Material Considerations in Structural Steel Design

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ABSTRACT

Engineering structures, with very few exceptions, perform safely and reliably. The safety and reliability of these structures has been achieved primarily by adhering to the appropriate specifications that govern the material, design, fabrication and inspection for the particular structure. These specifications undergo periodic reviews and, when necessary, are changed to improve their accuracy and applicability. Deviations from the specifications' requirements, misinterpretation of specifications, the use of highly restrained complex welded details and use of new and unproven concepts in design may impair the safety and reliability of a structure.

The collapse of a structure or the fracture of a structural component may occur as a result of improper material properties, design, fabrication, inspection, erection and operating conditions. This paper focuses on material considerations and presents a brief discussion of some material factors that should be understood and considered in the fabrication and design of steel structures. The effects of deoxidation practice on segregation in steel ingots, and in the final product are discussed. Also discussed are the variability in the yield and tensile strength properties within a plate or a structural shape and the effects of temperature and rate of loading on these properties. Finally, the paper discusses the variability in fracture toughness and the effects of temperature and rate of loading on this material property. Charpy V-notch test results are used to describe the variability in fracture toughness and the critical stress-intensity factor is used to describe the effects of temperature and rate of loading on fracture toughness. Correlations between CVN test results and the critical stress intensity factor are also presented.

Engineering structures, with very few exceptions, perform safely and reliably. The primary reason for such an excellent performance is the use of recognized national and international specifications for design, material, fabrication and inspection. Incorrect use and violation of the requirements of the specifications may result in failure of a component or an entire structure. Also, because the specifications present *minimum* requirements, the need for additional requirements must be investigated for new and unproven designs, for use of new materials, for use of common materials in new and unique applications and for any other nontraditional situation.

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This paper focuses on material considerations and presents a brief discussion of the causes of segregation in ingot cast steels and the resulting variability in the tensile and fracture-toughness properties in steel products. These phenomena have been known for many years and have been studied and discussed in the technical literature. Thus, the segregation and the variability in properties have been inherent characteristics of all constructional steels used successfully in engineering structures. In spite of some segregation, steels exhibit more uniform properties than most construction materials. Finally, the material is only one of several parameters governing the safety and reliability of structures. The best material properties may not be sufficient to overcome deficiencies in design, fabrication, inspection or usage.

Steel

Constructional steels are a mixture of iron and carbon with varying amounts of other elements—primarily manganese, phosphorus, sulfur and silicon. These and other elements are either unavoidably present or intentionally added in various combinations to achieve specific characteristics and properties of the finished steel product.

At elevated temperatures, steel is an amorphous, essentially homogeneous liquid. As the liquid steel cools, it solidifies and forms crystals or grains. Early in the solid state at elevated temperatures, grains known as austenite are formed, which are essentially a solution of carbon and other elements in iron. As the temperature of the steel decreases slowly, the austenite undergoes a transformation to ferrite which has a more limited solubility for carbon. To accommodate this limited solubility, the carbon precipitates as iron carbide which is concentrated into islands consisting of alternating lamellae of ferrite and iron carbide known as pearlite. These islands are surrounded by a matrix of ferrite. Thus, the steel becomes a mixture of a ferrite matrix and a pearlite matrix modifier. Examples of constructional steels having ferrite-pearlite microstructure are ASTM A36, A572 and A588.

Rapid cooling of the steel from elevated temperatures suppresses the transformation of austenite to ferrite and pearlite, and very hard microstructures known as martensite and bainite are formed. These microstructures are usually tempered by reheating the steel to a given temperature followed by slow cooling. This tempering operation determines the strength of the steel product and imparts toughness and ductility to the martensitic and bainitic microstructures. Examples of these quenched and tempered constructional steels are ASTM A852, A514 and A517.

Ingot Segregation

The most common and traditional steelmaking process is the one where molten steel is poured (teemed) into a series of molds. The steel solidifies in each of the molds to form a casting known as an ingot. All ingots exhibit some degree of nonuniformity of chemical composition known as segregation, which is an inherent characteristic of the cooling and solidification of the molten steel in the mold.

The first liquid steel to contact the relatively cold walls and bottom of the mold solidifies very rapidly having the same chemical composition as the liquid steel entering the mold. However, as the rate of solidification decreases away from the mold sides, crystals of relatively pure iron solidify first. Thus, the first crystals to form contain less carbon, manganese, phosphorus, sulfur and other elements than the liquid steel from which they were formed. The remaining liquid is enriched by these elements that are continually being rejected by the advancing crystals. Consequently, the last liquid to solidify, which is located at the axis of the ingot, contains high levels of the rejected elements. This segregation of the chemical elements is frequently expressed as a local departure from the average chemical composition. Thus, when the content of an element is greater than average, as at the top half of an ingot, the segregation is termed positive segregation; when the content is less than average, as at the bottom half of an ingot, it is negative segregation.

Certain elements tend to segregate more readily than others. Sulfur segregates to the greatest extent. The following elements also segregate, but to a lesser degree, and in descending order: phosphorus, carbon, silicon and manganese. The degree of segregation is influenced by the composition of the liquid steel, the liquid temperature and ingot size.[1]

Killed and Semi-killed Steels

The primary reaction involved in most steelmaking processes is the combination of carbon and oxygen to form carbon monoxide. The solubility of this and other gases dissolved in the steel decreases as the molten metal cools to the solidification temperature range. Thus, excess gases are expelled from the metal and, unless controlled, continue to evolve during solidification. The oxygen available for the reaction can be eliminated and the gaseous evolution inhibited by strongly deoxidizing the molten steel. Steels that are strongly deoxidized are called killed steels. Increasing the amounts of gas evolution result in semi-killed, capped or rimmed steels.

Figure 1[1] illustrates diagrammatically eight typical conditions of commercial ingots, cast in identical molds, in relation to the degree of suppression of gas evolution. The dotted line indicates the height to which the steel originally was poured in each ingot mold. The ingot structures range from that of a fully killed ingot (No. 1) to that of a violently rimming ingot (No. 8). The fully killed ingot (No. 1) evolved no gas, its top was slightly concave, and directly below the top was an intermittently bridged shrinkage cavity called pipe. Ingot No. 2 represents a typical semi-killed ingot in which only a slight amount of carbon monoxide was evolved. In general, killed ingots are less segregated than semi-killed ingots. Movement of liquid steel by convection currents in the ingot mold caused by gas evolution during solidification in semi-killed ingots increases the tendency of elements to segregate. They also contain negligible porosity when compared to semi-killed ingots.

Segregation in Semi-Finished and in Finished Steel Products

Steel products, like other metal alloys, exhibit chemical segregation that is an inherent characteristic of the cooling and solidification process. The amount of segregation for steels made from ingots is a function of several parameters, including the deoxidation practice, the size of the ingot and the amount of cropped metal.

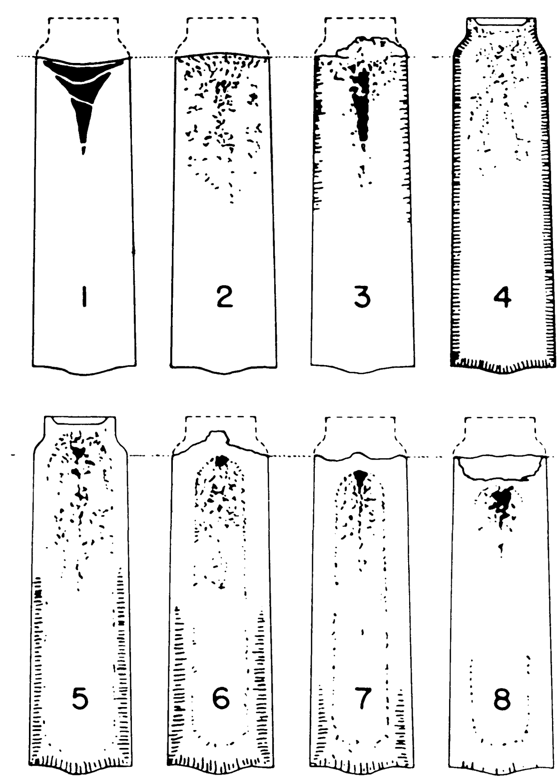

Fig. 1. Series of ingot structures

Ingots are usually reheated then rolled into products with square or rectangular cross sections. This hot-rolling operation elongates the ingot and produces semi-finished products known as blooms, slabs or billets. Although there is no widely accepted precise definition for these terms, Fig. 2[1] presents a crude definition based on their cross-sectional characteristics. Ingot segregation, porosity and pipe are an inherent characteristic of the cooling and solidification process for steels. A significant part of these characteristics is usually eliminated by cropping and discarding a relatively small part of the top and bottom of the ingot. The remaining part of these characteristics is rolled and distributed in the finished product.

