Structural Details To Increase Ductility of Connections

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Materials used in steel structures are increasingly becoming thicker and heavier. A greater chance of cracking during welding of beams to columns, for example, has resulted due to increased thickness of material. With weld shrinkage restrained in the thickness, width, and length, triaxial stresses develop that may inhibit the ability of steel to exhibit ductility. This paper will try to explain why these cracks may occur and what can be done to help prevent them by expanding on information presented in the AISC Supplement No. 1 (LRFD) or No. 2 (ASD).

We will first consider the pulling of a simple tensile specimen to find out what conditions cause this ductile behavior. Then we will find out why this behavior goes from ductile to brittle when triaxial tension is applied. Finally, we will see what conditions under triaxial stresses the ductility can be restored.

This information is then applied to the practical question of how wide the weld access hole in the web of a connection should be to avoid brittle behavior.

In Fig. 1a the member is unstressed and the atoms are spaced the proper amount.

In Fig. 1b, a tensile stress is applied and the atoms move apart elastically in the direction of the stress. If the stress is removed, the atoms will move back into their proper positions as in Fig. 1a.

In Fig. 1c a compressive stress is applied and the atoms move together elastically in the direction of the stress. Again, if the stress is removed, the atoms will move back into their initial proper positions, as in Fig. 1a.

In both tension and compression, if the applied stress does not exceed the yield strength σ_y, the action is elastic and the member will come back to the initial dimensions when the stress is removed.

In both cases the energy stored in the stressed member is elastic energy. Examples would be a wound-up clock, a structural member when stressed, etc.

If, however, as in Fig. 1d, the member is subjected to a shear stress that exceeds the critical value $\tau_{cr} = \frac{1}{2}\sigma_y$, then a permanent sliding action occurs along a plane between atoms which will not be recovered when the stress is removed.

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This is *plastic strain* and results in energy being absorbed. In Fig. 2a, the member is subjected to a tensile stress σ under the yield strength σ_y. As in Fig. 1b, this results in elastic strain and is recoverable when the stress is removed. Notice also in Fig. 2a that a shear stress occurs which has a maximum value of $\tau = \frac{1}{2}\sigma$ on a plane at 45°, with the axis of the applied tensile stress. If the applied stress σ is increased to a value of σ_y, the

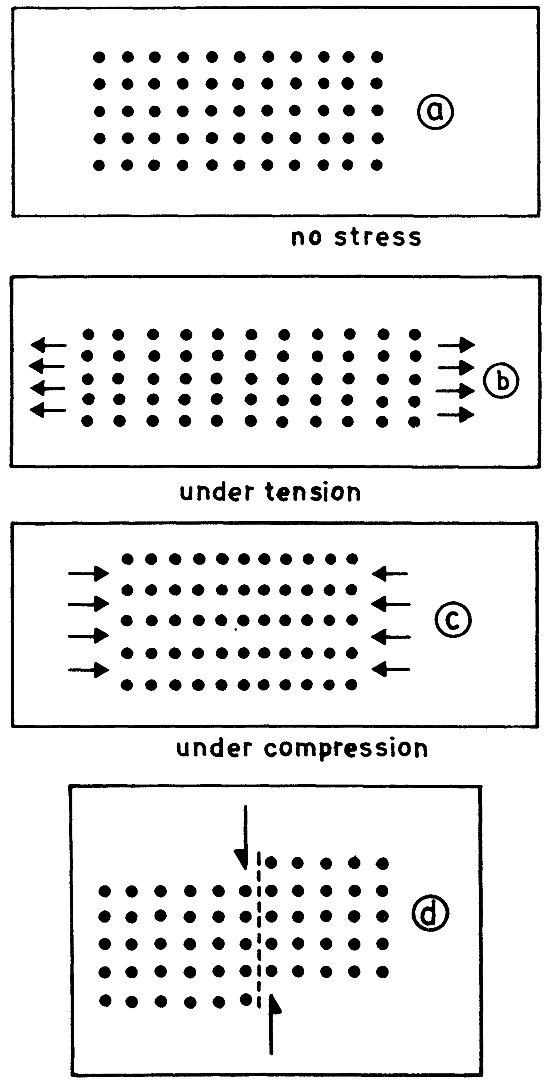


Figure 1

resulting shear stress exceeds its critical value $\tau_{cr} = ½\sigma_y$ then a permanent slip occurs on planes at 45° (Figs. 2c and d).

