travel to the free edge (B-B), a ductile fracture is obtained and the member is able to develop its full ultimate tension capacity. In the case of a notched plate (Fig. 6b), the plastic zones initiated at the points of elastic stress concentration (A) would have to meet at the centerline (B-B) to cause a ductile fracture.

Consequently, if the strain at "A" (Fig. 6), is less than the elongation capability of the material, just when the plastic zone initiated at "A" reaches the line B-B, then it can be said that the critical section is able to plastify. Thus, the minimum straining capacity ϵ_{min} which the material should possess for a ductile failure under static loading is given by:

$$\epsilon_{min} \geq (\epsilon_A)_{p\ell} \qquad (8)$$

where $(\epsilon_A)_{p\ell}$ = the strain at the point of largest elastic stress concentration at impending complete plastification. $(\epsilon_A)_{p\ell}$ can be obtained either experimentally or analytically. In the present study, perforated and notched plates were examined in the elastic-plastic range using an available computer program developed by Salmon et al (13). At first, the stress and strain distributions in the elastic range at the net section of a perforated plate were compared with the analytical results given by Howland (6), and in the plastic range with the experimental results of Theocaris and Marketos (16). These comparisons showed satisfactory correlation hence the finite element computer program was used to solve elasto-plastically six rectangular plates with different elastic stress concentrations. $(\epsilon_A)_{p\ell}$ was obtained for three perforated plates, with d/s ratios of 1/2, 1/3 and 1/5, and three notched plates with flank angles of 0°, 60° and 90°, (see Fig. 6). Typical finite element idealizations for perforated plate with d/s = 1/3 is shown in Fig. 7b.

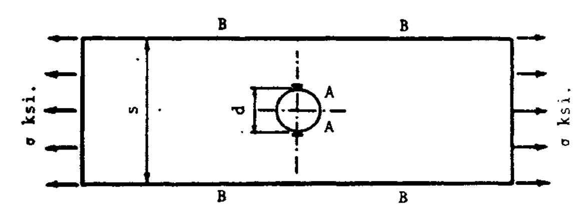
A bilinear idealized stress-strain curve of longitudinal Z steel (shown in Fig. 8) was used. The material properties of this Z steel are:

$$E = 30{,}000 \text{ ksi} \quad ; \quad E_{str} = 250.0 \text{ ksi}$$

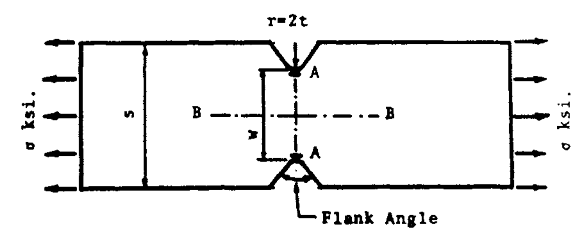
$$\sigma_y = 70.0 \text{ ksi} \quad ; \quad \mu = 0.30.$$

The spread of the plastic enclaves for various (σ_{mean}/σ_y) ratios, calculated on the net section of the perforated plate (d/s = 1/3), is given in Fig. 7a.

The load at which the plastic zone reaches the boundary of the perforated plate or meets at the center in a notched