The amount of the ingot segregation remaining in the semi-finished and finished products depends on many factors. However, the relative location, shape and distribution for the segregation in the product can be determined by using these simple principles:

1. The center of the ingot cross section remains the center of the cross section of the final product.
2. The contours that describe the cross section of the ingot remain contours that describe the cross sectional geometry of the finished product.
3. The ratios of the areas within the contours remain constant as the ingot is rolled into semi-finished and finished products.

The application of these principles indicate segregation, if present, would occur along the center of plate products and in the shape of a dog bone for a wide-flange structural shape (Fig. 3). The redistribution of segregation, porosity and pipe as a result of the elongation and shaping of ingots into the finished products may result in variation in the properties along the length and in the thickness directions of the final products.

TENSILE PROPERTIES

Variation of Tensile Properties

The AISI conducted a survey of the variation in tensile properties for carbon steel plates and wide-flange structural shapes.[2] The survey included data from several producers and for different steelmaking practices. The variation in tensile properties between plates obtained from different parts of an ingot and the variation within a given plate were

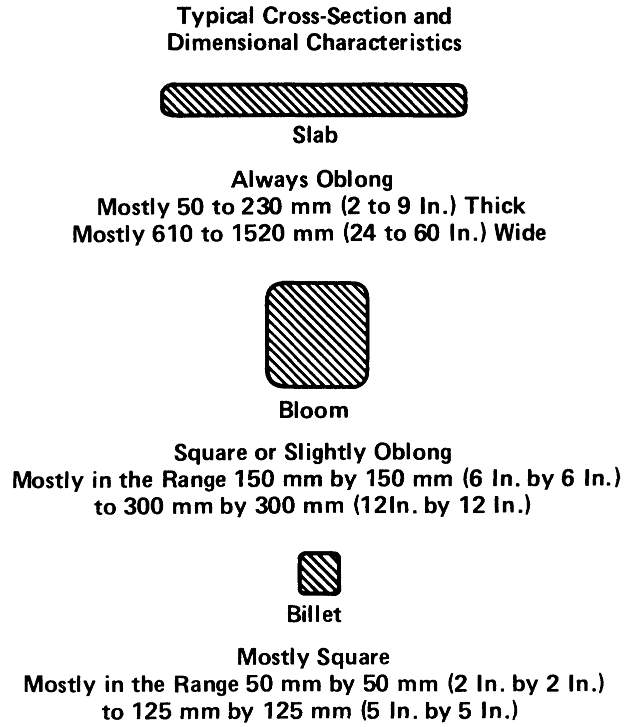

Fig. 2. Comparison of relative shapes and sizes of rolled steel governing nomenclature of products of primary and billet mills

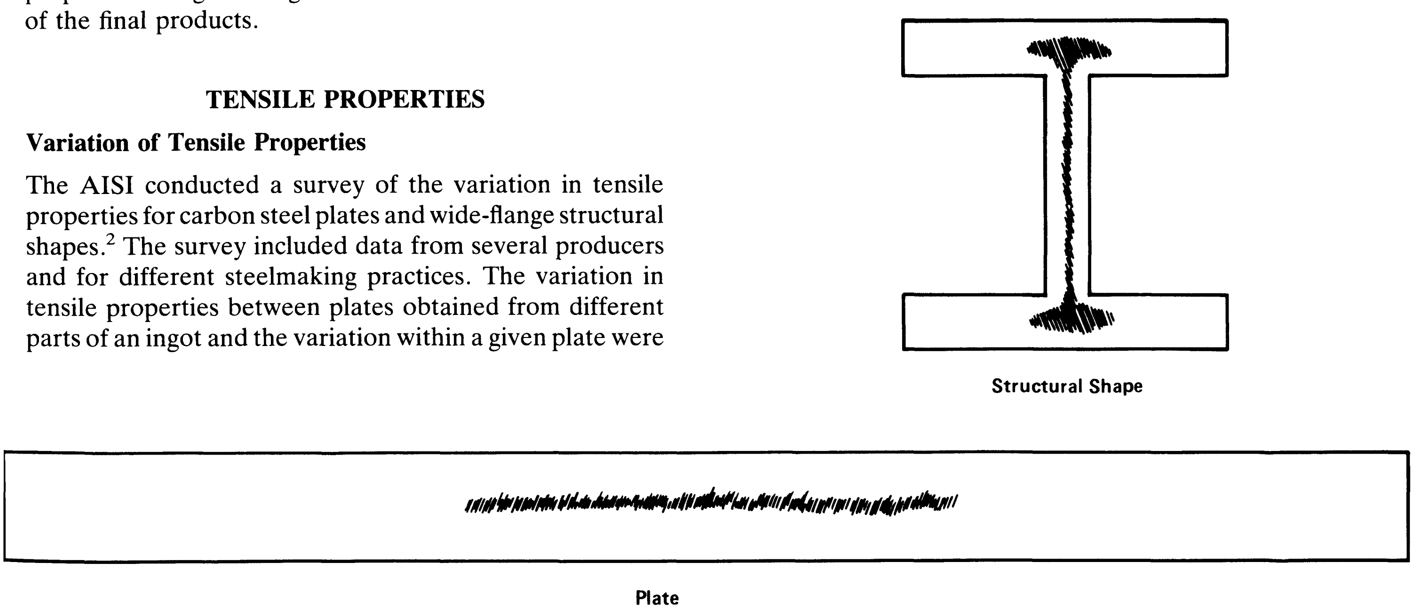

Fig. 3. Schematic representation of segregation in plates and structural shapes (not to scale)

investigated. Figures 4 and 5 show the sample locations for various plates from a given ingot and for a given plate, respectively. In all cases, the survey established the differences between the product test result obtained from the different locations and results obtained at the reference-test location dictated by specifications and used by producers to qualify their product. The AISI survey contains a significant amount of additional information. Only a small part of the information reported in the survey is presented in this section.

A summary of the differences between the product test minus the value of the associated reference test for different plates from a given ingot is presented in Table 1. The data indicate a tendency for the product test yield point to be higher than the reference test at lower levels of strength and lower than the reference test at higher levels. Assuming a normal distribution, the data also indicate that the probability does exist for a given product test to have a value less than the minimum value required at the reference test location. This observation is documented in the AISI survey by using a more precise statistical analysis of the data. Finally, the data show an effect of specimen geometry (round and rectangular) on the variation of product tests for elongation in 2 in. The standard deviation for the test results obtained by testing rectangular specimens were significantly higher than for round specimens. In other words, more variability and more data scatter occur when testing rectangular specimens than round specimens.

A summary of differences between the product tests minus the value of the associated reference tests for different locations within a given plate is shown in Table 2. As expected, a comparison of the data presented in Tables 1 and 2 shows that the variation within a plate, as measured by the standard deviation, was less than between plates within an ingot. The AISI survey also showed plate thickness did not have any effect on variability in plates less than 2-in. thick, but there was a significant decrease in variability in plates over 2-in. thick (Table 3).

The magnitude of the variation among tension test results obtained from the flanges and webs of wide-flange structural shapes was determined at the locations shown in Fig. 6. The within-heat variation was obtained by comparing the product test results with the reference test result.

