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Steel Products for Rollover Protective Structures (ROPS) and Falling Object Protective Structures (FOPS)

Foreword—This Reafffirmed Document has not changed other than to put it into the new SAE Technical standards Board Format. References were added as Section 2. All other section numbers have changed accordingly. Also SAE J410 was cancelled and replaced with SAE J1392.

1. Scope—The purpose of this SAE Information Report is to provide concepts for rational selection and application of materials for Rollover Protective Structures (ROPS) and Falling Object Protective Structures (FOPS) and to provide information about the properties that should be considered in selecting and utilizing material in protective structures. While other materials could conceivably be used successfully, this report is limited to a consideration of steel with discussion on its mechanical properties and processing characteristics. Emphasis is placed on the toughness aspect (ability to resist brittle fracture) as this property is of paramount importance to structure integrity. It is emphasized that specific values for material properties have relevance to performance only in conjunction with specific design considerations such as structure size or weld joint detail and location. Because there are many design-material systems which can be successfully employed to achieve the prescribed performance of protective structures, this report does not make categorical selection of steels.

2. References

2.1 Applicable Publications—The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated, the latest revision of SAE publications shall apply.

2.1.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAEJ435JUL74—Automotive Steel Castings
SAEJ1392—Steel, High Strength, Hot Rolled Sheet and Strip, Cold Rolled Sheet, and Coated Sheet

2.1.2 ASTM PUBLICATIONS—Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM A 27—Mild- to Medium-Strength Carbon-Steel Castings for General Application
ASTM A 36—Structural Steel
ASTM A 338 (1977)—Melleable Iron Flanges, Pipe Fittings, and Valve Parts for Railroad, Marine, and Other Heavy Duty Service at Temperatures up to 650°F (345°C)
ASTM A 572—High-Strength Low-Alloy Columbium-Vanadium Steels of Structural Quality

ASTM A 607—Steel Sheet and Strip, Hot-Rolled and Cold-Rolled, High-Strength, Low-Alloy Columbium and/or Vanadium
ASTM E 23 (1978)—Notched Bar Impact of Metallic Materials
ASTM E 208(1975)—Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels
ASTM E 399—Test for Plane-Strain Fracture Toughness of Metallic materials
ASTM E 604—Test for Dynamic Tear Energy of Metallic Materials

3. ***Design-Materials Interface—***When assessing the needs for specific values of engineering properties, it should be kept in mind that material properties need not necessarily be the same throughout the structure. A preferred design would be to size sections so that selected areas absorb most of the energy absorbed by the structure during a rollover. Then the material specifications and manufacturing procedures can be selected to match the design and service requirements of the different parts. In other words, some sections of a ROPS or FOPS should use materials with higher toughness levels whereas other sections are designed to be stressed low enough such that fracture or collapse of the structure would not be influenced by this property. It is therefore desirable to identify the highly stressed and high energy absorption areas in the structure during a rollover so that these areas receive the control and inspection of both the materials properties and fabrication procedures they deserve to insure the integrity of the structure. Plastic hinges (location designed to deform plastically and thereby absorb energy—see Figure 1) are examples where close control and inspection should be exercised. The choice of the balance between the design configurations and the selections of materials must be reserved for the manufacturer since it may be preferable to emphasize one aspect over another. These choices will depend upon several variables such as manufacturing capabilities and the volume of the manufactured units.