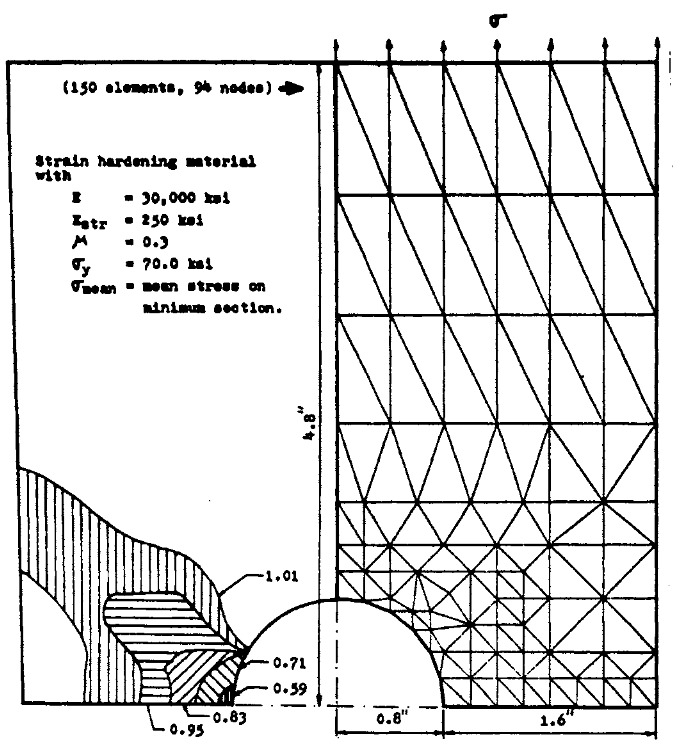


(a) Perforated Plate



(b) Notched Plate

Fig. 6. Tension Members with Elastic Stress Concentrations at A.



(a) Spread of plastic zones for various ratios of σ_{mean}/σ_y.　　(b) Finite element idealization.

Fig. 7. Perforated tension strip (d/s = 0.33), plane stress.

plate is designated as the impending complete plastification load level. The maximum strains $(\epsilon_A)_{p\ell}$ directly at the stress raisers, for these loads are recorded in Table 3. The computed values of $(\epsilon_A)_{p\ell}$ range from 1.1 to 2.6 percent. From the practical viewpoint of establishing minimum ductility requirements these values of minimum strains, necessary for complete plastification of the critical section, are the important findings of this study.

It was discussed earlier that ductility of a material is made up of local and uniform elongation capabilities. Local ductility is characterized by the descending branch of the stress-strain curve. Unfortunately, as postulated by Drucker (4), the classical "Theory of Plasticity" (on which the finite element program is based), cannot utilize this unstable falling branch of the stress-strain curve. Therefore, the ductility requirement (ϵ_{min}) cannot be correlated explicitly with the ductility parameters of the material.

__Evaluation of Experimental and Analytical Results__. - As noted earlier, low ductility X, Y, and longitudinal Z steel failed in a ductile manner in all tension tests. Steels X and Y (i.e. 1205Y, 1205X, and 1605X in Table 2) had very little strain hardening capacity (average σ_t/σ_y = 1.01), and consequently a very small amount of uniform ductility (average ϵ_{un} of about 0.6%). However, these steels had significant local ductility; i.e. the average elongation $\epsilon_{1/2}$, in a 1/2 inch G.L. including fracture, was about 24%. According to the results presented in Table 3, ϵ_{un} = 0.6% is much lower than $(\epsilon_A)_{p\ell}$ = 1.1 to 2.6%, the minimum ductility at the stress concentration required for complete plastification of the critical section. This suggests that in conjunction with uniform ductility of the order of 0.6%, the additional local ductility $\epsilon_{1/2}$ of about 24% in these X and Y steels was sufficient to wipe out the effects of elastic stress concentrations, and completely plastify the critical section.

Thus, in X and Y steels, local ductility was needed in addition to uniform ductility, to avoid premature brittle fracture at stress concentrations. Unfortunately, it is difficult to quantify the required local ductility for the following reasons:

(a) Local ductility, when measured in a 1/2 inch G.L. in rectangular tension coupons, is dependent on the thickness of the material.

(b) Significant member ductility (i.e. plastification of sections other than the critical one) is obtained only if the material possesses definite strain hardening ability or uniform ductility.

(c) $(\epsilon_A)_{p\ell}$ in Table 3 was derived according to the classical "Theory of Plasticity". However the theoretical plasticity calculations do not admit the descending unstable branch of the stress-strain curve (4), which accounts for the local ductility of the material.