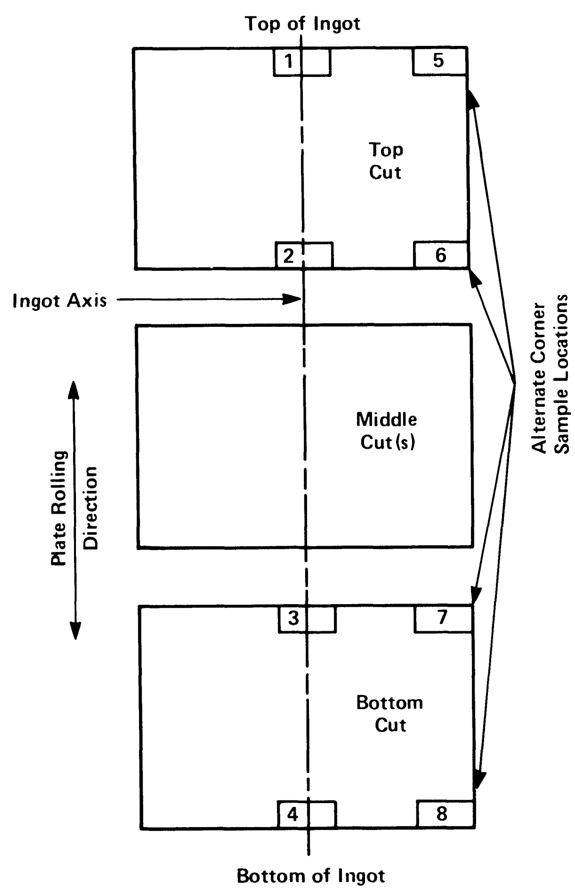

Fig. 4. Sample locations in the product of an ingot rolled into carbon steel plates

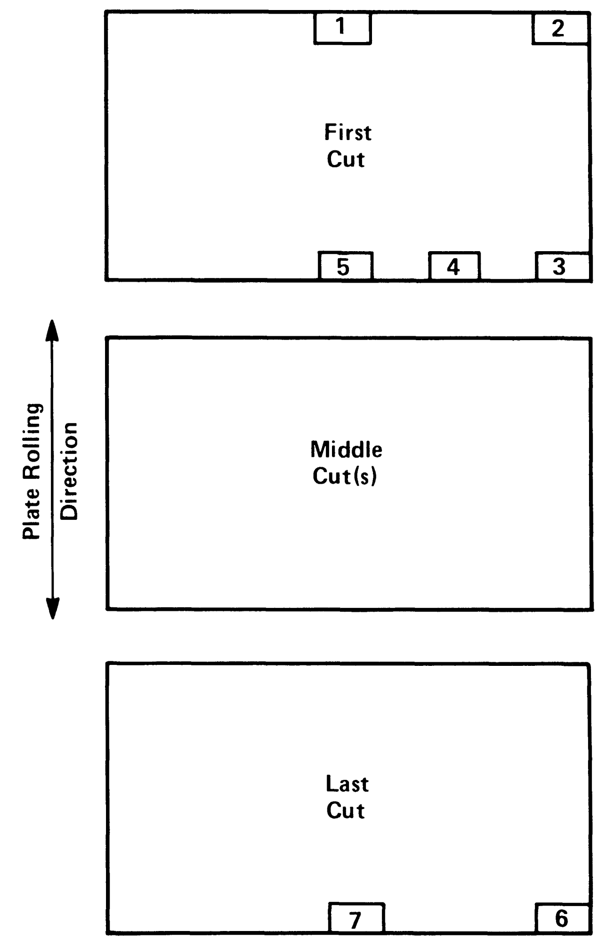

Fig. 5. Sample locations within a carbon steel plate

Table 1. Variation of Product Tension Test Properties with Increasing Reference Test Properties

Tensile Strength

	Reference Tensile Strength, ksi, Cell Boundaries			
	Under 60	60–70 excl.	70–80 excl.	80 & over
Number of tests	329	1,119	701	152
Reference test average, psi	57,187	65,321	74,519	84,488
Average difference, psi	−115	+108	+15	−367
Standard deviation, psi	1,577	2,166	3,245	3,058

Yield Point

	Reference Yield Point, ksi, Cell Boundaries			
	Under 30	30–40 excl.	40–50 excl.	50 & over
Number of tests	50	1,265	813	168
Reference test average, psi	28,557	35,651	43,412	55,646
Average difference, psi	+732	−142	−1,427	−1,915
Standard deviation, psi	2,711	2,673	3,253	4,017

Elongation

	Ref. 2-in. Round Elongation Cell Boundaries, percent			Ref. 8-in. Rectangular Elongation Cell Boundaries, percent		
	Under 30	30–35 excl.	35 & over	Under 25	25–30 excl.	30 & over
Number of tests	269	452	122	179	645	593
Reference test average, %	26.91	31.66	36.27	22.10	27.46	31.94
Average difference, %	−0.36	−1.45	−2.38	+1.27	+0.01	−2.17
Standard deviation, %	3.51	2.41	2.52	3.54	3.55	3.34

Table 4 presents the averages and standard deviations of the differences between the product test results and the reference test result. These data indicate that, on the average, the yield point and tensile strength in the web are close to those for the reference test and are higher than those for the flanges. The distributions of differences, as expressed by the standard deviations, are fairly comparable at all test locations. Also, the variability for wide-flange structural shapes was larger than for plates. Finally, the tensile test results for wide-flange shapes showed the elongation in 2 in. in the flanges averaged higher than for the reference test, whereas averages for the web test were lower than for the reference test. Also, the elongation in 8 in. agreed close to the reference test and showed less variability than elongation values measured in 2 in.

Barsom and Reisdorf[3] obtained an extensive amount of information concerning the variability of chemical, microstructural and mechanical (including fracture toughness) properties for heavyweight, wide-flange structural shapes of A36, A572 Gr. 50 and A588 Gr. A steels. Their data show, among other things, the variability in tensile and yield strengths measured at the quarter and mid-thickness

Table 2. Summary of Differences* from the Reference Test Location

Property	Number of Tests	Average Differences	Standard Deviation
Tensile strength, psi	2,125	+115	1,890
Yield point, psi	2,125	−117	2,219
Elongation in 2 in., %			
Round test	512	0.0	2.42
Rectangular test	1,203	+0.2	5.04
Elongation in 8 in., %			
Rectangular test	1,599	+0.6	2.97

*Value of product test minus value of reference test (#2 corner)

Table 3. Effect of Plate Thickness on the Variability Tensile Strength Differences between Locations 2 and 5

Plate Thickness	N	Average Difference	Standard Deviation
¼ in. and Less	72	−440	1960
Over ¼ in. to ½ in., excl.	56	−410	2130
½ in. to ⅝ in., incl.	71	−60	1760
Over ⅝ in. to 1 in., incl.	52	−880	2080
Over 1 in. to 2 in., excl.	32	−310	1750
2 in. and over	72	−250	1220
Total	355	−370	1830

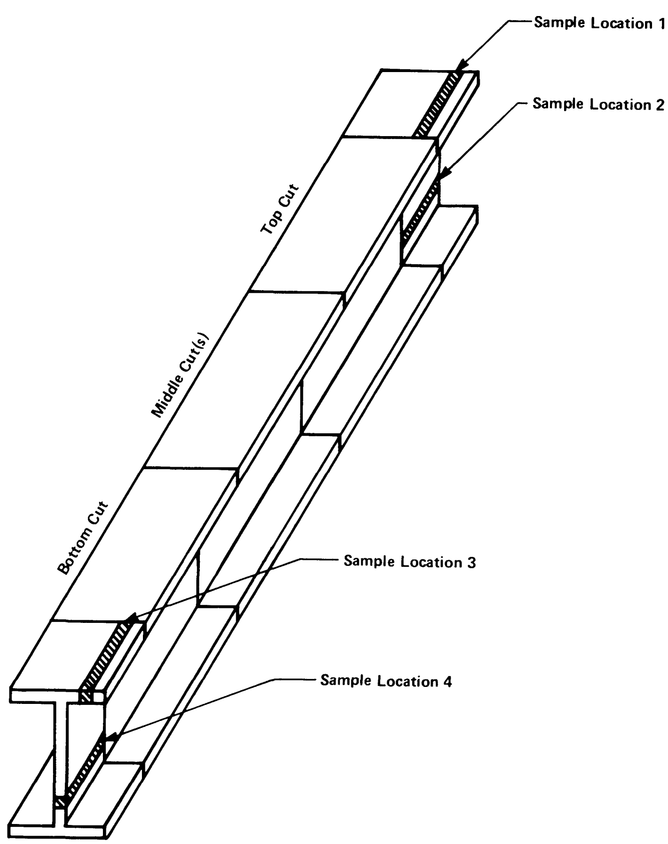

Fig. 6. Sample locations within a structural shape

Table 4. *Distribution of Tension Test Differences**

	Tensile Strength Differences, psi			Yield Point Differences, psi		
Product Test	No. of Tests	Aver-age	Std. Dev.	No. of Tests	Aver-age	Std. Dev.
Top flange	358	−987	3270	358	−2460	3899
Top web	359	+585	3843	359	+497	3897
Bot. flange	357	−1522	3374	357	−2838	3914
Bot. web	359	−687	3588	359	−193	3217
All flange	715	−1254	3330	715	−2649	3908
All web	718	−51	3770	718	+152	3588
All positions	1433	−652	3600	1433	−1246	4003