This is plastic strain and, if continued, will cause the specimen to neck down (Fig. 2c). As the cross-sectional area continues to become smaller, the tensile stress finally exceeds the critical normal stress (tensile strength) and the member fails.

All of this can be seen in the stress-strain curve of Fig. 3. Region **a** below the yield strength covers the elastic strain portion. Region **c** covers the plastic strain portion with the member necking down. Point **d** is tensile failure.

In the stress-strain curve of Fig. 3, region **a** is all elastic strain. The resulting shear stress τ is under the critical value $\tau_{cr} = ½\sigma_y$ so no plastic strain takes place.

In region **c,** the resulting shear stress exceeds the critical value and plastic strain takes place with more and more necking down.

The ductility of the simple tensile test specimen occurs because there is a shear stress component from the particular load condition and, more importantly, because it exceeds its critical value by a considerable amount.

Let us see if we can find why this test specimen is ductile; then we can check the ductility of other loaded members or details.

The ductility of a simple tensile specimen occurs because there are two shear stresses, τ_{1-3} and τ_{2-3}, resulting from the applied tensile stress σ_3. (See Fig. 4a.) Notice when the stress σ_3 reaches its critical value for failure (70 ksi in this example), the two shear stresses have already exceeded their critical value of 20 ksi. There are two shear stresses because there are two circles: circle **1-3** and circle **2-3.** The third circle, **1-2,** has no radius, hence no shear stress, since it is a point.

Any value of shear for τ_{1-3} and τ_{2-3} above the critical 20 ksi will cause plastic strain.

Notice in Fig. 4b that both circle **1-3** and circle **2-3** cause plastic strain $\varepsilon_{3(1-3)}$ and $\varepsilon_{3(2-3)}$. Therefore, the total plastic strain in the direction of the applied stress σ_3 will be:

$$\varepsilon_3 = \varepsilon_{3(1-3)} + \varepsilon_{3(2-3)}$$

Since $\varepsilon_{3(1-3)} = \varepsilon_{3(2-3)}$, we then have:

$$\varepsilon_3 = 2\varepsilon_{3(1-3)}$$

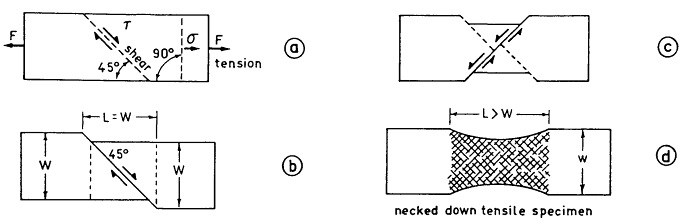
which will tend to reduce the residual tensile stress.

If the specimen is pulled to failure, σ_3 will reach its critical value, or tensile strength. (See Fig. 5.) By this time the two shear stresses are above the critical value and plastic strain or movement will take place. Notice that the total plastic strain consists of two values: $\varepsilon_{3(1-3)}$ and $\varepsilon_{3(2-3)}$. The movement ε_3 acts in the direction of the stress σ_3 and would tend to reduce any residual stress.

This member should behave in a ductile manner.

Plastic behavior takes place from σ_3 = 40 ksi up to 70 ksi and is caused by two different plastic strains, $\varepsilon_{3(1-3)}$ and $\varepsilon_{3(2-3)}$.