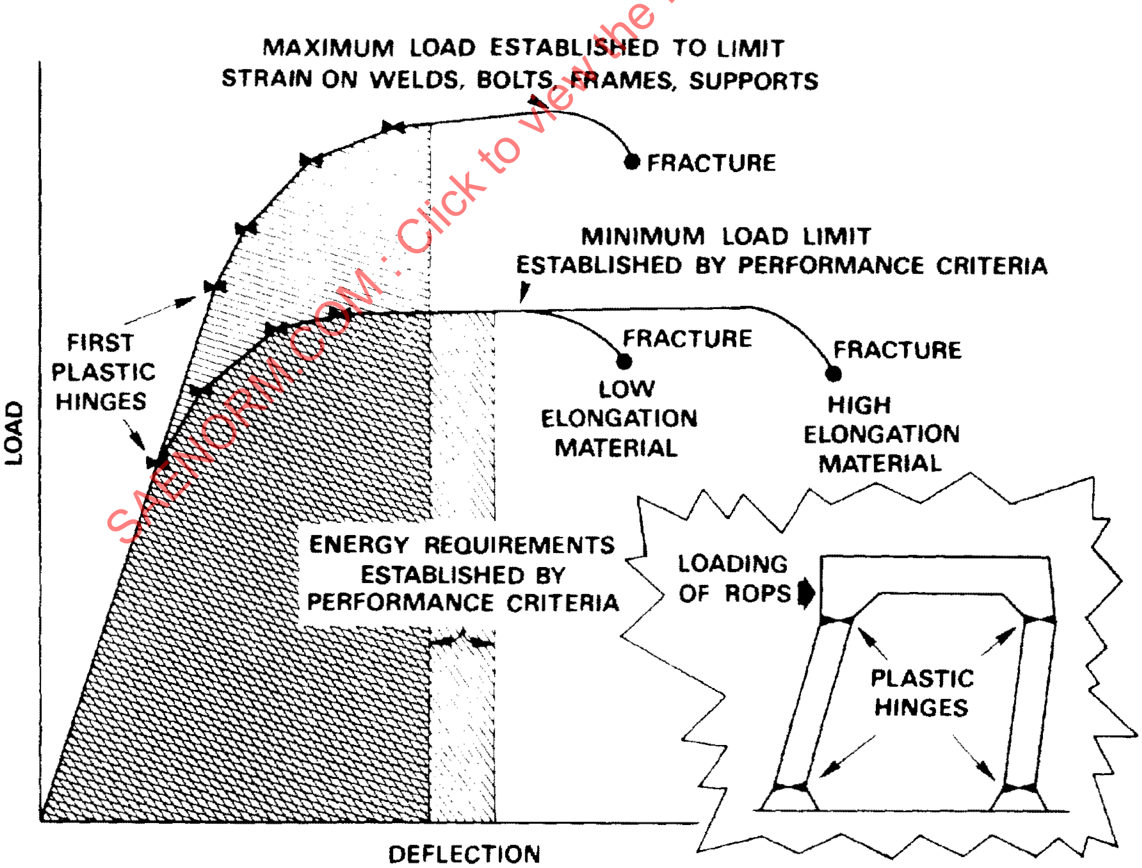

FIGURE 1—LOAD/ENERGY CHARACTERISTICS OF PROTECTIVE STRUCTURES

4. ***Mechanical Properties***—The two most important properties of steel that can be used to evaluate the successful performance of ROPS and FOPS are monotonic yield strength and resistance to fracture.

ROPS and FOPS are unique in that they are intended to perform their function only once, and while they may bend, they must not break in performing this function. Material considerations associated with the bend behavior of ROPS relate to monotonic yield strength and elongation. These properties are discussed under Tensile Properties, while resistance to fracture are discussed under Toughness Considerations.

4.1 Tensile Properties—As illustrated in Figure 1, minimum yield strength of the steel must be maintained to insure against collapse of the structure when subjected to performance criteria forces. Imposing a maximum on yield strength helps to insure against excessive plastic strain within localized regions such as weld zones, fasteners, or geometric discontinuities where capacity for absorbing energy is more limited. Because of these considerations, some manufacturers impose a yield strength range for certain steel commodities. Tubing is such a commodity, as it is commonly employed in main structural members designed to resist rollover forces as well as serve to absorb energy via plastic hinges. Yield strength ranges of 345 to 485 MPa and 345 to 510 MPa are examples being specified for tubing by some manufacturers of protective structures. Different values of nominal and range of yield strengths are equally valid for use providing they are compatible with protective structure and machine designs. Other commodities such as plate or rolled sections would of course demand the same consideration for yield strength control when used as members controlling the behavior of the structure.

While yield strength of the steel controls forces within the structure, elongation of steel for the most part establishes the ability of the structure to absorb energy without fracture. Efficient designs will usually offer large and/or multiple plastic hinge areas for deformation to occur. When structures have minimal hinge areas, energy absorption capacity is dependent upon the steel's ability to stretch prior to rupture. Toughness of the structure in these situations relates directly to the elongation properties of the steel as implied in Figure 1.