	Elongation Differences in 2 In., %			Elongation Differences in 8 In., %		
Product Test	No. of Tests	Aver-age	Std. Dev.	No. of Tests	Aver-age	Std. Dev.
Top flange	151	+2.80	4.22	343	+0.67	3.48
Top web	151	−0.65	4.19	342	−0.52	3.23
Bot. flange	150	+2.81	5.33	343	+0.83	3.70
Bot. web	150	−0.01	4.49	343	−0.39	3.03
All flange	301	+2.80	4.79	685	+0.75	3.59
All web	301	−0.33	4.34	685	−0.46	3.13
All positions	602	+1.24	4.83	1370	+0.15	3.42

*Value of product test minus value of reference test.

of the webs and of the flanges for W14 structural shapes weighing from 243 to 730 lb./ft. They also presented average tensile values corresponding to ingot-top locations and ingot-bottom locations. It is recommended that users of steel familiarize themselves with the extent of variability found in these products.

Producers are aware of the chemical segregation and the variability in the properties of steel products. Consequently, based on their experience, they establish aim chemical compositions that would ensure meeting the requirements of the material specifications. Because of the recognized variations, the aim chemistries are usually selected to result in properties that would exceed the minimum properties required by the material specifications.

Effect of Temperature on Tensile Properties

Tensile data for various steels show the yield strength and ultimate tensile strengths of steels increase by approximately 60 ksi when the temperature decreases from 70 to −320°F., Figs. 7 and 8, respectively.[4] Since the absolute increases are about the same for all steels, the percentage increase is much larger for the low-strength steels. More importantly, the data show that in the temperature range of interest for most structures ($-60°F. < T < 120°F.$) the yield strength and ultimate tensile strengths of constructional steels remain essentially constant.

Finally, the ductility of steels as measured by the fracture strain of uniaxially loaded, smooth, cylindrical specimens is

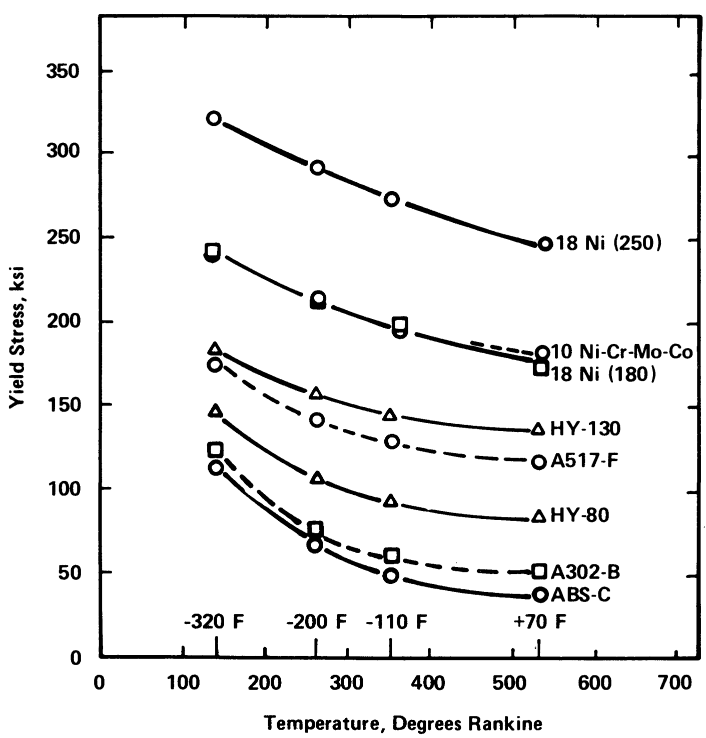

Fig. 7. Yield stresses of eight structural steels

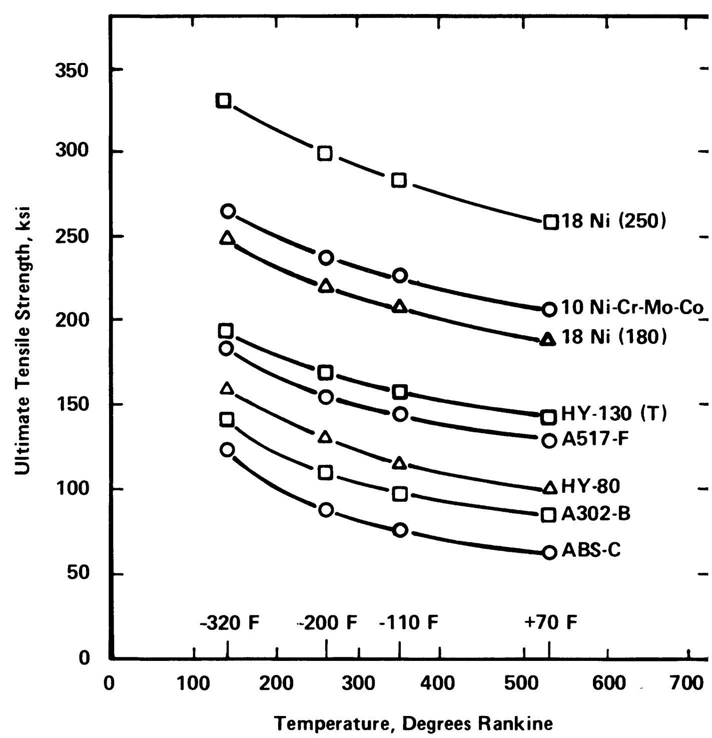

Fig. 8. Ultimate tensile strengths of eight structural steels

essentially independent of temperature in the range 70 to −200°F., Fig. 9.[4] Also, the fracture strain had very little dependence on the yield strength.

Effect of Loading Rate on Tensile Properties

The primary effect of increased loading rate (i.e., decreased loading time) is to increase the yield strength of steels. Yield strength increases by about 5 ksi for every order of magnitude increase in loading rate. Thus, the absolute increase in yield strength between slow loading and impact loading is 25 to 30 ksi.[5] Since the absolute increases are essentially the same for all steels, the percentage increase is much larger for the low-strength steels. Also, the yield strength obtained under slow loading in accordance with ASTM Specifications is about 4 ksi higher than under static loading (complete absence of loading rate).[6]

FRACTURE TOUGHNESS

Most constructional steels can fracture either in a ductile or in a brittle manner. The mode of fracture is governed by the temperature at fracture, the rate at which the loads are applied and the magnitude of the constraints that would prevent plastic deformation. The effects of these parameters on the mode of fracture are reflected in the fracture-toughness behavior of the material. In general, the fracture toughness increases with increasing temperature,

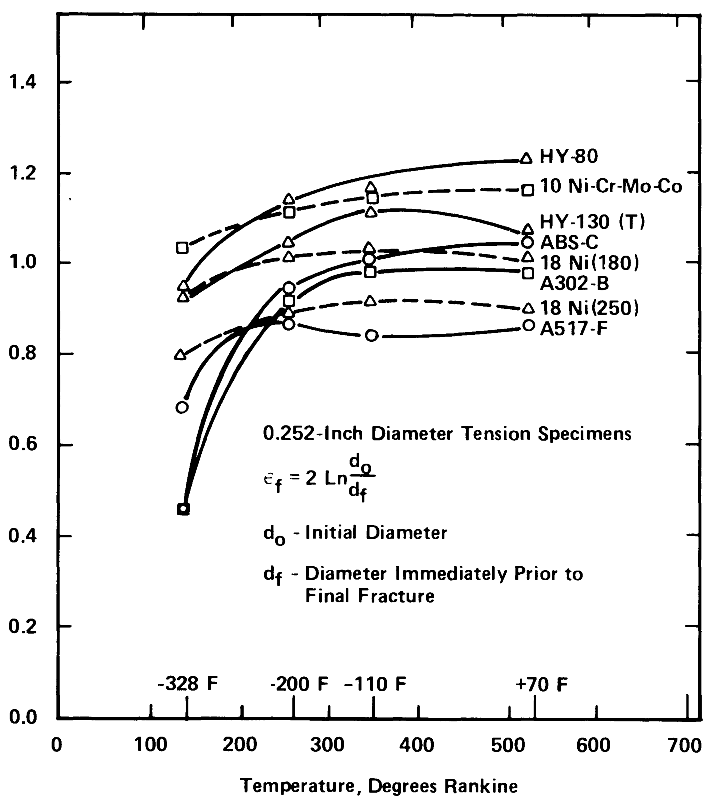

Fig. 9. Fracture strain of eight structural steels

decreasing load rate and decreasing constraints. Furthermore, there is no single unique fracture-toughness value for a given steel even at a fixed temperature and loading rate.

