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INVESTIGATION OF
THE FRACTURE OF MEDIUM STRENGTH STEELS
WITH A PROPOSED DESIGN RATIONALE

by

Mohammed Hussein Magued, B. Eng., M. Eng.,

A Thesis submitted to the Faculty of
Graduate Studies and Research in partial
fulfillment of the requirements for
the degree of
Doctor of Philosophy

Faculty of Engineering
Carleton University

Ottawa, Ontario

May 1975

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With a Proposed Design Rationale"
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ABSTRACT

A series of notched static tension tests were carried out through a range of temperatures to study the influence on the fracture behaviour of a medium strength steel of such parameters as the width of the specimen, the depth of the notch, the thickness of the specimen, the notch geometry, the root radius of the notch and residual stresses. Based on these tests the concept of Strength Interaction Surfaces has been developed. The major portion of this surface, determined empirically, the Strength Col, was found to be dependent on the temperature, the width, the notch depth, and the thickness of the specimen. Strain rate and residual stresses are also expected to affect this surface.

From the concept of the Strength Interaction Surfaces a procedure is proposed to prevent the fracture in service of medium strength structural steel (up to 50 ksi yield strength) members containing flaws and subject to low ambient temperatures (down to -50°C) using the criterion that general yielding of the member should occur prior to fracture across the flawed section at the lowest expected operating temperature.

The need for this procedure is apparent from the inadequacies or inapplicability of available procedures for the prevention of brittle (with little overall deformation) fractures in structures made of the grades of steel, and subject to the range of temperatures of concern.

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NOTATION

a	notch depth for edge notches, or half notch depth for internal notches;
A_g	gross cross-section area;
A_n	net area through notched section;
b	half specimen width;
c_0, c_1, c_2	Constants;
c_3, c_4	
K, ΔK	stress intensity factor, and stress intensity factor range for fluctuating loading;
$P, \Delta P$	load on specimen; and load range for fluctuating loading;
P_f	ultimate load sustained by the specimen;
P_y	load causing yielding on gross area = $\sigma_y \cdot A_g$;
P_{yn}	load corresponding to change in linearity for net section, as in Fig. 3-2;
t	specimen thickness;
β	ratio of uniaxial ultimate strength to uniaxial yield strength = σ_u / σ_y ;
λ	fracture load to yield load ratio, load ratio, P_f/P_y ;

ρ net area to gross area ratio, area ratio,
 A_n/A_g ;
 $\sigma, \Delta\sigma$ gross cross section stress, and gross stress
range, i.e. P/A_g , and $\Delta P/A_g$;
 σ_f nominal ultimate net section stress = P_f/A_n ;
 σ_u uniaxial ultimate strength;
 σ_y uniaxial yield strength;
 σ_{yn} nominal net stress = P_{yn}/A_n

CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

The problem of predicting the behaviour and failure mode of a structure is essential to the design process. For the structural designer, the most acceptable mode of failure is that of extensive yielding of part, or whole of the structure because it is predictable within relatively narrow limits, and because, with yielding, redistribution of the load may occur preventing local overload and the collapse of part or all of the structure. Moreover, evidence of distress is clearly visible before such a collapse. The brittle fracture of part of the structure occurring with little deformation at a load less than that which causes general yielding of that part may have catastrophic results in the loss of life or property.

In service, structural steels become susceptible to brittle fracture in the presence of stress raisers, and fracture can occur when sufficiently low temperatures and high stresses exist. The "low temperatures" and "high stresses" are relative and depend on the toughness of the steel, the severity of the stress raiser, and the rate of load transfer to the member.

Stress raisers may exist in the member in the form of weld defects, fatigue cracks, base metal flaws or simply due to design details. Stresses higher than the assumed design values may arise from unknown residual stresses, thermal stresses, settlement stresses, or other effects unrecognized by the designer.

Control of brittle fracture can be achieved by reducing the chance of buildup of unknown stresses, by proper design, by eliminating the existence of flaws, by proper inspection and repairs, and by the use of a steel of appropriate toughness for the application.

The key issue to which this thesis is directed is the definition of the required toughness of low to medium strength structural steels (up to 50 ksi yield) for a particular application. A steel, it is submitted, should possess enough toughness for the particular application if the member containing an expected flaw size, estimated or measured, could sustain a load that would cause general yielding of the member prior to fracture across the flawed section at the lowest expected operating temperature. A member with such capability could sustain sufficient deformation to allow for distortion and load redistribution in the structure, thereby reducing or eliminating the effect of secondary stresses, such as construction stresses, and thermal stresses, and thus further reduce the probability of brittle fracture. Also, such a member would provide ample warning before its failure.

1.2 SCOPE

A series of notched static tension tests were carried out through a range of temperatures to study the influence on the fracture behaviour of a medium strength steel, of such parameters as the width of the specimen, the depth of the notch, the thickness of the specimen, the notch geometry, the root radius of the notch and residual stresses. Based on these tests the concept of Strength Interaction Surfaces has been developed. The major portion of this surface, determined empirically, the Strength Col, was found to be dependent on the temperature, the width, the notch depth, and the thickness of the specimen. Strain rate and residual stresses are also expected to affect this surface.

From the concept of the Strength Interaction Surfaces a procedure is proposed to prevent the fracture in service of medium strength structural steel members containing flaws using the criterion that general yielding of the member should occur prior to fracture across the flawed section at the lowest expected operating temperature.

1.3 AVAILABLE PROCEDURES

The procedures available for the prediction of the fracture performance of structural steel components can be divided into two general categories. The first, based on stress analyses using a basic defined material property as a fracture criterion, is expected to yield engineering data

in terms of stresses and crack sizes. The second category based on empirical correlations with impact tests generally yields data in terms of allowable lowest operating temperatures. Because of the limitations of each category, as is discussed further on, some researchers have tried to combine the procedures and analyses in each category to overcome these limitations as well as to take advantage of the lower costs of impact tests with the engineering data provided by the first category. Works by Irwin and Paris cited in the Bibliography provide an excellent source of basic research, and references on the first category. Publications cited by Pellini provide the same for the second category. Key research on attempts to combine the first and second categories were carried out by Rolfe, Barsom, and Novak.

Discussions of the limitations, advantages and other aspects of the different procedures in each category have been all but exhausted, and have been especially well presented in the different ASTM Special Technical Publications on the subject. To provide another discussion here on the various procedures, would be redundant as these discussions are easily found. However a brief account of some of the procedures available in each category is presented to highlight the salient points for each procedure as they relate to the general trend of development in each category.