4.2 Toughness Considerations—Fracture toughness is required in materials used for ROPS and FOPS to prevent brittle fractures. Despite the recent development of many sophisticated ASTM tests to ascertain the toughness requirements of steels such as Nil-Ductility Transition (NDT) (E 208), Dynamic Tear (E 604), and Plane-Strain Fracture Toughness (K_{Ic}) (E 399), the often criticized Charpy V-Notch (CVN) test (E 23) remains as the most widely used test specified for procurement purposes. Its popularity over many years has enabled many useful empirical relations of CVN energy and structure performance to be developed. CVN tests are quick and convenient to perform, but suffer from the fact that the absorbed energy measured cannot be related directly to structural design parameters. Furthermore, tests are conducted on small specimens, at extremely high strain rates (typically 10^1 - 10^2 s^{-1}) and involve fracture ahead of shallow, rounded notches. The advantages of the CVN approach compared to the technical merit of the K_{Ic} approach have prompted many investigators to propose relationships for converting CVN data to a fracture mechanics characterization, thus permitting a quantitative assessment of critical flaw size and allowable stress level. Recently developed structural steel specifications such as those for bridges and welded ship hulls are based on fracture mechanics principles, but the specific toughness requirements for procuring the steel are based on CVN impact energy values. However, such CVN/K_{Ic} correlations are totally empirical in nature, valid only for restricted ranges of data. In characterizing the toughness of structural steels, there is no single test that takes into account all factors; namely, temperature, strain rate, section size, notch acuity, and size of flaws that affect the toughness of these steels.

4.2.1 Transition Temperature Behavior and the Loading Rate Effect—Note from Figure 2 that the structural steels exhibit a marked decrease in toughness with decreasing temperature and/or increasing rate of loading. This transition from elastic (plane-strain) to plastic (plane-stress) behavior of notched specimens occurs over a temperature range, dependent on loading rate. It is seen from Figure 3 that for static loading, the transition region occurs at lower temperatures than for impact loading. For steels having yield strengths between 345 and 485 MPa, the transition temperature shifts between static and impact test results are typically 56 to 78 °C with the material behavior being a function of strain rate in a continuous manner. The low end of the yield strength range shown in Figure 3 exhibits the greater shift of transition temperature and vice versa. The loading time identified as ROPS in this figure is based on the recording of strain-time during an actual rollover of a large earthmoving vehicle. Loading rate will vary depending upon the structure stiffness, mass of the vehicle, and the nature of the terrain. When the actual loading rates are not well defined, a conservative approach can be applied by assuming that impact rates apply and specifying steels which will remain tough at these strain rates.