In this case of triaxial stresses, all are tensile (Fig. 6). If



Ductility of Steel

Figure 2

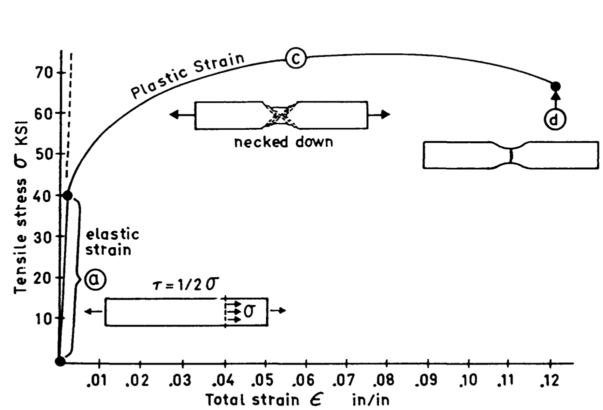


Figure 3

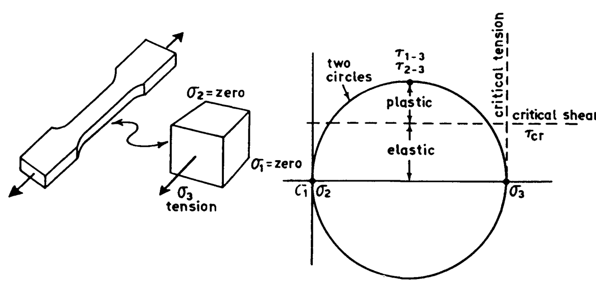


Figure 4a

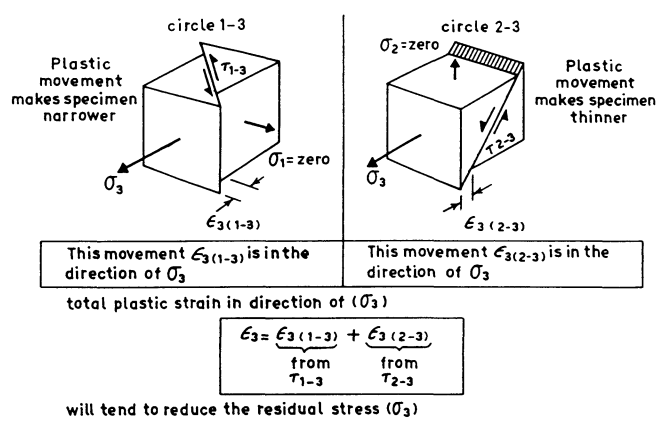


Figure 4b

they have different values, there would be three different circles: **1-2, 1-3,** and **2-3.** If stresses σ_1 and σ_2 are equal, circle **1-2** will have zero radius and will be represented by a point. Notice in Mohr's circle of stress, if σ_3 reaches its critical value σ_{cr} or ultimate tensile strength, the two shear stresses τ_{1-3} and τ_{2-3} do not reach their critical value and there will be no plastic strain or ductile movement. (See also Fig. 7.)

This condition would result in rather brittle behavior.

For ductile behavior, there must be a shear stress component, τ, resulting from the applied tensile (normal) stress, σ. (See Fig. 8.)

These tensile stresses must differ considerably in value in order to produce shear stresses of any reasonable value because the value of the shear stress is the radius of the circle drawn through any two tensile stresses. (See Fig. 9.)