For these reasons $(\epsilon_A)_{p\ell}$ will be correlated with the uniform ductility of the material to establish minimum ductility requirements; the additionally required local ductility will be regarded as a ductility reserve. As discussed earlier, __longitudinal__ Z steel which had a conventional elongation capability

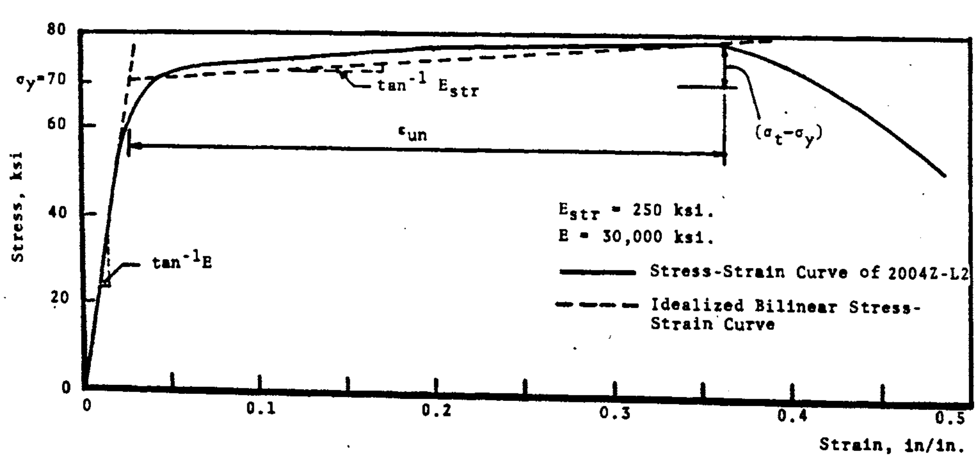


Fig. 8. Idealized Stress-Strain Curve of Z Steel (2" Gage Length)

in a 2 inch G.L. of about 4.4% had fractured in a ductile manner in all tension member tests. This steel had very low local ductility ($\varepsilon_{1/2}$ of about 10%), but had significant strain hardening capacity (average σ_t/σ_y = 1.08), and consequently significant uniform ductility, ε_{un} = 2.7%. The finite element computer program utilized in this paper incorporated the idealized stress-strain curve of longitudinal Z steel (Fig. 8). From this computer program the required uniform ductility $\varepsilon_{un} = (\varepsilon_A)_{p\ell}$ was computed to be between 1 and 3 percent, for complete plastification of the critical section in various tension members with stress raisers (see Table 3). Therefore, from the analytical as well as experimental investigation it is concluded that a material possessing an ε_{un} of about 3 percent along with σ_t/σ_y of about 1.1, has sufficient ductility to wipe out the effects of elastic stress concentrations and completely plastify the critical section in thin rectangular plates with geometric discontinuities, or in bolted or welded connections.

On the other hand, Z steel in the transverse direction had a uniform ductility ε_{un} of only 0.5 percent and σ_t/σ_y = 1.0, which, by analysis, should be insufficient to fully plastify the critical section in a tension member with stress raiser. In addition transverse Z steel had $\varepsilon_{1/2}$ = 4% which too was considerably lower than the 25% possessed by steels X and Y. In fact, in tension tests on perforated plates and some bolted connections the failure in transverse Z steel occurred in a semi-brittle manner, because the material did not have sufficient elongation capability (neither local nor uniform) to completely plastify the critical section. In transverse Z steel tension members, the failure loads, based on complete plastification of net section, ranged from 73 to 94 percent, i.e. they were smaller than those for full plastification.

Thus, to ensure a ductile fracture of a thin-walled tension member with the usual stress concentrations, the analytical and experimental investigations indicate that the uniform ductility of a material, ε_{un}, should be greater than about 3% along with $\sigma_t/\sigma_y \geq 1.1$ and $\varepsilon_{1/2} \geq 25\%$.

CONCLUSIONS

The following conclusions arrived at in this investigation have been interpreted against the background of overall observations made on the low ductility project steels (2).

(1) In dealing with the problem of ductility measurement in a standard tension coupon it appears necessary to distinguish between (a) local ductility, and (b) uniform ductility, which when added together, give total ductility of the material.