1.3.1. Linear Elastic Fracture Mechanics Analyses

The essential concept of analyses of the first category is the linear elastic fracture mechanics analyses, LEFM, that originated with the work of Griffith (1922) in which the criterion was developed, based on the elastic stress analysis of a cracked plate of Inglis (1913), that fracture will start from a flaw or crack when the elastic energy released by crack extension exceeds the surface energy of the crack. The theory was modified by Irwin (1948), and Orowan (1955) by the addition of a plastic work term to the surface energy term. In 1957 Irwin showed that the energy criterion is equivalent to a stress-intensity criterion which states that the existing crack propagates rapidly when the stress field in the vicinity of the crack tip reaches a certain critical intensity which is a material property. This critical value of the stress field intensity depends on both temperature and degree of triaxiality of stress at the crack root between the extremes of plane stress and plane strain states. The critical stress intensity is thus dependent on the material thickness and the extent of plastic relaxation at the crack root. The critical stress intensity factor for a given material at given temperature is determined by testing a cracked specimen for which geometry an elastic analysis was carried out to determine the relation of the stress intensity factor to the load. The value of the stress intensity factor for that specimen at fracture is termed the critical stress intensity factor. With suitable elastic stress

analysis the failure load of a cracked structural member of the same material could then be determined. This procedure is detailed very clearly, e.g., by Paris and Sih (1965), Brown and Srawely (1966), and Anderson and James (1970).

In the case of ductile materials significant plastic deformation takes place prior to fracture and corrections for the existence of a plastic zone ahead of the crack could be made if the plastic zone is small compared to the elastic zone. However, with increasing ductility the plastic zone increases in size and an elastic analysis becomes less and less accurate until at some stage it is no longer applicable to the problem by simple corrections and a plastic solution becomes necessary. Plastic solutions are very limited and quite difficult to obtain, and so far rigorous fracture mechanics analyses have been limited to the linear elastic range. To ensure the applicability of elastic analyses, ASTM committee E24 developed maximum toughness to yield strength ratios as a function of the specimen thickness for valid measurement of the critical stress intensity factor. These limitations, later adopted in the ASTM Standards, would stipulate a minimum thickness of approximately 15 in. for a material with a critical stress intensity to yield strength ratio of $2.5 \text{ in}^{\frac{1}{2}}$. Apart from the impracticality of testing such a specimen, the results obtained will obviously be too conservative for application to considerably thinner plates, and as well the thicker steel of the specimen may not be representative of that in the actual member.

1.3.2 Charpy Notch Impact Tests

Charpy notch impact tests are representative of impact test procedures. Correlations with service performance of steel plate used in naval construction during the second world war provided the well known criterion that the steel should have an energy absorption level of 15 ft. lbs. determined from V-Notch tests at the lowest operating temperature. This criterion included a considerable margin of safety when related to the service failures that the criterion was based on. The 15 ft. lb. criterion makes no allowance for design details, working stresses, construction stresses, or other considerations that may exist in a real structure. However, the criterion has been used extensively as a basis for material selection for most applications of structural steel where low temperature embrittlement was considered possible.

The drawbacks of this test are that it does not give data in terms of stresses and crack sizes, thus it cannot evaluate the safety of a flawed or cracked structure, the strain rate in the test is not typical of that to which the structure is subjected, and the size of the specimen does not represent typical structural dimensions. The advantages of the test are that it provides comparative data for the toughness of different steels and could be used for material screening purposes because of the small size and simplicity of the test.

1.3.3. Correlations Between Charpy Notch Tests and Stress Intensity Values

Recent research work, Barsom and Rolfe (1970), has been directed toward the development of correlations between Charpy V-Notch tests, as well as other impact tests, and critical stress intensity factors. Such correlations were apparently obtained for high strength materials. By extrapolating these correlations to the case of low and medium strength steels, design criteria have been obtained, Barsom (1974). In view of the deficiencies in small impact tests and the amount of scatter in the correlations, the validity of these correlations and the design criteria based on them is questioned.

1.4 STATED NEED

In view of the limitations of analytical methods of category one, empirical methods based on the correlations between impact test results and service performance, category two, and combinations of the two categories, correlations of simple tests and analytical methods, the program outlined in the section on Scope was undertaken.

1.5 OUTLINE OF THESIS

Following this introductory chapter, Chapter 2 gives the details of the test program carried out in this investigation and highlights the test procedures. The test data are presented

in Chapter 3, the data are analyzed and discussed in Chapter 4. Chapter 5 gives the proposed method for preventing fracture in service of structural steel members containing flaws. Chapter 6 consists of a Summary and Conclusions, as well as, suggestions for further research work. Appendix 1 describes the instrumentation and equipment used in the tests.

CHAPTER 2

EXPERIMENTAL INVESTIGATION

2.1 INTRODUCTION

The main portion of the test program consisted of a series of static tension tests on notched steel specimens to provide data on the load carrying capacity of the specimens as a function of the test temperature, the width of the specimen, the depth of the notch, and the thickness of the specimen. A limited number of tests were also conducted to investigate the effect of the root radius of the notch, the notch geometry, i.e. a single internal notch as compared to a pair of external notches, and the effect of a longitudinal residual stress field. It was expected that the behaviour of the test specimens, as a function of the parameters investigated (width, thickness, and notch depth), would allow the prediction of the fracture behaviour of a structural steel tension member with a defect at various temperatures, and from this the determination whether or not that the member could fulfill the criterion for safe performance that a tension member with a defect should undergo yielding on a cross-section away from the defect prior to fracture through the section containing the defect.

Specimens sizes were limited by the capacity of the testing equipment available. At Carleton University where most of the tests were conducted, the maximum capacity was 400 kips.

The 1200 kip testing machine at the University of Toronto was available for a limited period of time.

Ancillary tests included tests to determine variation in yield and ultimate tensile strengths as a function of temperature, Charpy V-notch impact tests, and as well hardness profiles through the 3 in. thick plate used and residual stress measurements on specimens with weld beads placed on both surfaces were made.

The considerable instrumentation developed for the notched tension tests is described briefly in this chapter and in more detail in Appendix 1.

2.2 STEEL USED

Because of the number of tests required to investigate in some depth the parameters previously described, it was intended that only one grade of steel, CSA G40.8-1971, Grade B, "Steels With Improved Resistance To Brittle Fracture," would be used. In order to minimize metallurgical differences from specimen to specimen, the plate, ordered from the Steel Company of Canada, was to be rolled from a single heat of about 22 tons to the two thicknesses of 1 in. and 3 in. Due to problems during rolling, part of the 1 in. thick plate was scrapped and some of the 1 in. plate was supplied from a different heat. As one series of notched static tension tests had to be conducted from this different heat of steel an

additional series from this heat was made to obtain comparative data. In addition, one series of tests was also made from the CSA G40.8 Grade A steel used in the previous investigations of Kus and Leung (1970).