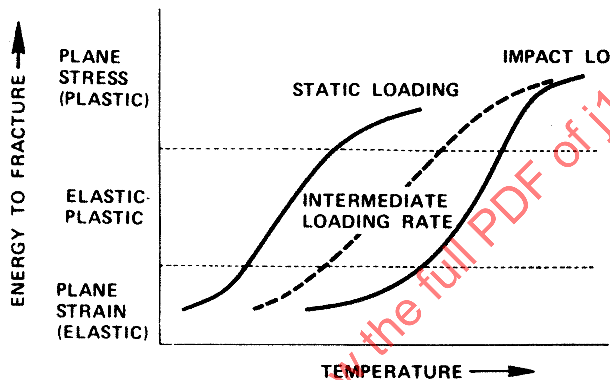

FIGURE 2—TRANSITION TEMPERATURE BEHAVIOR

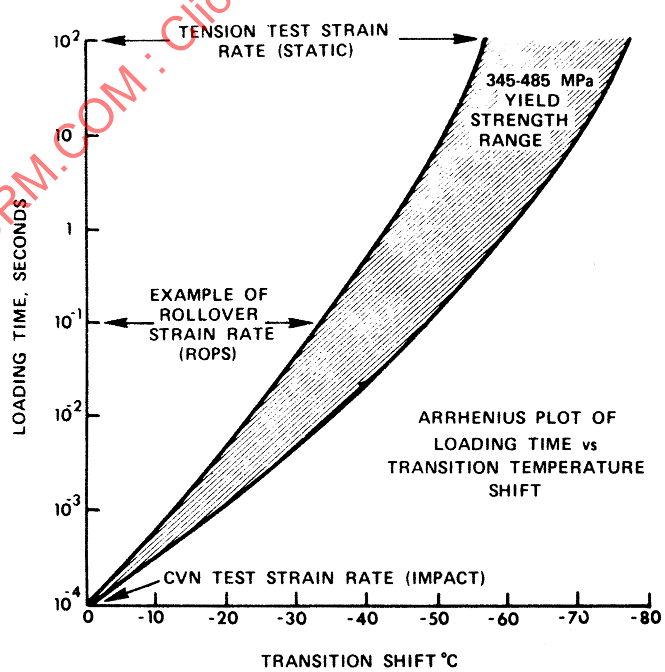

FIGURE 3— LOADING RATE EFFECT

4.2.2 Effect of Thickness—Increasing the thickness of material develops increasing constraint and tendencies for brittle behavior. Examples of this effect are shown in Figure 4 where significant increases in transition temperatures resulted when the standard 16 mm thick Dynamic Tear (DT) specimens were increased in thickness to 25 mm. This effect occurred at both slow loading rates (static) and high loading rates (impact). Note that the accumulative effects of loading rate and thickness affected a transition temperature shift of about 50 °C.

It follows then that if increased thickness increases tendencies for brittleness, that decreased thickness increases tendencies for toughness. Sheet steels as evaluated by ASTM A 338 double edge notch tests have shown that both SAE 1008 and ASTM A 572, grade 42 steels remain tough at temperatures down to –60 °C when tested in thickness up through 4 mm. Because decrease in thickness results in increased ductile behavior, it should not be necessary in most instances to qualify thin products except for compositions and metallurgical process control.