Traditionally, the fracture toughness for low- and intermediate-strength steels has been characterized, primarily by testing Charpy V-notch (CVN) specimens at different temperatures. However, the fracture toughness for materials can be established best by using fracture-mechanics test methods. The following presents a few aspects of fracture toughness of steels by using CVN and fracture-mechanics test results.

Charpy V-Notch Fracture Toughness

The Charpy V-notch impact specimen has been the most widely used specimen for characterizing the fracture-toughness behavior of steels. These specimens may be tested at different temperatures and the impact fracture toughness at each test temperature may be determined from the energy absorbed during fracture, the percent shear (fibrous) fracture on the fracture surface or the change in the width of the specimen (lateral expansion). At low temperatures, constructional steels exhibit a low value of absorbed energy (about 5 ft-lb.), and zero fibrous fracture and lateral expansion. The values of these fracture-toughness parameters increase as the test temperature increases until the specimens exhibit 100% fibrous fracture and reach a constant value of absorbed energy and of lateral expansion. This transition from brittle-to-ductile fracture behavior usually occurs at different temperatures for different steels and even for a given steel composition. Consequently, like other fracture-toughness tests, there is no single unique CVN value for a given steel even at a fixed temperature and loading rate. Therefore, when fracture toughness is an important parameter, the design engineer must establish and specify the necessary level of fracture toughness for the material to be used in the particular structure or in a critical component within the structure.

Variability of Charpy V-Notch Toughness

The AISI conducted two systematic surveys to investigate the extent of CVN variability to be expected for steel plates.[7,8] The various participants in the first survey tested the plate product of two slabs from each of five heats of each of three steel grades. Seven sets of tests were taken from the plate rolled from each slab at the locations shown in Fig. 10. Each set of tests consisted of three longitudinal and three transverse tests and each of these triples was tested at three test temperatures. The steels, plate thicknesses and test temperatures investigated are shown in Table 5. The fracture toughness was measured as foot-pounds of absorbed energy and as lateral expansion in mils (0.001 in.). The number 2 position (top corner in Fig. 10) was selected as the reference test for the plate and the difference between the three-test average at each of the other six locations and the average at the number 2 location was calculated for each plate.

Table 5. Steels and Test Temperatures Investigated

Steel	Condition	Thickness, in.	Test Temperature, F.
A572 Gr. 50 Killed fine-grain	As-rolled	¾ to 1½	0, +40, +70
A516 Gr. 70	Normalized	7/16 to 3	−50, 0, +32
A537 Class 2	Quenched and tempered	7/16 to 2½	−75, −50, 0

The second AISI survey was very similar to the first survey in many respects, except it was conducted on thick plates (up to 4 in.) of A572 Gr. 50 and A588 steels. Although the data have not been published yet, the information presented at various AASHTO meetings indicates the variability in the thick plates was not significantly different from that observed in the first survey on thinner plates.

The AISI surveys contain an extensive amount of valuable information concerning the extent of CVN variability to be expected in steel plate. Similar data for heavyweight, wide-flange structural shapes have been reported by Barsom and Reisdorf.[3] The information will not be repeated in this paper, and only a few of the findings from the AISI surveys will be presented to emphasize specific observations. Thus, it is recommended users of steel products familiarize themselves with the extent of variability found in these investigations.

Figure 11 shows the distribution of averages of three longitudinal CVN tests for A572 Gr. 50 steel and for each test temperature. The percent frequency for each cell and the cell boundaries are shown above and below this histogram bar, respectively. The data show that, as expected, the mean values and the variabilities increase with increasing test temperature. In other words, as the test temperature increases, the fracture-toughness values increase and the scatter around the average increases. This behavior was observed for the transverse-test averages and for all the steels tested. Furthermore, the survey showed the mean and the standard deviation for the test averages at the reference location were essentially identical to those for the test averages throughout the plate.

Producers are aware of the chemical segregation and the variability in the properties of steel products. Consequently, based on their experience, they establish aim chemical compositions that would ensure meeting the requirements

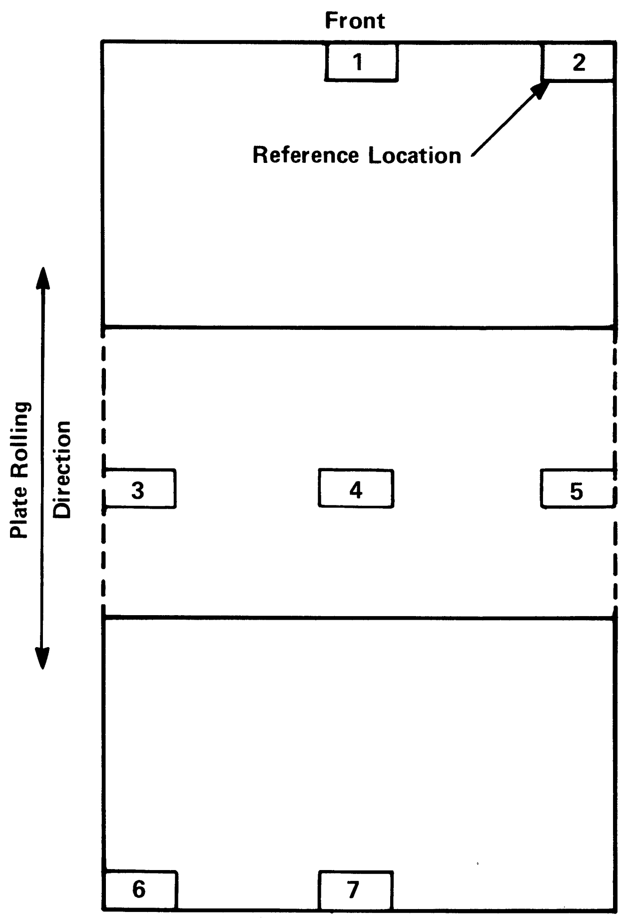

Fig. 10. Sample locations within a plate

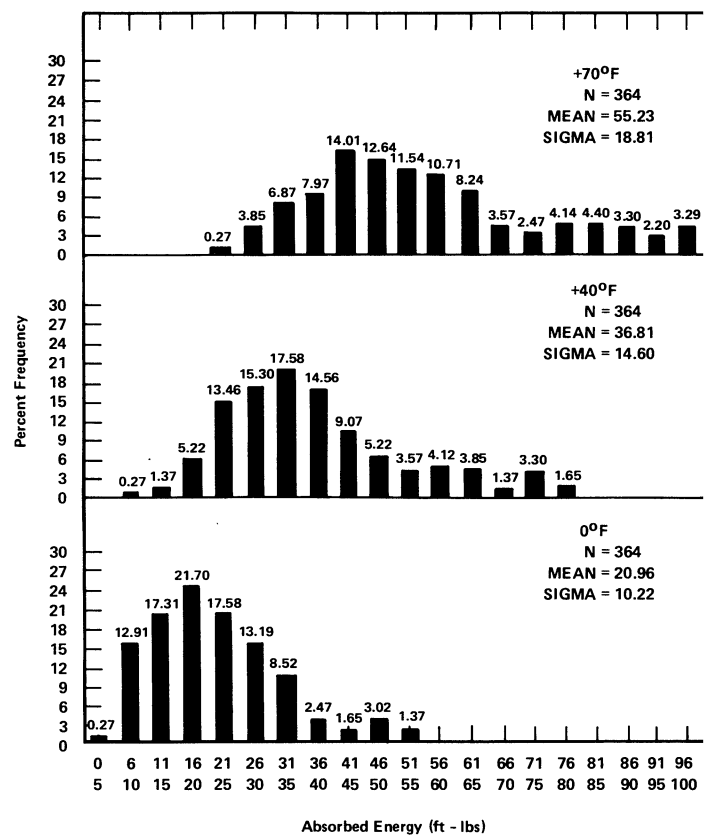

Fig. 11. Frequency distribution of longitudinal 3-test average Charpy V-notch impact tests A572 Gr. 50 plates, absorbed energy, ft-lbs.

of the material specifications. Because of recognized variations, aim chemistries are usually selected to result in properties that exceed the minimum properties required by the material specifications.