Table 2-1 gives the chemical composition of the steels as reported on the mill test certificates, as determined for this investigation, and as well the requirements of the respective CSA Standards for G40.8 Grade A or Grade B steels. Also given are the mechanical properties at room temperature as reported on the mill test certificates, determined for this investigation, and required by the standards. Steels designated A1 and A3 are steels rolled from the same heat in 1 in. and 3 in. thicknesses, while the steel designated B is 1 in. thick plates from the second heat, and steel designated C is that from the previous investigation.

2.3 TEST SPECIMENS

In addition to a few tests conducted for familiarization with the procedures and equipment, a total of 131 notched static tension tests in 16 different groups were conducted to provide some scope to the investigation of the effect of the different parameters. Table 2-2 lists the series of tests that were conducted as related to the particular parameter being investigated. In the investigation of a parameter, in so far as possible, the other parameters are held constant to

enable an evaluation of the effect of each parameter to be made over the range of test temperatures. The various effects investigated are described in the following.

2.3.1. Effect of Width

Four groups of 8 specimens each 3 in., 6 in., 12 in., and 18 in. wide as shown in Fig. 2-1 were tested. The specimens were all 1 in. thick with double edge notches of constant proportion of the total width to provide a ratio of area at the notch to gross area, $A_n/A_g = \rho = 0.75$. The double edge notch is shown in Fig. 2-2 and the details of the notch are given in detail "E" of the same figure. The 3 in. 6 in., and 12 in. wide specimens are made from Steel A1, and the 18 in. wide ones were made from Steel B. The specimens were flame cut from the plate to the pattern shown in Fig. 2-3, except that the 3 in. wide specimens were machined from the 4 in. wide strips left between the 6 in. wide specimens. The specimens were numbered consecutively for each size starting from the upper left hand corner of the plate. The enlarged section at the ends of the 6 in., 12 in., and 18 in. wide specimens contained varying numbers of 1-3/16" diameter bolt holes on 3 in. grid lines for bolting to end adaptors, made specially for this investigation, to fit the machine heads.

2.3.2. Effect of Notch Depth

Four groups each consisting of eight 1 in. thick by 6 in. wide double edge notched specimens, with area ratios,

ρ , of 0.90, 0.75, 0.50 and 0.40 were tested. All had the same notch root radius of 0.003 in. and were made from Steel A1.

2.3.3. Effect of Thickness

Again four groups of eight double edge notched specimens all 6 in. wide and with a 0.003 in root radius as shown in Fig. 2-3 were used to investigate this effect. The specimens were machined equally on both surfaces, as required, to the thicknesses of 1/2 in., 1 in., 2 in., and 3 in. from the 3 in. thick steel plate designated A3. Fig. 2-5 shows the pattern used for flame cutting of the specimens from the parent plate.

2.3.4. Effect of Notch Root Radius

To investigate the effect of notch root radius two groups of eight double edge notched specimens 1 in. thick by 6 in. wide with an area ratio, $\rho = 0.75$ were used, the first with a notch root radius of 0.003 in. (taken as one-half of the width of the saw cut) and the second precracked in fatigue on one side for the last 0.05 in. of notch depth as shown in detail "F", of Fig. 2-2. These specimens were flame cut from Steel A1.

2.3.5. Effect of Notch Geometry

Two groups of specimens, one with an internal notch and the other with external edge notches as shown in details

"I" and "E" Fig. 2-2, respectively, were used. The specimens were 1 in. thick by 6 in. wide and were made from Steel A1.

2.3.6. Effect of Residual Stresses

To assess the effect of residual stresses the results of tests of two groups of internally notched specimens 1 in. thick by 6 in. wide with $\rho = 0.75$ and a notch root radius = 0.003 in. were used. The first group of eight was one of the groups I-G, used to assess the effect of notch geometry and the second was in all respects similar except that two discontinuous weld bead runs were applied on each face of the specimen to the sequence shown in Fig. 2-6. The weld beads were applied in tandem by the submerged arc process using 27V., 400A. per bead, and a weld deposition rate of 25 i.p.m. The beads were applied after the central portion of the notch was milled out, but before the hack saw and jeweller's saw cuts were made. The distance between the ends of the beads, 1 inch, was chosen so that the heat affected zone would lie outside of a line drawn at 45° from the notch tip to prevent a metallurgical change in the steel along the potential path of the crack.

2.3.7. Additional Notched Specimen Groups

Because the steels supplied for this investigation came from two different heats, and also to correlate the results of this investigation with those of the earlier investigations of Kus and Leung (1970), two additional groups of 1 in. thick by 3 in. wide double edge notched specimens were tested.

2.4 TEST EQUIPMENT AND INSTRUMENTATION

As a notched static tension test was carried out measurements of the temperature, load on the specimen, longitudinal strain on a section away from the notches, lateral contraction at the root of both notches, and the notch opening displacement at one edge of the double edge notched specimen, or at the notch centerline of internally notched specimens, were obtained. The temperature readings were taken at periodic intervals. Four X-Y recorders were used to record the other data as follows:

- i) load versus the longitudinal strain, on the gross section taken at a distance equal to the width of the specimen away from the notch,
- ii) load versus the lateral contraction at a point $1/32$ in. ahead of the notch tip,
- iii) load versus notch opening displacement; of course, for the fatigue precracked specimens the notch opening displacement was measured at the edge of the precracked notch.

The load signal was obtained from a potentiometer mounted on the gear train of the load readout pointer on the testing machine. This potentiometer was excited by a 1.5 V. battery pack. The longitudinal strain, lateral contraction, and notch opening displacement signals were obtained from four custom designed transducers of the double cantilever type, as

described in Appendix 1, with a full bridge of four 500 Ohm strain gages mounted on the four faces of the double cantilevers. A single 30V., 5A. DC Power Supply provided the excitation to the four transducers. The excitation and signal control for each transducer was provided through a custom designed four channel signal conditioner, described in Appendix 1.

To avoid damage to the longitudinal strain transducer, when testing specimens that were gripped directly in the machine heads, 120 Ohm strain gages, with a gauge length of 0.250 in. were used instead and were directly mounted on the specimen surface at a distance from the fracture path equal to the width of the specimen. The signal from these gages was conditioned using a commercially available balance and amplifier unit, the output of which was input into the X-Y recorder used for plotting the load vs. longitudinal strain record.