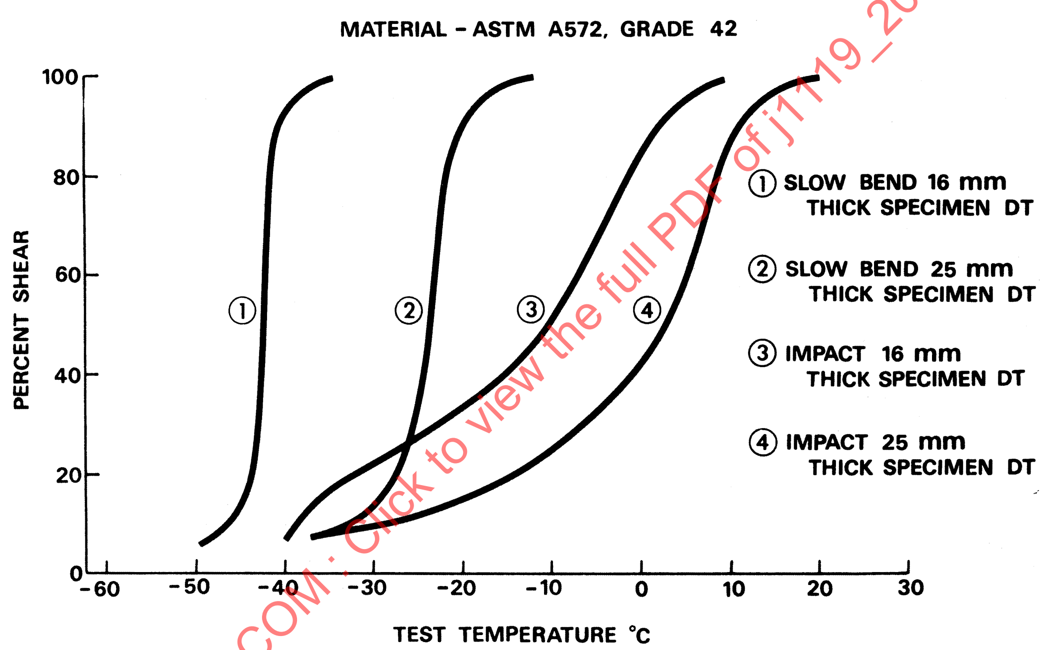

FIGURE 4—EFFECT OF THICKNESS

4.2.3 An Example of CVN-K_{Id} Correlation and Design Considerations—As discussed in 4.2, several correlations have been attempted in the past between CVN energy and fracture toughness (K_{Ic}) values. These correlations have been made despite the great differences in strain rates and notch acuities of these tests in spite of the sensitivity of structural steels to these variables. An improved approach is to correlate CVN energy to fracture behavior via the dynamic fracture toughness parameter, K_{Id}. Figure 5 shows a correlation developed from dynamic testing transverse CVN specimens and 12.7 mm IT compact tension specimens (ASTM E 399) from three heats of ASTM A 36 and ASTM A 572 steels. Although data is invalid per ASTM E 399 criteria for establishing K_{Ic} values because of less than prescribed thickness, data points 1 to 4 meet all requirements for plane-strain fracture. Data points 5, 6, and 7 are invalid as they exhibit plane-stress type fracture. A relationship of $K_{Id} = 26\ (CVN)^{0.43}$ results from a best-fit line drawn through the data. The loading time utilized in establishing the dynamic fracture toughness, K_{Id} in this testing was of the order of one-tenth that recorded for a ROPS rollover as previously referred to in Figures 3 and therefore reflects a conservative value. It is cautioned that this correlation like any other empirical correlation is valid for restricted ranges of data and for the class of steels for which it was developed. For illustrative purposes, the CVN data via this correlation are related to allowable crack sizes as a function of applied stress as shown in Figure 6.