One of the most significant results of the AISI survey is presentation of the data in graphical form to predict the probability that average CVN toughness values at other locations may be a given ft-lb. value lower than the reference test. Figure 12 illustrates the usefulness of these plots. The reference-test line in the figure represents the minimum probability a test in the plate will be equal to or exceed a specified difference from the reference test. The figure represents average CVN impact test results at +40°F. for A572 Gr. 50 with a reference-test value between 20 and 29 ft-lb. (Different reference-test ranges are represented by different lines.) Thus, −10 on the *x*-axis corresponds to the situation where the average product test somewhere in the plate would be 10 ft-lb. less than the reference test reported by the manufacturer.

Assume a manufacturer reports a 25 ft-lb. (which is within the 20 to 29 ft-lb. range) average longitudinal CVN impact test value at the reference temperature. The probability other tests from the same plate will average 15 ft-lb. (i.e., −10 ft-lb. from the reference test) or greater, is 95%. (In Fig. 12, the vertical line at −10 ft-lb. intercepts the reference test line at 95%.)

The AISI surveys present probability curves for various steel grades and test temperatures. These curves can be used to predict the minimum probability a three-test average anywhere in the plate will equal or exceed a given difference from the reference test. Correlaries to these results are the expectation of differences between test results obtained at different locations within a plate and the probability a given test result may fall below a minimum value required at the reference-test location.

Fracture Mechanics Concepts

Fracture mechanics concepts relate the applied nominal stresses and the tolerable crack size and shape to the fracture toughness of the material. Thus, by knowing the fracture toughness for a given material of a particular thickness and at a specific temperature and loading rate, the designer can determine the crack sizes that can be tolerated in structural members for a given design stress. Conversely, for a given design stress and a crack size present in a structural component, the designer can specify a fracture-toughness value for the material necessary to ensure the safety and reliability of the structure.

This general relationship among material toughness K_c, nominal stress σ and crack size a is shown schematically in Fig. 13. If a particular combination of stress and crack size in a structure K_I reaches the K_c level, fracture can occur. Thus, there are many combinations of stress and flaw size (e.g., σ_f and a_f) which may cause fracture in a structure fabricated from a steel with a particular value of K_c at a particular service temperature, loading rate and plate thickness. Conversely, many combinations of stress and flaw size (e.g., σ_o, and a_o) will not cause failure of a particular structural material. Thus, material is only one of several parameters contributing to the safety and reliability of structures.

Effects of Constraint, Temperature and Loading Rate

Fracture toughness K_c varies with the degree of localized constraint to plastic flow along the tip of the fatigue crack. Thus, cracks in very thick members or in structural details having complex geometries are subjected to higher constraints than are cracks in thinner members. As the magnitude of the constraint increases, the fracture toughness

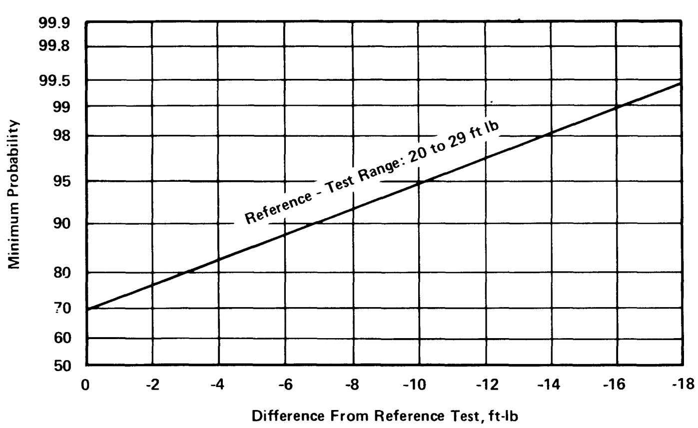

Fig. 12. Minimum probability that product test will equal specified difference from reference test, A572 Gr. 50 plate, longitudinal Charpy V-notch impact test, absorbed energy at +40°F. 3-test

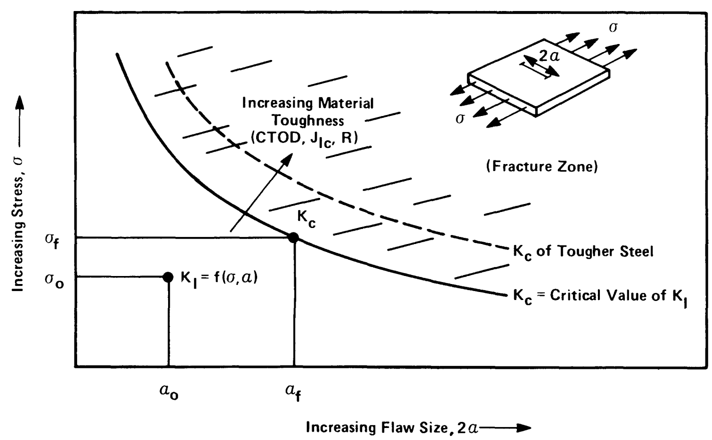

Fig. 13. Schematic illustration of relationship among stress, flaw size and material toughness

decreases until it reaches a constant minimum value, K_{Ic}, which is a measure of the inherent fracture toughness of the material under the most severe state of triaxial stresses.

Fracture toughness K_{Ic} of constructional steels under a constant rate of loading increases with increasing temperature.[5] The rate of increase of K_{Ic} with temperature does not remain constant, but increases markedly above a given test temperature. An example of this behavior is shown in Fig. 14[5] for A36 steel plate tested at three different loading rates. This transition in plane-strain fracture toughness is related to a change in the microscopic mode of crack initiation at the crack tip from cleavage to increasing amounts of ductile tearing.

An analysis of plane-strain fracture toughness data obtained for constructional steels and valid according to ASTM standard procedures shows the fracture toughness transition curve is translated (shifted) to higher temperature values as the rate of loading is increased. Thus, at a given temperature, fracture toughness values measured at high loading rates are generally lower than those measured at lower loading rates. Also, the fracture-toughness values for constructional steels decrease with decreasing test temperature to a minimum K_{Ic} value equal to about 25 ksi $\sqrt{\text{in.}}$ This minimum fracture-toughness value is independent of the rate of loading used to obtain the fracture-toughness transition curve.

Data for steels having yield strengths between 36 and 250 ksi, such as those in Fig. 15[5] show the shift between static and impact plane-strain fracture-toughness curves is given by the relationship[5]

$$T_{\text{shift}} = 215 - 1.5\sigma_{ys} \quad \text{for } 28 \text{ ksi} < \sigma_{ys} \leq 130 \text{ ksi} \tag{1a}$$

and

$$T_{\text{shift}} = 0 \text{ for } \sigma_{ys} > 130 \text{ ksi} \tag{1b}$$

where T is temperature in °F and σ_{ys} is room-temperature yield strength. The temperature shift between static and any intermediate or impact plane-strain fracture-toughness curves is given by the equation[5]

$$T_{\text{shift}} = (150 - \sigma_{ys})\,\dot{\varepsilon}^{0.17} \tag{2}$$

where T is temperature in °F, σ_{ys} is room-temperature yield strength in ksi, and $\dot{\varepsilon}$ is strain rate in sec^{-1}. The strain rate is calculated for a point on the elastic-plastic boundary according to the equation

$$\dot{\varepsilon} = \frac{2\sigma_{ys}}{tE} \tag{3}$$

where t is the loading time for the test and E is the elastic modulus for the material. The data indicate temperature shift is primarily a direct consequence of the relative increase in yield strength with increasing load rate.