The loading machines used were of the standard hydraulic type provided with Bourdon tubes for load measurement. All the test groups with a gross cross-sectional area of 6 sq. in. or less were tested on the 400 kip Tinius-Olsen universal testing machine at Carleton University and those with larger gross cross-sectional areas were tested on the 1200 kip Baldwin universal testing machine at the University of Toronto.

The temperature of the specimen was measured by means of four to six, depending on specimen size, iron-constantan thermocouples clipped to the specimen surface using a copper

and rubber shield as described in Appendix 1. Two of the thermocouples were on opposite sides and opposite faces of the specimen as close as possible to the fracture path, with the rest spread out along the length of the specimen on alternating faces. The thermocouple signals, transmitted to a commercial digital thermocouple readout instrument calibrated in degrees Fahrenheit, were not recorded continuously.

Cooling of the test specimens below room temperature was provided chiefly by using dry ice slabs placed directly against the specimen above and below the fracture path as described more fully in Appendix 1. Early trials using liquid nitrogen as a coolant proved costly both in time and expense and this procedure was abandoned.

2.5 TEST PROCEDURES

After the specimen was positioned in the testing machine, an initial load of about 1 kip or less was applied, the transducers for measuring the longitudinal strain, the lateral contraction and the notch opening displacement were then mounted and adjusted and their initial signal set to zero by use of the X-Y recorder and/or the signal conditioner zero control. The testing machine load readout was then zeroed.

For tests at room temperature it was only necessary to record the ambient temperature before proceeding to load the specimen.

For tests at temperatures down to about -10°C , after clipping the thermocouples to the specimen, the specimen was packed in the dry ice, tightly wrapped in the insulating blanket, and allowed to cool down to a temperature a few degrees below the proposed test temperature. The dry ice slabs were then quickly removed and the specimen rewrapped with insulation and allowed to soak until the temperatures indicated by the different thermocouples were within 2° to 3° of each other, and, hopefully, close to the desired test temperature. With experience and quick action, provided no untoward incidents occurred, satisfactory and uniform temperature could be obtained.

For tests below about -10°C , cooling times were proportionately longer and to prevent dislodgement of the transducers and make the handling of the dry ice less awkward, the transducers were only positioned after the specimen had been cooled down to below the proposed test temperature.

Once the specimen had achieved a relatively uniform temperature, within a few degrees of the desired test temperature, loading was started. The rate of loading was kept reasonably uniform to reach yield level in about 15 sec. providing a strain rate of about $80 \mu\text{e}/\text{sec}$. Once the initial setting of the loading valve was made, the valve was left untouched until fracture occurred.

In addition to the continuous records provided by the X-Y recorders of load versus longitudinal strain, lateral contractions, and notch opening displacement, the temperature

was monitored throughout the test. Specimen temperatures at the thermocouple locations, did not increase by more than about 2°C during the test, and the temperature recorded in the test data as the test temperature was the average temperature of the two thermocouples adjacent to the fracture path at fracture. It is noted, however, that especially in the highly deformed plastic zones, temperatures could be elevated due to the energy of deformation. Comparable elevation of temperature could occur in a failing structure under service conditions.

2.6 ANCILLARY TESTS

2.6.1. Mechanical Properties

Standard tensile specimens were made for steels A1, A3, and B to establish their yield and ultimate strengths as a function of temperature over the range from room temperature down to about -70°C , at intervals of about 10°C . Data for steel C was available from Kus and Leung (1970). The Specimens were machined to ASTM specification A370, as shown in Fig. 2-7, with a cross section 1 in. thick by 1.5 in. wide. Elongations were measured on an 8 in. gauge length. The specimens were of full thickness for steels A1 and B, and for steel A3 were machined symmetrically to a thickness of 1 in. from the 3 in. thick plate.

The variation of yield strength across the plate width and along its length was not investigated separately as the

notched tensile specimens themselves were instrumented to evaluate when yielding occurred on the gross section. However, five specimens from different locations of steel A1 plate were tested at room temperature to determine if significant variations in strengths existed over the plate area.

Deformation of the test coupons was determined by using two linear-variable-differential-transformer type transducers, LVDT, with a total stroke of 2 inches, (-1.0 in. to +1.0 in. from the null position), mounted on opposite faces of the specimen over an 8 in. gauge length by means of specially designed brackets. The LVDT's gave strain readings of up to 25%. Also, two 120 Ohm strain gages with a 0.250 in. gauge length were mounted at mid length of the specimen on opposite faces for better determination of strains up to about 1%. For tests below room temperature, specimen temperature measurements were made by means of four iron-constantan thermocouples clipped to the specimen surface and shielded with a copper and rubber shield.

The load was plotted versus the output of the two LVDT's continuously by using a two pen X-Y-Y recorder. The load was also plotted against an electronically averaged output from the strain gages on another X-Y recorder. During the tests, the load was read and recorded when yielding was evident from the continuous record of LVDT's output; the ultimate load was also recorded. The strain rate used was about 40-50 $\mu\text{e}/\text{sec}$.

The thermocouple output was monitored using a digital readout unit. The initial temperature of the specimen was recorded. Temperature variations of the specimen were not

appreciable for strains up to the strain hardening region. However, with the extensive plastic deformation at necking the temperature of the specimen increased by as much as 30°C and the specimen temperature corresponding to ultimate load was recorded.

Cooling of specimens tested below room temperature was achieved by enclosing the specimen, after mounting, in an insulated box and lowering the temperature inside the box by a controlled flow of liquid nitrogen sprayed into the box through a perforated copper tube so as not to impinge on the specimen. A fan circulated the air within the box to provide a uniform temperature regime.

2.6.2. Charpy V-Notch Impact Tests

Standard Charpy V-Notch specimens as shown in Fig. 2-8 were machined for steels A1, A3, and B. Steel C data was available from Kus and Leung (1970). The specimens were machined from mid-thickness of the plate along the rolling direction with the notch normal to the plate surfaces. Test specimens and procedures were in accordance with ASTM specification E23-72. Test temperatures ranged from room temperature down to about -70°C at intervals of about 10°C .

2.6.3. Determination of Residual Stresses

in Specimens with Weld Beads

One of the specimens prepared with weld beads, Group I-RS of Fig. 2-6, was used to determine the residual stress pattern

at the notched section resulting from the deposition of the weld beads. The residual stress pattern was determined by the method of sectioning in which the relaxation in strains on the specimen surface is measured when a section is removed from the specimen. The section removed was approximately 3/8 in. wide and symmetric with the notched section. Eleven 120 Ohm strain gages of varying widths and gauge lengths were placed on each side of the notch on both surfaces of the specimen. The specimen was cut transversely, as closely as possible to the strain gages at both ends of the gages, using a band saw equipped with a fresh fine-toothed blade and adequate lubricant. The strains before and after sectioning were recorded using a sixty channel digital strain indicator with an integral printer.