(2) For a given material, the elongation as measured in a fixed gage length (usually 2 or 8 inches) varies with the thickness of the rectangular standard tension coupon specimen (Eq. 4). Therefore the conventional elongation in a 2 inch G.L. cannot be used as a reliable measure of ductility for comparing elongation capabilities of materials with different sheet thicknesses. Furthermore over the range of different ductility steels investigated herein, elongation in a 2 inch G.L. did not correlate satisfactorily with either the local or the uniform ductility of the material.

(3) Localized elongation at the eventual fracture zone is designated as local ductility, and is identified in the elongation equation (Eq. 2) by the constant K. Other measures for local ductility are the reduction in area or the elongation in a small gage length across the neck. Uniform ductility is the ability of a tension coupon to undergo sizeable plastic deformations along its entire length prior to necking, and is identified by the elongation equation constant α in Eq. 2, as well as by the strain, ε_{un}, in a tension coupon excluding fracture, or by the σ_t/σ_y ratio.

(4) From an analytical investigation of plates with geometric discontinuities, and from observations on tension tests on perforated plates, and bolted and welded connections, approximate minimum ductility requirements have been established for thin tension members under a monotonically increasing static load. To redistribute the stresses in the plastic range so as to avoid premature brittle fracture, and achieve full net-section strength in a tension member with stress concentrations, it is suggested that the minimum elongation in a 1/2 inch gage length of a standard tension coupon including the neck be at least 25 percent; the minimum uniform elongation in a 3 inch gage length minus the elongation in a 1 inch length containing neck and fracture be at least 3 percent; and the σ_t/σ_y ratio be at least 1.1.

TABLE 3

MAXIMUM STRAIN $(\varepsilon_A)_{p\ell}$ AT THE POINT OF ELASTIC STRESS CONCENTRATION AT IMPENDING COMPLETE PLASTIFICATION IN PERFORATED AND NOTCHED PLATES

Rectangular Plate	Elastic Stress Concentration Factor		$(\varepsilon_A)_{p\ell}$ (%)
	K_{appl}*	K_{net}**	
Perforated Plates			
$\frac{d}{s} = \frac{1}{5}$	2.68	2.14	1.16
$\frac{d}{s} = \frac{1}{3}$	3.09	2.06	1.07
$\frac{d}{s} = \frac{1}{2}$	3.99	1.99	1.21
Notched Plates			
Flank Angle=90°	3.75	2.03	1.11
Flank Angle=60°	4.58	2.68	2.58
Flank Angle=0°	5.93	2.96	2.34

* K_{appl} based on applied stress = $(\frac{\sigma_{max}}{\sigma_{appl}})$

** K_{net} based on net section mean stress = $(\frac{\sigma_{max}}{\sigma_{mean}})$

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APPENDIX II. - NOTATION

The following symbols are used in this paper:

A = Gross cross-sectional area of coupon or tension member.

A_{net} = Net cross-sectional area of a tension member or connection.

b = Constant used in Eq. 1.

c = Constant used in Eq. 1.

d = Diameter of hole in a perforated plate.

K = Elongation equation constant which indicates local ductility of the material.

L = Gage length of standard tension coupon.

P_{ult} = Ultimate load.

s = Width of plate.

t = Thickness of a coupon specimen or a tension member

α = Elongation equation constant which indicates strain hardening capacity of the material.

ϵ_L = Elongation in gage length L in standard tension coupon test.

$(\epsilon_A)_{p\ell}$ = The strain at the point of largest elastic stress-concentration at impending complete plastification.

ϵ_{un} = Uniform elongation in a tension coupon excluding 1/2 inch of the central fractured portion.

ϵ_{min} = Minimum straining capacity the material should possess for a ductile failure of tension members with stress concentrations under static loading.

σ_t = Ultimate tensile strength of the material.

σ_{tt} = Average tensile stress at P_{ult} calculated on the net area, A_{net}, of the tension member.

σ_y = 0.2% offset tensile yield strength of the material.