A proper use of fracture-mechanics methodology for

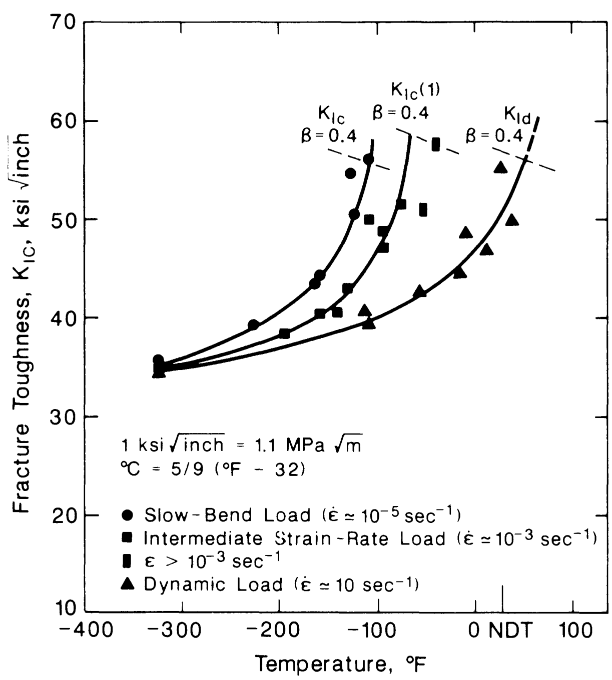

Fig. 14. Effect of temperature and strain rate on plane-strain fracture-toughness behavior of ASTM Type 36 steel

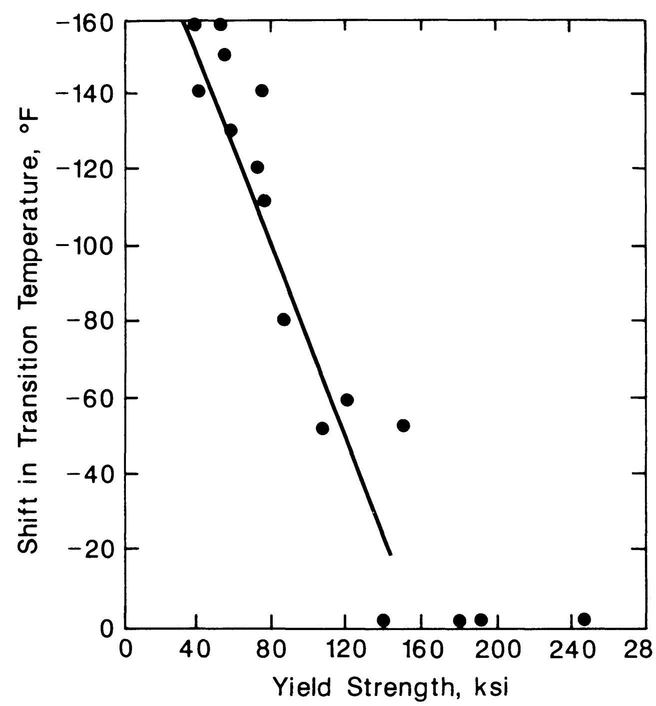

Fig. 15. Effect of yield strength on shift in transition temperature between impact and static plane-strain fracture-toughness curves

fracture control of structures necessitates the determination of fracture toughness for the material at the temperature and loading rate representative of the intended application.

Morphology of Fracture Surfaces

The morphology of fracture surfaces for steel can be understood by considering the fracture-toughness transition behavior under static and impact loading, Fig. 16.[5] The static fracture-toughness transition curve depicts the mode of crack initiation at the crack tip. The dynamic fracture-toughness transition curve depicts the mode of crack propagation.

The fracture-toughness curve for either static or dynamic loading can be divided into three regions, as in Fig. 16. In region I_s for the static curve, the crack initiates in a cleavage mode from the tip of the fatigue crack. In region II_s, the fracture toughness to initiate unstable crack propagation increases with increasing temperature. This increase in crack-initiation toughness corresponds to an increase in the size of the plastic zone and in the zone of ductile tearing (shear) at the tip of the crack prior to unstable crack extension. In this region, the ductile-tearing zone is usually very small and difficult to delineate visually. In region III_s, the static fracture toughness is quite large and somewhat difficult to define, but the fracture initiates by ductile tearing (shear).

Once a crack has initiated under static load, the morphology (cleavage or shear) of the fracture surface for the propagating crack is determined by the dynamic behavior and degree of plane strain at the temperature. Regions I_d, II_d, and III_d in Fig. 16 correspond to cleavage, increasing ductile tearing (shear) and full-shear crack propagation, respectively. Thus, at temperature A, the crack initiates and propagates in cleavage. At temperatures B and C, the crack exhibits ductile initiation but propagates in cleavage. The only difference between the behaviors at temperatures B and C is the ductile-tearing zone for crack initiation is larger at temperature C than at temperature B. At temperature D, cracks initiate and propagate in full shear. Figure 17[5] shows the fracture surfaces and toughness levels (CVN and K_c) for an A572 Gr. 50 steel. The specimen tested at −42°F. exhibited some small amount of shear initiation at a temperature slightly below B, Fig. 16. The specimen tested at +38°F. exhibited increasing shear initiation (between B and C). The specimen tested at +72°F. exhibited full shear initiation (temperature C) and despite the high fracture toughness (49 ft-lb. and 445 ksi $\sqrt{\text{in.}}$) still exhibited a large region of cleavage propagation, Fig. 17. Thus ductile crack propagation (dynamic) would only occur at temperature D, which is essentially dynamic upper-shelf CVN impact behavior (i.e., 80% or above shear fracture appearance). Consequently, full-shear fracture initiation and propagation occur only at temperatures for which the static and dynamic (impact) fracture behavior are on the upper shelf.

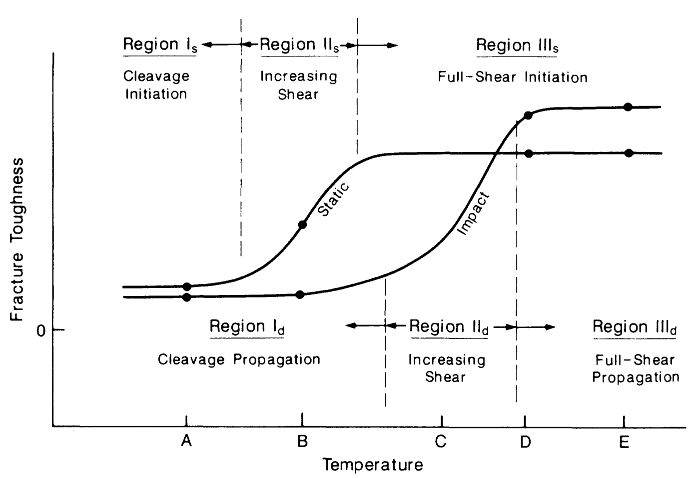

Fig. 16. Fracture-toughness transition behavior of steel under static and impact loading

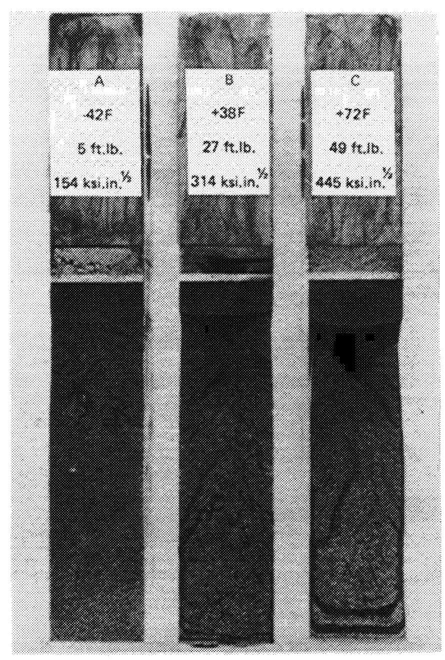

Fig. 17. Fracture surfaces of full-thickness (β = 1.5 in.) 4 − T compact-tension specimens of A572 Gr. 50 steel tested under load-control conditions using a total unload/reload loading sequence

Most constructional steels exhibit adequate initiation fracture toughness at the temperatures and loading rates for common engineering structures. However, once this fracture-toughness level is exceeded, the crack would propagate unstably exhibiting a flat, cleavage, brittle fracture surface.