By determining the strain relaxation on both surfaces, the through thickness average value of the residual stress pattern could be found.)

The extent of the heat affected zone beyond the end of the weld bead was established by a microscopic examination of the grain structure following the polishing and etching of a longitudinal section through one of the beads.

2.6.4. Hardness Profile

A rockwell B scale hardness profile was established through the thickness of the 3 in. thick plate of steel A3 to get a measure of the variation of the ultimate tensile strength through the thickness.

CHAPTER 3

TEST RESULTS

3.1 GENERAL

In this chapter the results of the notched static tension tests and the ancillary tests are presented and brief discussions, relating to the effects investigated, are given.

3.2. NOTCHED STATIC TENSION TEST RESULTS

For each test specimen, the width, the thickness, and notch depth were measured with a vernier caliper with a resolution of 0.001 in. During each notched static tension test, conducted at a particular temperature, continuous records of the longitudinal strain, lateral contraction at both notch roots, and the notch opening displacement were obtained.

From the longitudinal strain measurements, the load at which yielding occurred on the gross section, P_y , was found. The maximum load measured in the test has been recorded as the fracture load, i.e. not the load at fracture but the maximum load sustained that lead to fracture, P_f .

In tables 3-1 to 3-16 are given, for each specimen tested, arranged in the groups discussed in Chapter 2, the significant data obtained from the test records. In addition to the test temperature is given the net area (the area through the notched

section), A_n , the gross cross-section area, A_g , and the area ratio $\rho = A_n/A_g$.

The load and stress at which yielding occurred on the gross section, P_y and σ_y , respectively, the load and stress at fracture on the net section, P_f and σ_f , respectively and the ratio of fracture load to yield load, $P_f/P_y = \lambda$, are also tabulated. For ease in treating the data, the ratio P_f/P_y shown in the tables has been modified by multiplying the test value of P_f/P_y by the nominal value of ρ divided by the test value of ρ . A second entry in the table in the columns headed P_y and σ_y relating the lateral contraction and notch opening displacement curves, as discussed in the following, is also given.

Figures 3-1, and 3-2 give respectively typical records of load vs. lateral contraction measured at the notch root and load vs. notch opening displacement. Fig. 3-3 gives a record of the load vs. lateral contraction at the notch root for the case in which the crack grew nonsymmetrically from the two notches resulting in effect in an eccentric load on the remaining area at the crack.

A comparison of Figs. 3-1 and 3-2 show that the curves for the lateral contraction at the notch root and the notch opening displacement vs. the load are very similar. From the figures the lateral contraction at fracture, l_{cf} , and the notch opening displacement at fracture, nd_f , are easily obtained and are given in Tables 3-1 to 3-16. The lateral contraction at yield, l_{cy} , and the notch opening displacement at yield, nd_y ,

are those corresponding to the yielding of the gross section as determined from the load vs. longitudinal strain record.

To characterize the curves for lateral contraction and notch opening displacement, a third point on the graphs with co-ordinates (lc_{yn} , P_{yn}) or (ndy , P_{yn}) were established by drawing a line tangent to the curve in the region of the yield load and a second line rising from the origin as a secant to the curve such that the two areas indicated A1, and A2, Fig. 3-2, approximately equal. The values of lc_{yn} and nd_{yn} are given in Tables 3-1 to 3-16 and the values P_{yn} , and σ_{yn} , are the second entries in the column headed P_y and σ_y in these tables.

Of course, the two entries in Tables 3-1 to 3-16 for the different values of lateral contraction are the records obtained from the two notches. The value of the load P_{yn} obtained from the two lateral contraction curves and the notch opening displacement curve for each test were found to be in close agreement. The first entry for lateral contraction corresponds to the lateral contraction on the side of the notch opening displacement measurements. Fig. 3-3 shows that the lateral contraction measured on the side subjected to lesser tension reached a limiting value and reversed because of decreasing strain at the notch.

For certain specimens in Tables 3-1 to 3-16, fracture occurred prior to yielding on the gross section and therefore no entry appears for P_y . The value of σ_y , entered in the tables for these tests was obtained from the ancillary tests at the temperature corresponding to the test in question.

In certain tests one of the lateral contraction transducers did not function and the tables therefore have an entry "Out of Order". In cases where the specimen cracked nonsymmetrically, as indicated by the typical record in Fig. 3-3, the values of lateral contraction at fracture are considered to be non-applicable and are shown in the tables with the designation "n.a.".

The data given in Tables 3-1 to 3-16 are presented in graphical form relating to temperature the fracture yield loads ratio, λ , the lateral contraction at the root of the notch, and the notch opening displacement as described in the following sections.

3.2.1. Fracture-Yield Loads Ratio vs. Temperature

On Figures 3-4 to 3-10 is plotted the Fracture-Yield loads Ratio, λ , vs. temperature from all groups tested. For any particular group of tests the data show that at relatively high temperatures an upper limit to λ exists. With decreasing temperature the value of λ obtainable decreases. For some of the groups of wider specimens tested, even at high temperatures, a value of λ equal to one was not reached. While scatter exists it is possible to determine mean curves to give the variation of λ with temperature. Sources of error leading to the scatter would include errors in temperature and load measurement. The most important source of scatter would however appear to be for tests in which yielding of the gross section did not occur and the estimation of the yield strength was based on the

determination of the yield strength vs. temperature from standard tension tests. This error results from the variation in the yield level of the steel from point to point in the plate.

3.2.2. Lateral Contraction at the Notch Root

Figures 3-11 to 3-17 show the variation of the lateral contraction at the root of the notch vs. temperature for all group of tests. For any group of tests, in addition to the lateral contraction at fracture, the lateral contraction corresponding to yielding of the gross section is also plotted, if yielding on the gross section occurred before fracture. The values of lateral contraction are, in general, the average obtained from both sides.

In general as for the variation of fracture-yield loads ratio with temperature, the variation of lateral contraction with temperature has high plateau values at higher temperatures and decreases markedly with decreasing temperature. The lateral contraction at yield did not show a great variation with temperature. For most groups it tended to increase slightly with decreasing temperature although for some groups this was not obvious.

The curves show that considerable scatter exists. Possibly this arises chiefly from difficulty in placing the lateral contraction transducer in the same relative position to the notch in each test.