The greatest shear stress would occur if one of the normal

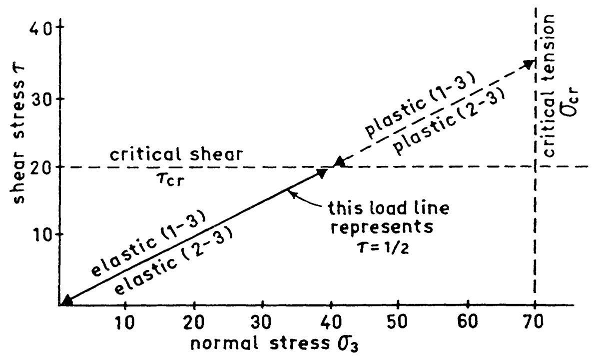


Figure 5

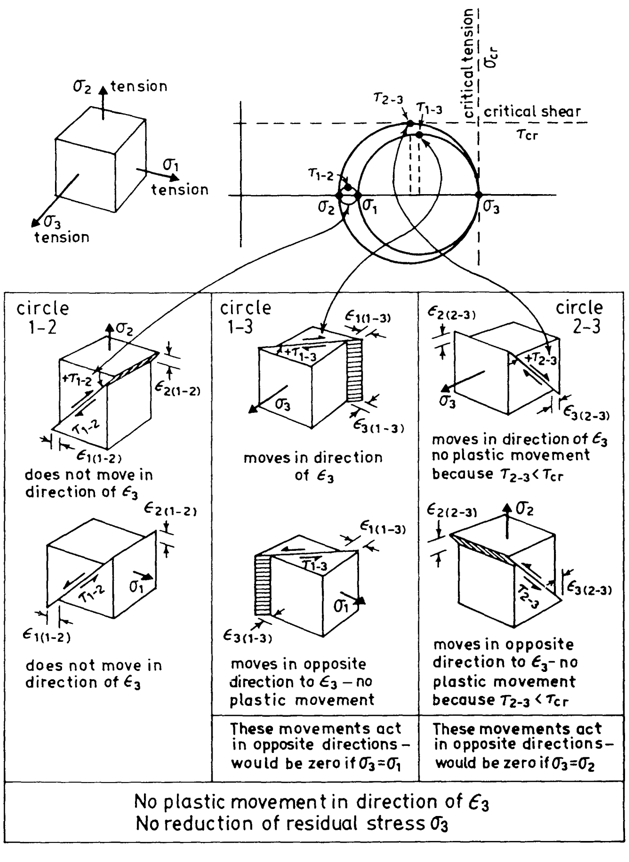


Figure 6

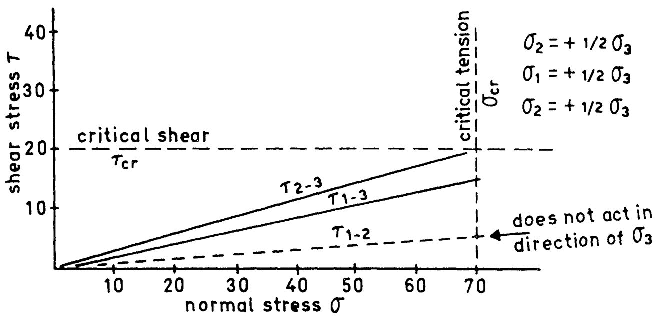


Figure 7

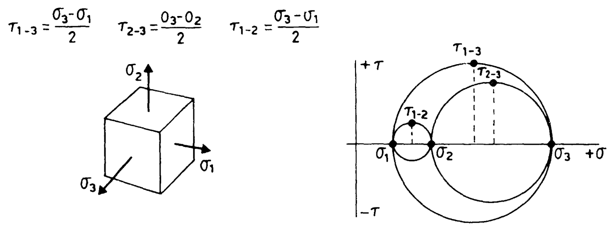


Figure 8

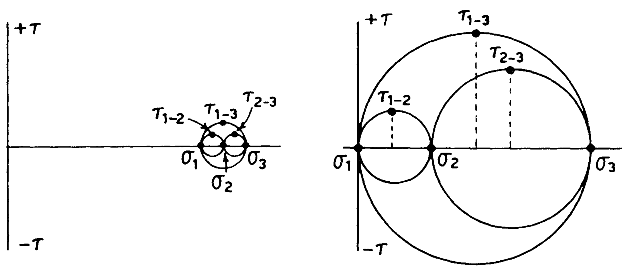


Figure 9

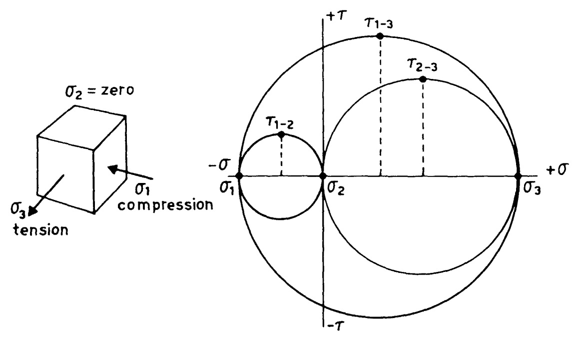


Figure 10

stresses is in compression in this example, σ_1, while the other is in tension, σ_3. (See Fig. 10.)

In order to produce *plastic* strain (ductility) and be helpful, the shear stress must exceed the critical stress $\tau_{cr} = \frac{1}{2}\sigma_y$. (See Fig. 11.) Otherwise, only *elastic* strain results with no help for ductile behavior.

No matter how large the resulting shear stress is, or how much plastic strain is produced, it is of little or no value in relieving the applied tensile stress σ_3 unless it acts in the direction of σ_3. Plastic strains $\varepsilon_{3(1-3)}$ and $\varepsilon_{3(2-3)}$ from circle **1-3** and circle **2-3** act in this direction and are helpful. Plastic strain ε from circle **1-2** does not act in this direction and does not help.

We are not talking about overall elongation of a specimen. This is complex and consists of varying amounts of plastic strain along the length of the necked-down specimen.