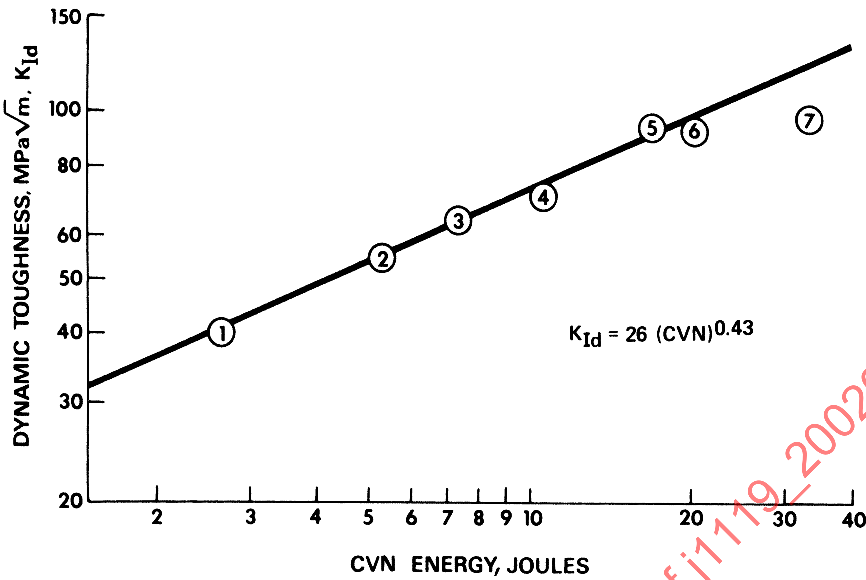

FIGURE 5—CVN—K1D CORRELATION

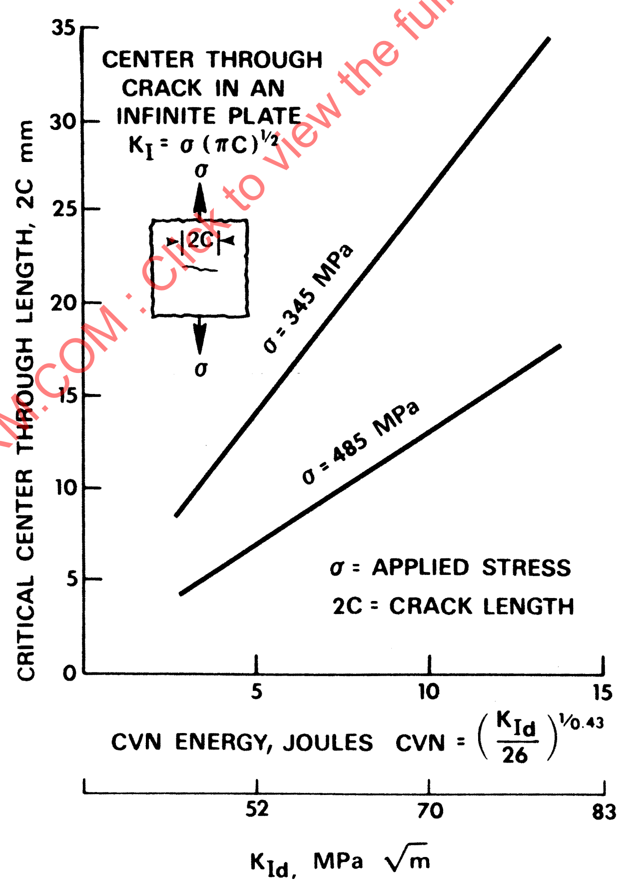

FIGURE 6—CVN—CRACK SIZE RELATIONSHIP EXAMPLE

During rollover of machines, certain sections of typical ROPS may be required to absorb significant amounts of energy (plastic hinges). Therefore, these critical sections should be designed for through thickness yielding. There is a significant increase in the rate at which through thickness deformation occurs in the presence of a discontinuity when the fracture toughness parameter K, exceeds the quantity $\sigma_{ys} \sqrt{t}$ where σ_{ys} is yield strength (under static loading) and t is thickness of plate. This relationship is shown schematically in Figure 7.

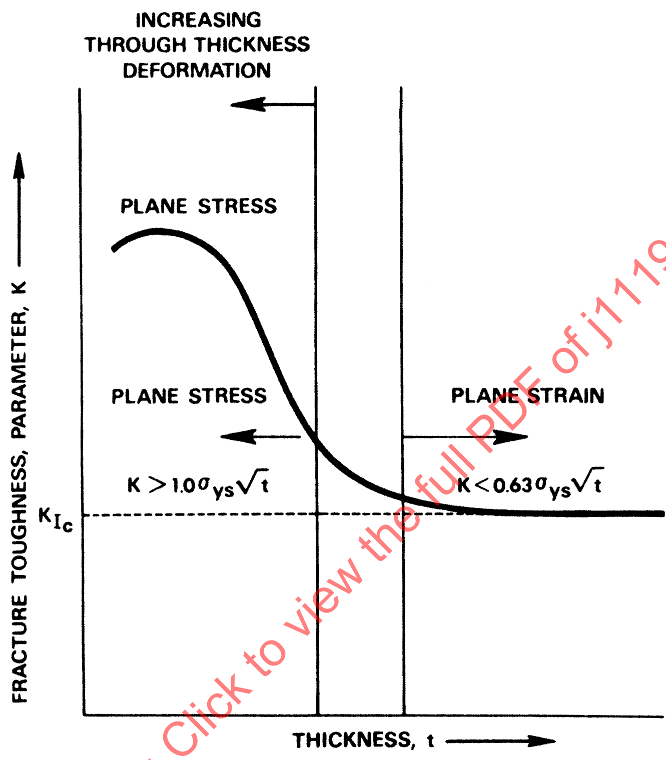

FIGURE 7—THROUGH THICKNESS DEFORMATION VERSUS PLATE THICKNESS

Since ROPS are located at a higher rate than static loading, K_{Ic} should be replaced with K_{Id} and the static yield strength adjusted to reflect the pertinent loading rate and temperature. A yield strength range of 345 to 485 MPa at ambient temperature under static loading conditions would increase to an approximate range of 550 to 690 MPa at –30 °C and loading rates of vehicle rollovers. From the previous considerations, the K_{Id} values required (and the corresponding CVN values) for through thickness yielding before fracture are as shown in Figure 8.