3.2.3. Notch Opening Displacement

On Figures 3-18 to 3-23 are plotted the notch opening displacement vs. temperature curves for the various groups of tests. These curves are similar in appearance to those of lateral contraction vs. temperature. At fracture for high temperatures the notch opening displacements are relatively large and then decrease to low values with decreasing temperatures. At yielding of the gross section the notch opening displacements show in general some tendency to increase with decreasing temperature. This characteristic would appear to reflect the increase in yield strength with decreasing temperature. The considerable scatter in the notch opening displacement vs. temperature curves is attributed to variations in the depth of the notch, in the yield strength as discussed in Sec. 3.2.1, and variations in the amount of crack extension before final fracture.

3.3. ANCILLARY TEST RESULTS

3.3.1. Standard Tensile Test Results

Tables 3-17, 3-18 and 3-19 summarize the results of the standard tensile tests for steels A1, B, and A3 respectively. Fig's. 3-24, 3-25 and 3-26 show respectively stress strain records obtained for steels A1, B, and A3. In Fig's. 3-27 through 3-30 are plotted for the four steels the variation of ultimate and yield strengths vs. temperature. The yield strength results plotted are based both on the standard tensile

tests and on the notched plate tests. For all steels, both the yield strength and the ultimate tensile strength increase with decreasing temperature. For steel A1, as shown in Fig. 3-27, the results for yield strength fall in a band with a width of about 8%, and for the ultimate tensile strength in a band with a width of about 6%. For steel B, as shown in Fig. 3-28, the scatter band has a width of about 5% for yield strength and of about 3% for ultimate strength. For steel C, as shown in Fig. 3-30, the scatter band has a width of about 4% for both ultimate and yield strengths.

For steel A3, as shown by the stress-strain curve, Fig. 3-26 a well defined yield plateau does not exist, because of this the definition of the yield strength is somewhat less exact and on Fig. 3-29 the scatter band has a width of about 8 ksi or 20-30%. The ultimate tensile strength has a scatter band of about 12% based on fewer number of tests. The scatter in the values of the yield strength as shown in Fig's 3-27 through 3-30, and to lesser extent the scatter in the ultimate tensile strength, are considered to be the chief source of scatter in the curves relating the fracture-yield loads ratio λ to the temperature.

3.3.2 Charpy V-Notch Tests

Results of Charpy V-Notch Impact tests for steels A1, B, A3 and C are presented in Fig's 3-31 to 3-34 in the form of absorbed energy vs. temperature. A 15 ft.lb. energy level is obtained at temperatures of -20° , -32° , -41° , and -37° for the four steels respectively. The data for steel C was obtained by Kus (1970).

3.3.3. Hardness Profile.

The results of a hardness profile for steel A3 based on Rockwell B scale are shown in Fig. 3-35. This figure indicates that the average hardness for the 1/2" thick specimens was about 73.2 R_b , and 73.6, 74.3, and 75 R_b , for 1", 2" and 3" thick specimens respectively. This would indicate that there is approximately 4-5 ksi (6-8%) variation in the average ultimate strength of the material between the 1/2" and 3" thick specimens.

3.4 PARAMETRIC EFFECTS

In this section the test results are presented to enable the later study of each of the various parameters to be made independently.

3.4.1. Effect of Width

From the graphs of the loads ratio, λ , vs. the temperature can be obtained for a group of tests for a particular temperature the load ratio, λ , as given in Table 3-20 for specimens of different widths all with the same area ratio $\rho = 0.75$ for the three steels A1, B and C. Table 3-20 also gives for the temperature range indicated of 0° to -60°C the ultimate to yield strength ratio, β , and the normalized value of λ , the loads ratio, obtained by dividing λ by β . Fig's. 3-27 through 3-30 show that the value of β does not vary by more than about 5%. From the data in Table 3-20, Fig's. 3-37, 3-38 and 3-39

giving the load ratio λ vs. the specimen width, $2b$, are obtained. For each steel a curve giving the fracture-yield loads ratio λ as a function of width is drawn for a series of temperatures. Three values of the loads ratio, λ , are significant. A $\rho = 1.0$ indicates that yielding is reached on the gross section prior to fracture on the net section and therefore above this line yielding on the gross section will be ensured before fracture on the net section. The upper limit of the loads ratio

λ that could be obtained provided fracture did not occur on the net section is the ratio of the ultimate to yield strengths β . The upper portions of the curves are however shown dotted because assuming that there is not an increase in the ultimate strength due to the restraint at the notches, the maximum attainable value of λ will be equal to the ultimate to yield strength ratio β multiplied by the area ratio ρ ; that is to say, the maximum load that can be carried,

$$P_{f \max} = \sigma_u \cdot A_n$$

and therefore the loads ratio,

$$\begin{aligned} \lambda_{\max} &= P_{f \max} / P_y = (\sigma_u \cdot A_n) / (\sigma_y \cdot A_g) \\ \lambda_{\max} &= (\sigma_u / \sigma_y) \cdot (A_n / A_g) \\ &= \beta \cdot \rho \end{aligned}$$

the curves in Fig's. 3-37, 3-38, and 3-39 are therefore cut off at λ values of 1.24, 1.25, and 1.35 respectively.

3.4.2. Effect of Notch Depth

By using the data from the graphs of load ratio λ vs. temperature, previously plotted on Fig. 3-7, data can be obtained,

as given in table 3-21, relating for specimens of constant thickness of 1 in. and width of 6 in. the load ratio λ to the area ratio $\rho = A_n/A_g$, that is the notch depth. These data can be extracted from Fig. 3-7 for any desired temperature in the given range of temperatures and are presented in Table 3-21 for temperatures varying in 20°C intervals from 0° to -60°C . Table 3-21 also includes information for steel C by Kus and Leung (1970). As in Table 3-20, Table 3-21 contains normalized values of the loads ratio, i.e. λ divided by β . Figure 3-40 presents in graphical form the variation of the load ratio λ as a function of the area ratio, ρ , for steel A1 for four different temperatures. Above the horizontal line at a load ratio of one lie the portion of the curves where the yield load could be obtained before fracture. For an area ratio $\rho = 1.0$, the curve of course intersects the loads ratio axis at the ratio of the ultimate tensile strength to yield strength, that is the value $\beta = \sigma_u / \sigma_y$. For a net to gross area ratio of zero the specimen could carry no load. The curves are limited to the right by a Strength Cutoff Line determined as was established for Fig. 3-37 as follows. The maximum load $P_{f \max} = \sigma_u \cdot A_n$. The yield load $P_y = \sigma_y \cdot A_g$, therefore $P_{f \max} / P_y$ equals $\lambda_{\max} = (\sigma_u / \sigma_y) \cdot (A_n / A_g) = \beta \cdot \rho$. The curves to the right of this line are therefore shown dotted.