We have here a practical problem of predicting a crack next to a weld access hole (a very limited region), so we are interested in the plastic strain at this critical point to see if it is sufficient to relieve tensile stress σ_3 and prevent a crack from forming.

Figure 12 shows the beneficial effect of having at least one stress in compression. When stress σ_3 reaches the critical value σ_{cr} for failure, shear stress τ_{1-3} has been above its critical value for some time, resulting in quite a bit of plastic strain in the direction of the stress σ_3. Although stress τ_{1-2} is above

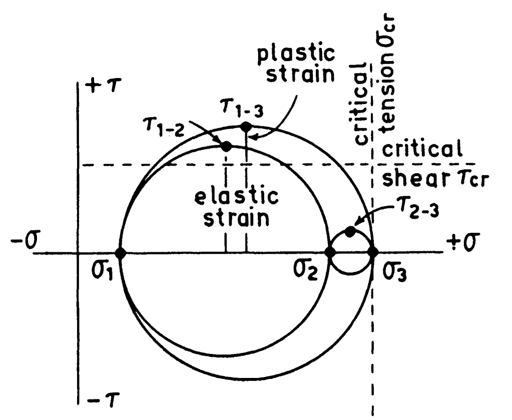


Figure 11

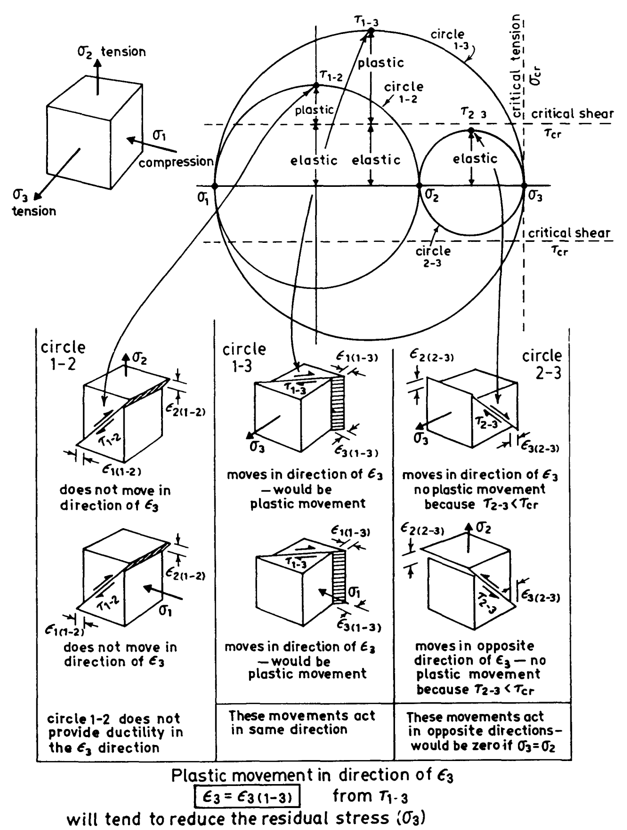


Figure 12

Table 1. $\varepsilon_3 = \left(\frac{\sigma}{116}\right)^{6.8}$			
1 Normal Stress	**2 Elastic Strain**	**3 Total Strain**	**4 Plastic Strain**
σ_3	ε_e	ε_τ	ε_p
10	.00033	.00033	—
15	.00050	.00050	—
20	.00067	.00067	—
25	.00083	.00083	—
30	.00100	.00100	—
35	.00117	.00117	—
40	.00133	.00133	—
45	.00150	.00230	.0008
50	.00170	.00330	.0016
55	.00180	.00500	.0032
60	.00200	.00760	.0056
65	.00220	.01180	.0096
70	.00230	.01830	.0160

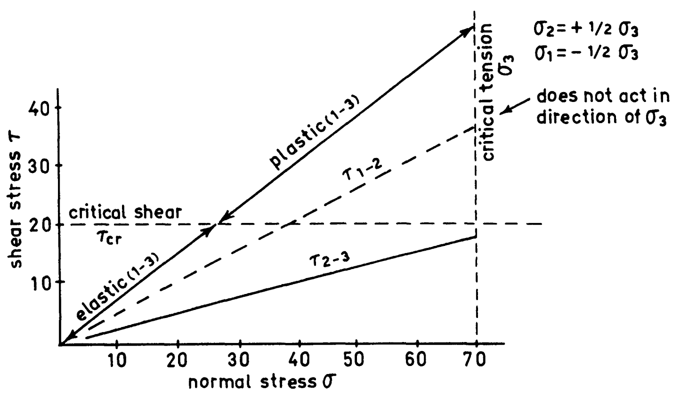


Figure 13

Table 2.