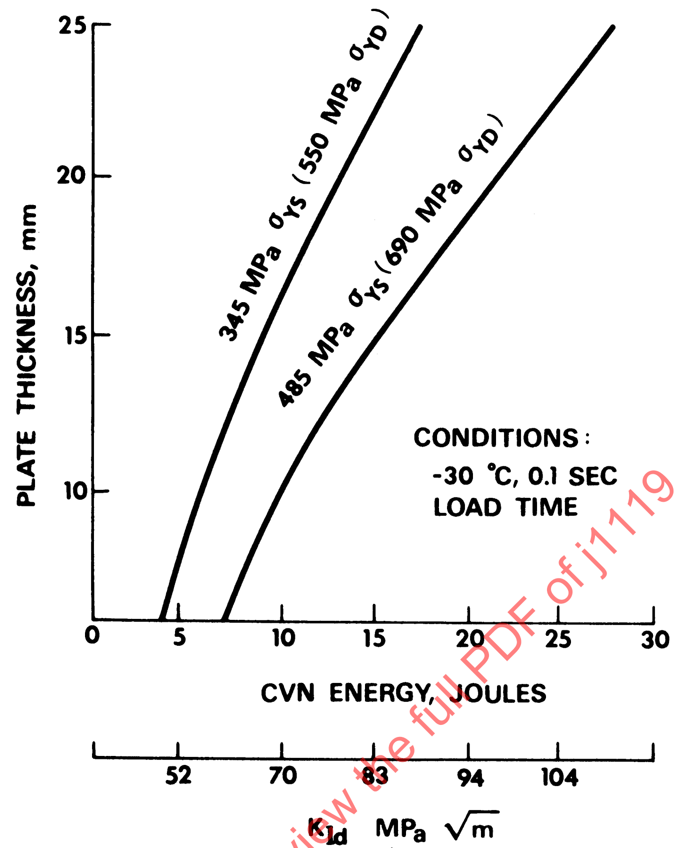

FIGURE 8— K1D AND CVN VALUES REQUIRED FOR THROUGH-THICKNESS YIELDING BEFORE FRACTURE

Although it was said that the applicability of the data in Figure 5 and the extension of these data in Figure 6 and 8 is limited to certain steels, it is believed that the dynamic fracture toughness data obtained on the ASTM E 399 IT compact tension specimens at loading rates comparable to those encountered by ROPS are useful in both material selection and design. Through empirical correlation with K_{Id}, CVN energy values have a meaningful relationship to performance. CVN tests thereby become useful as a quality control test for material.

It cannot be over-emphasized that the previous analyses for arriving at toughness requirements for steels represent a very generalized approach. For instance, it is not sufficient to relate material thickness alone as the variable relating to intrinsic toughness requirements to resist brittle behavior. Additional restraint imposed by welding parts together can restrict plastic deformation in a manner that requires a greater but undefined toughness value. And, of course, smooth, discontinuity-free members of the structures can behave in a ductile manner with very low values of intrinsic toughness. Sound engineering judgment must be exercised in selecting materials as there is no universal set of material properties suitable for all designs, processing variables, and service conditions.

5. ***Processing Characteristics***—Discussion up to this point dealt with the properties and behavior of steel as measured on commodities such as unformed plate. However, until such commodities are processed into parts and assemblies, they serve no useful purpose. Behavior of structures therefore relates to properties of material as influenced by processing such as cold forming and welding. These processes usually lower toughness while at the same time they shape the steel in a manner which increases restraint and creates notch conditions which therefore demand more toughness of the steel to counter brittle fracture.

5.1 **Weldability**—The weldability of material is not an independent or absolute quality and as such must be assessed under defined conditions. American Welding Society (AWS) defines weldability as the capacity of a material to be welded under the fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactorily in the intended service. Limiting this definition to protective structure material-design systems narrows its scope to a manageable situation. Assuming the steel for protective structures usage consists of the low carbon, low carbon-manganese or the micro-alloyed grades of weldable steel, most commonly used weld processes are acceptable. Only low hydrogen versions of the processes, however, are suggested when the carbon equivalency (C.E.) exceeds 0.45% as determined by the equation:

$$C.E. = C\% + \frac{Mn\%}{6} + \frac{Cr\% + Mo\%}{10} + \frac{Ni\%}{20} + \frac{Cu\%}{40} \quad \text{(Eq. 1)}$$

This is not a precise value, however, as it is influenced by material thickness and joint design. In addition, the factors in the denominators appear to be too low for low carbon steels. Preferred practice would be to use only low hydrogen versions as a consecutive approach. Pre-heat recommendations of the manufacturer of proprietary grades should be followed with consideration of material thickness and the joint restraint. For the manufacturer, pre-heat will normally consist of allowing the steel to achieve near room temperature prior to welding. Field repair welding on the other hand may require considerable effort to bring the weld zone to suitable temperatures by the use of torches, or when practical perform the welding after the structure is warmed in a heated building or enclosure. Any repair or modification of ROPS and FOPS by welding should be only as instructed by the manufacturer.