Figure 3-41 presents the information of Fig. 3-40 but with the load ratio λ being normalized by dividing by the ultimate to yield strength ratio β . The vertical axis

therefore has a unit length. Also plotted on Fig. 3-41 in this normalized form is the test data for steel C for the three temperatures 0° , -20° , and -40°C . It is seen that the curves have the same characteristics as for steel A1.

3.4.3. Effect of Thickness

From the graphs of Fig. 3-8 the data in Table 3-22 can be obtained and from these can be plotted the data in Fig. 3-42 giving the variation in the load ratio λ as a function of the thickness, t . All the data in Fig. 3-42 are for specimens 6 in. wide with an area ratio, $\rho = 0.75$. The ultimate to yield strength ratio β for this steel, A3, based on the results of the standard tensile tests was 2.07. It is appreciated however that a variation in strength exists through the thickness of the plate as discussed in Sec. 3.3.3. For the lower test temperatures where yielding did not occur prior to fracture, i.e. $\lambda < 1.0$, the yield load, not measured in the test, is determined from the standard tensile test data. As these data showed considerable variation, especially when compared with yield strength determined where possible from the notched static tension tests, the lower two curves have been shown as a range of values to reflect the possible variation in the yield load P_y .

3.4.4. Effect of the Notch Root Radius

The basic data for specimens with fatigue precracked notches is given in Table 3-14. On Fig. 3-9 is plotted the

load ratio λ vs. temperature for the two groups of tests I-R and II-W that are comparable in every respect having area ratios, ρ , of 0.75 and specimen dimensions of 1 in. by 6 in., except that group I-R had fatigue precracked notches and group II-W had notches with a minimum of width of 0.006 in. Fig's 3-16 and 3-22 plot the lateral contraction at the root of the notch and the notch opening displacement vs. temperature for these two groups of tests. All these data indicate that the sawn notch with a width of 0.006 in. is as severe as a fatigue precracked notch of the same depth. The effect of this parameter will not be further discussed.

3.4.5. Effect of Notch Geometry

Two groups of tests with internal and external notches but otherwise similar, groups I-G and II-W provide the data for the investigation of the effect of the geometry of the notch. Table 3-15 contains the basic data for the group of tests with the internal notch and in Fig. 3-10 are plotted the load ratio, λ , vs. temperature for the two groups of tests I-G and II-W. Fig's. 3-17 and 3-23 have similar plots for lateral contraction and notch opening displacement vs. temperature for the two groups.

From an examination of Fig. 3-10, within the limit of the errors of the investigation, as evidenced by the scatter in the data, there does not appear to be a discernible difference attributable to the effect of the geometry of the notch.

Linear elastic fracture mechanics analyses would predict a difference of about 10%, Paris and Sih (1965), with the external notches being more severe. It appears that the yielding at the notch roots has tended to obliterate the differences predicted by an elastic analysis.

The effect of this parameter will not be further discussed.

3.4.6. Effect of Residual Stresses

It had been intended that a whole group of specimens I-RS with residual stresses would be tested to provide a comparison with group I-G, which is in other respects similar, and thus determine the effect of a residual stress pattern on the behaviour of the specimens with a defect. Ten specimens were prepared but due to distortions and non-uniformity of weld beads only four specimens were satisfactory for use in spite of the fact that two beads were applied in tandem to minimize distortion and provide symmetry. Unfortunately however this operation was apparently somewhat difficult to control. One of these specimens was used to determine the residual stress pattern, as previously discussed in Sec. 2.6.3. and Appendix 1, leaving three specimens for notched static tension tests. The residual stress pattern determined from the one specimen is shown on Fig. 3-36. The results of the notched static tension tests are presented in Fig. 3-10 where the load ratio λ is plotted vs. temperature, and Fig's. 3-17 and 3-23 where the lateral contraction and notch opening displacement are plotted vs. temperature.

Although residual tensile stresses at the notch tip were about 24 ksi on the average the data for the residual stress group plotted on Fig. 3-10 do not show an appreciable effect on the load carrying capacity of the specimen at fracture. This result is not considered to be conclusive in as much as the three tests carried out were at relatively high temperatures (above -25°C) and plastic deformation at these higher temperatures would have been instrumental in relieving the effect of the residual tensile stresses prior to fracture. At lower temperatures where the general behaviour of the specimens in the tests indicate that the ductility is impaired, it is anticipated that the effect of residual stresses would be noticeable and detrimental.

CHAPTER 4

DISCUSSION

4.1 GENERAL

In this Chapter is discussed the effect of various parameters, thickness, width, and area ratio on the capacity of a notched steel specimen to carry axial tensile loads as developed by considering the tests carried out in this investigation.

From the discussions on the effect of width and the area ratio, (size of defect), is developed the concept of a Strength Interaction Surface relating the load ratio to the area ratio and the width of the test piece. A portion of this surface, a plane, is termed the Strength Cutoff Plane, the remaining major portion defined experimentally is termed the Strength Col as it has a shape resembling a Col, (Col = noun, depression in mountain chain (Oxford Dictionary 5th Ed. 1969)). The effect on the Strength Interaction Surface of variations in the temperature, thickness, strain rate, and residual stresses is then discussed. Analytical expressions are developed relating the loads ratio to the width and to the area ratio. Some comparisons with the work of other researchers is given.

A brief discussion of the relationship between Charpy V-notch tests and the data derived from the notched static tension tests is presented.

4.2 EFFECT OF THICKNESS

From Fig. 3-42 there is no apparent effect of increasing thickness for the steel tested at 0°C . This is ascribed to the capacity of the steel at this temperature to yield and thereby overcome the effect of stress triaxiality at the notches in the thicker test specimens.

For any thickness with decreasing temperatures the loads ratio attainable is decreased as all the graphs relating the load ratio to temperature indicate.

As the thickness is increased for temperatures below 0°C , the value of λ decreases, first rapidly and then less so, and appears, in the cases investigated, to approach a horizontal asymptote. Thus the performance of metallurgically similar steel in thicknesses greater than about 3 in. would not apparently be inferior to the performance at 3 in. thickness.

At the area ratio for which Fig. 3-42 is drawn, $\rho = 0.75$, yielding takes place on the gross section before fracture down to temperatures of about -35°C for the 1 in. thick specimens, -30°C for the 2 in. thick specimens, and -20°C for the 3 in. thick specimens. For operations at lower temperatures than these, members of these respective thicknesses would therefore have to have cracks comprising proportionately smaller ratios than 25% of the area in order that yielding could occur before fracture.