$$\varepsilon_3 = \left(\frac{\tau}{64}\right)^{6.8}$$

Shear Stress	Plastic Strain
τ_{1-3}	ε_3
20.0	.00036
22.5	.00080
25.0	.00160
27.5	.00310
30.0	.00570
32.5	.00970
35.0	.01610

the critical value, its plastic strain does not act in the direction of stress σ_3.

This condition should result in rather ductile behavior. Plastic behavior occurs from $\sigma = 26$ ksi up to 70 ksi. (See Fig. 13.)

It would be very helpful if this data on plastic strain could be put into the form of a stress-strain curve for this critical location.

Table 1 lists the data from a typical stress-strain curve for structural steel (Fig. 14a). Total strain is listed in Column 3. The elastic strain, calculated from $\varepsilon = \sigma / E$, is listed in Column 2. By subtracting the elastic strain from the corresponding total strain, we obtain the plastic strain (Column 4). This plastic strain is shown in Fig. 14b.

Since the plastic strain in Column 4 and Fig. 14b is caused by the corresponding shear stress τ which exceeds its critical value τ_{cr}, we would like to convert the tensile plastic stress tensile-strain curve into a plastic stress shear-strain curve (Fig. 14c). This can be done with Fig. 14b by taking one-half of the tensile stress value, since $\tau = \frac{1}{2}\sigma$, and also one-half of the plastic strain, since, in a simple tensile specimen, we found $\varepsilon_3 = 2\varepsilon_{3(1-3)}$. From this we get the curve of Fig. 14c.

For plastic strain in terms of tensile stress:

$$\varepsilon_3 = \left[\frac{\sigma_3}{116}\right]^{6.8}$$

since $\varepsilon_3 = 2\varepsilon_\tau$ and $\sigma_3 = 2\tau$, so

$$2\varepsilon_\tau = \left[\frac{2\tau}{116}\right]$$

(See Table 2.)

This data will then be used for the case of (a) a narrow-weld access hole in which the triaxial stresses are all tension; and (b) a wide-weld access hole in which one of the triaxial stresses is in compression to construct a stress-strain curve for the critical region in the flange at the edge of the hole. This shows the possible difference in ductile-to-brittle behavior of the two details. A simple tensile test specimen is presented as a reference.

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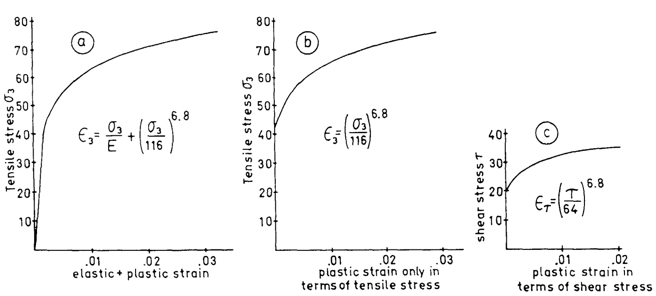

Figure 14

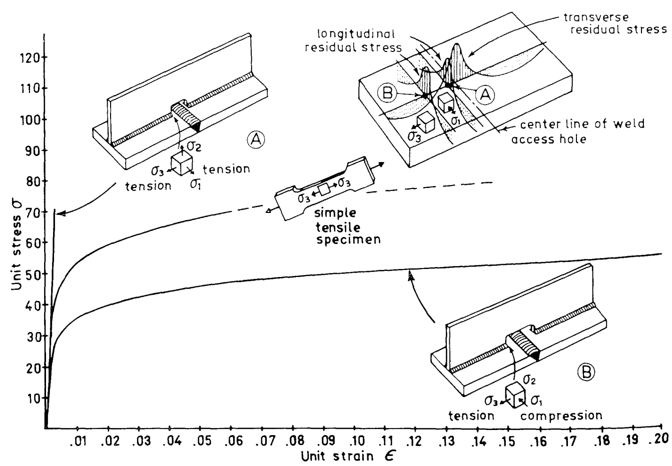

Figure 15