5.2 **Weld Joint Material**—Sizing of welds to match or exceed the static strength of adjoining members is normally a straightforward design situation. However, weld joints represent a very complex situation with regard to resistance to brittle fracture. This occurs from the complex restraint-notch condition of most weld joints and the further complication of not usually having sufficient information on the notch toughness of the weld joint material. Where weld metal cannot be maintained at low stress levels, weld metal toughness may become an acute factor in structure integrity.

Figure 9 shows the range of toughness of weld deposits determined by the Dynamic Tear (DT) test on the common weld process (Flux Cored Arc, Gas Metal Arc, and Submerged Arc) using a variety of weld consumables. Exact toughness of a weld process will be influenced by electrodes, fluxes, weld parameters, size, and composition of the material being welded, pre- and post-heating, and other factors. Attention must therefore be given these factors to assure toughness throughout highly loaded weld joints.

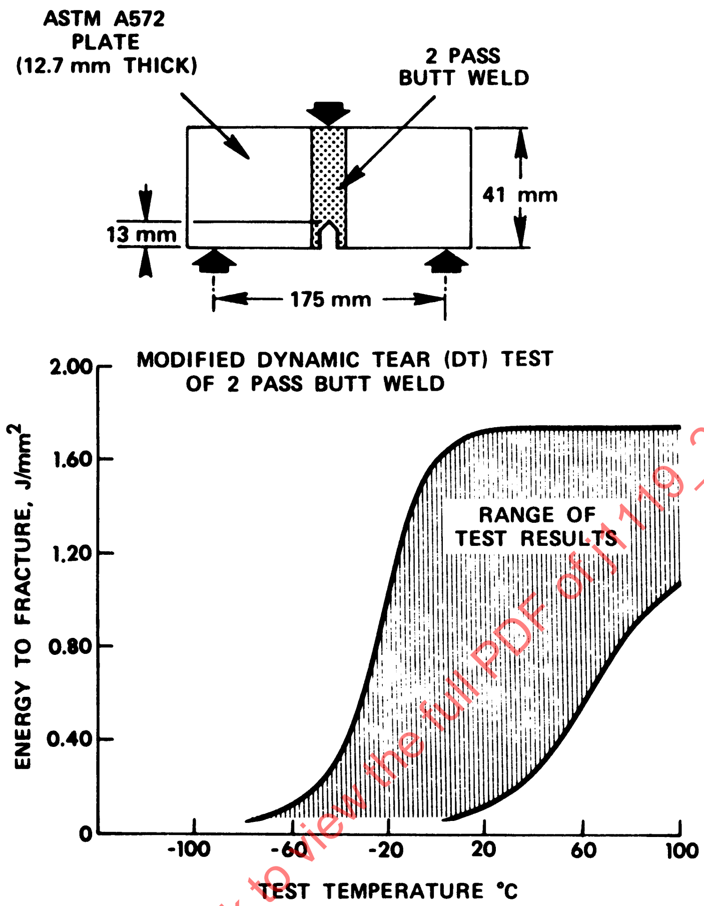

FIGURE 9—TOUGHNES OF WELD DEPOSITS

While Figure 4 portrays the effect of material thickness on transition temperature, it does not however portray the additional restraint that results from shaping and joining members as mentioned previously. Figure 10 is an example where the resultant restraint from joining two plate members with weld metal contributed to fracture initiation which propagated in a low energy mode through the additionally restrained section and the cold formed bend section of plate. Note that it propagated in a high energy absorbing shear mode through the less restrained section of 16 mm plate. Such increase in restraints and effects from forming are all but impossible to prevent in practical designs and therefore must be considered when assessing fracture initiation sites and mode of failure.