Correlations of K_{Id}, K_{Ic} and Charpy V-Notch Impact Energy Absorption

The Charpy V-notch impact specimen is the most widely used specimen for material development, specifications and quality control. Moreover, because the Charpy V-notch impact energy absorption curve for constructional steels undergoes a transition in the same temperature zone as the impact plane-strain fracture toughness (K_{Id}), a correlation between these test results has been developed for the transition region and is given by the equation[5]

$$\frac{(K_{Id})^2}{E} = 5(\text{CVN}) \qquad (4)$$

where K_{Id} is in ksi$\sqrt{\text{in.}}$, E is in ksi and CVN is in ft-lb. The validity of this correlation is apparent from the data presented in Fig. 18[5] for various grades of steel ranging in yield strength from about 36 to 140 ksi and in Fig. 19[5] for eight heats of SA 533B, Class 1, steel. Consequently, a given value of CVN impact energy absorption corresponds to a given K_{Id} value (Eq. 4), which in turn corresponds to a given toughness behavior at lower rates of loading. The behavior for rates of loading less than impact are established by shifting the K_{Id} value to lower temperatures by using Eqs. 1 or 2. Conversely, for a desired behavior at the minimum operating temperature and maximum in-service rate of loading, the corresponding behavior under impact loading can be established by using Eqs. 1 or 2, and the equivalent CVN impact value can be established by using Eq. 4.

SUMMARY

1. Steel structures, with very few exceptions, perform safely and reliably when design, material selection, fabrication and inspection are performed in accordance with recognized codes, standards and producers' recommendations.
2. Codes, standards and producers' recommendations provide *minimum* requirements for common materials and structures. Therefore, the need for additional requirements must be investigated for new and unproven designs, for use of new material, for use of common materials in new and unique applications and for any other nontraditional situation.

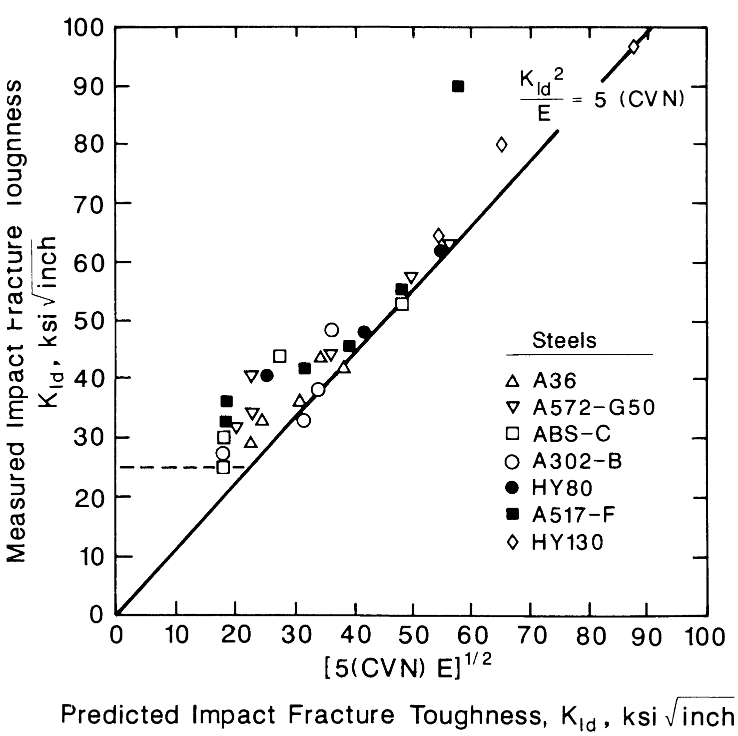

Fig. 18. Correlation of plane-strain impact fracture toughness and impact Charpy V-notch energy absorption for various grades of steel

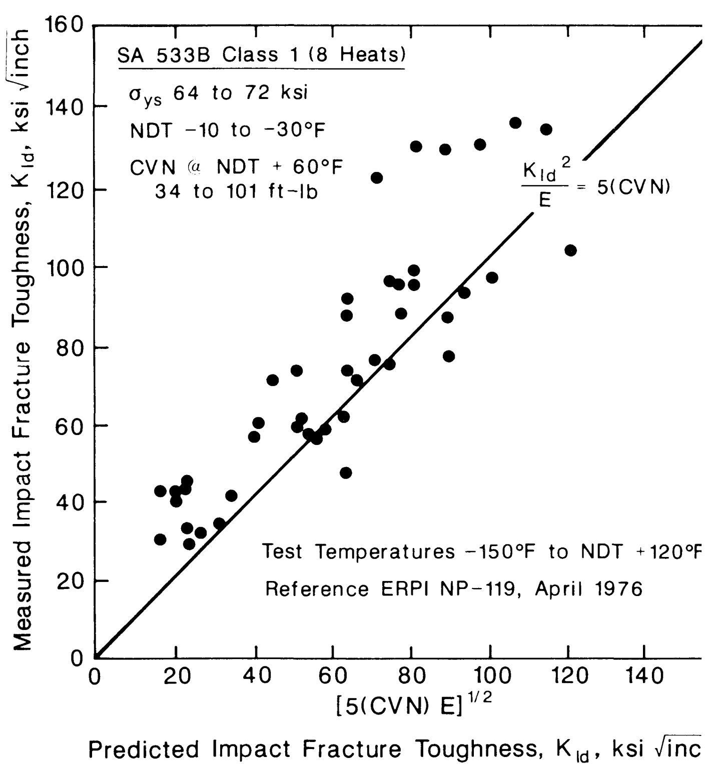

Fig. 19. Correlation of plane-strain impact fracture toughness and impact Charpy V-notch energy absorption for SA 533B Class 1 steel

3. Steel products, like other metal alloys, exhibit chemical segregation, i.e. an inherent characteristic of the cooling and solidification processes. The amount of segregation for steels made from ingots is a function of several parameters including the deoxidation practice, the size of the ingot and the amount of cropped metal.
4. Usually, products that are produced from killed steel exhibit negligible pipe and porosity and, on the average, less segregation and improved fracture toughness.
5. Steel products may exhibit variability in tensile properties and in fracture toughness.
6. The ASTM requirements for chemical composition and mechanical properties are reference tests valid for the specified test location. Product properties measured at different locations may differ from those of the reference-test location.
7. The tensile strength and yield strength increase with decreasing temperature and with increasing rate of loading. However, at a given loading rate, these properties remain essentially constant between −60°F. and +120°F. The yield strength increases about 5 ksi for every order of magnitude increase in loading rate.
8. Fracture toughness for steels decreases with decreasing temperature and increasing load rate. Consequently, operating temperatures and loading rates are essential parameters in the development of fracture toughness requirements for a particular structure.
9. There is no single unique fracture toughness value for a given steel even at a fixed temperature and loading rate. Therefore, when fracture toughness is an important parameter, the design engineer must establish and specify the necessary level of fracture toughness for the material to be used in the particular structure or in a critical component within the structure.
10. The fracture-toughness value necessary to ensure the adequacy of the material for a particular application is governed, besides the temperature and loading rate, by the magnitude and fluctuation of stresses and by the size of the crack-like imperfections that would be expected in the structure. Thus, fracture toughness requirements can be established best by using fracture mechanics concepts.
11. Fracture mechanics shows the material is only one of several parameters contributing to the safety and reliability of structures. The best material properties may not be sufficient to overcome deficiencies in design, fabrication, inspection or usage.
12. Correlations between fracture mechanics and Charpy V-notch fracture-toughness values combined with the temperature-shift relationships permit the use of the CVN test for screening and selecting materials which possess adequate fracture toughness for a particular structure.
13. Most constructional steels exhibit adequate initiation fracture toughness at the temperatures and loading rates for common engineering structures. However, once this fracture-toughness level is exceeded, the crack would propagate unstably, exhibiting a flat, cleavage, brittle fracture surface.

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