4.3 EFFECT OF WIDTH

The curves of Fig's 3-37, 3-38 and 3-39 for the three different steels, A1, B and C, all have the same shape and indicate that with decreasing temperatures, for a given width, the load that can be carried decreases. As the width of the specimen increases, at any temperature, the load ratio decreases but at relatively large widths, say greater than 12 in. the rate of decrease of λ with width is relatively small. This effect has previously been noted by Boodberg, et al (1948), in testing plates with central notches at widths from 3 to 108 in., where it is reported that increasing the specimens width beyond 24 in. had little effect on the strength and that specimens as wide as 108 in. failed at practically the same stress as a 24 in. specimen. The curves of Boodberg et al, relating the nominal stress at fracture to plate width, are quite similar to the curves of Fig's 3-37, 3-38 and 3-39 relating the loads ratio to width.

The curves of Fig. 3-37, 3-38, and 3-39 also show, at this particular area ratio of 0.75, that the specimens must be relatively narrow, particularly at lower temperatures in order that the yield load will be reached.

A comparison of Fig. 3-37 for steel A1, with $\beta = 1.65$, and Fig. 3-38 for steel C, $\beta = 1.80$, shows that as the ratio of ultimate to yield strength is increased the width of the specimen, for a particular set of test conditions, that can carry the yield load is increased, i.e. by increasing β

a steel with a better performance is obtained.

By a process of curve fitting it was established that an equation in the form

$$\frac{P_f}{P_y} = \beta - c_1 \arctan c_2 b \quad (4.1)$$

would fit the experimental data provided that appropriate values of the two constants c_1 and c_2 for each curve are obtained. In Eq. 4.1, b is half the width of the specimen. For example for steel A1 at -60°C , as drawn in Fig. 3-37, the values determined for c_1 and c_2 are respectively 0.62 and 1.23. The curve,

$$P_f/P_y = 1.65 - 0.62 \arctan 1.23 b \quad (4.1a)$$

is drawn in Fig 4-1 along with the corresponding experimental data points. In a similar manner constants could be calculated for the other experimental curves of Fig's 3-37, 3-38 and 3-39.

By Linear Elastic Fracture Mechanics analyses, Paris and Sih (1965), the gross fracture stress σ_c , for a given crack size, a , and crack size to width ratio, a/b , is given by,

$$\sigma_c = \frac{K_c}{\sqrt{a} \cdot \psi(a/b)} \quad (4.2a)$$

$$= \frac{K_c}{\sqrt{b} \sqrt{a/b} \psi(a/b)} \quad (4.2b)$$

$$= \frac{c_3}{\sqrt{b}} \quad (4.2c)$$

where, c_3 is a factor independent of the specimen width given by,

$$c_3 = \frac{K_c}{\sqrt{a/b} \cdot \psi(a/b)}$$

From Eq. 4.2c the loads ratio P_f/P_y could be calculated,

$$\frac{P_f}{P_y} = \frac{\sigma_c \cdot A_g}{\sigma_y \cdot A_g} \quad (4.3a)$$

$$= \frac{c_3}{\sigma_y \cdot \sqrt{b}} \quad (4.3b)$$

$$= \frac{c_4}{\sqrt{b}} \quad (4.3c)$$

where c_4 is given by c_3 / σ_y .

On Fig. 4-1, assuming coincidence of the two expressions, 4.1 and 4.3c, at a width of 6 in., Eq. 4.3c is plotted. It is seen from Fig. 4-1 that Eq. 4.3c does not agree with the experimental data, rising to too high values for small widths and dropping to too low values at large widths, contrary to experimental evidence herein presented and to that of Boodberg et al (1948). In fact for large widths Eq. 4.3c is asymptotic to a loads ratio of zero suggesting that a very wide plate with a defect has no strength.

Because Eq. 4.1 has two constants, apart from β , to be evaluated for any curve then at least two bits of experimental evidence are required to establish a given curve, not one bit as suggested by Eq. 4.3c.

The plastic deformation at the notch root modifies the behaviour to the extent that elastic analyses are no longer applicable and the specimen is able to sustain greater load than would be expected by these analyses.

4.4. EFFECT OF AREA RATIO

Figs 3-40 and 3-41 show against the area ratio, ρ , the loads ratio, λ , or the load ratio, λ , divided by the ultimate to yield strength ratio β . As the area ratio is decreased for any particular temperature the loads ratio decreases from the limiting value β to zero when no net area remains, and thus an area ratio is reached at which fracture will occur through the notches before yielding on the gross section occurs.

With lowered temperatures the curve relating the load ratio, λ , to the area ratio, ρ , is itself lowered and the intercept of the curve with a λ equals one occurs at higher and higher values of ρ . Thus as the temperature decreases the size of the defect that the specimen can have and still retain the capacity to reach a λ value of one becomes smaller. For steel A1 plotted on Fig. 3-40, as the temperature drops from 0°C the size of the defect that can be tolerated in order to reach the yield load before fracture reduces from 0.33 of the width to 0.12 of the width.

The Strength Cutoff Line $P_f/P_y = \lambda = \beta \cdot \rho$ as developed in Sec. 3.4.2. limits the curves to the right. One data point

for 0°C with co-ordinates (0.4, 0.66) falls on this line.

In the normalized relationship of Fig. 3-41 with the loads ratio λ divided by β , the data for steel C give curves for a range of temperatures from 0° to -40°C similar to those for steel A1 plotted on Fig. 3-40. Because the curves have been normalized, the value of the normalized loads ratio corresponding to a load ratio of 1.0 is equal to $1/\beta$, or 0.65 for steel C, and 0.61 for steel A1. For steel C as the temperature is reduced from 0° to -40°C the tolerable defect, that size which still allows the yield load to be obtained before fracture, reduces from 0.44 of the width to 0.24 of the width. This tolerable defect size is, of course, only valid for the conditions of the tests for which the data was obtained, i.e. for 6 in. width, 1 in. thickness and for a strain rate of about 80 $\mu\text{s}/\text{sec}$. For a given temperature the curve for steel C lies above that for steel A1, indicating that steel C is less notch sensitive: the higher the curves at a given temperature, the tougher the steel.

By increasing the value of β , in effect, on a Figure such as Fig. 3-40, the value of $\lambda = 1.0$ is at a relatively lower position on the graph: for the normalized curves the value of the loads ratio, λ , above which yielding occurs, $1/\beta$, is lower for steels with a higher value of β . Thus better performance can be attained by supplying steels with a higher value of β , the ultimate to yield strength ratio, assuming that other metallurgical considerations remain constant.

Based on the criterion that the structure is to yield

before fracture, then to attain lighter structures simply by increasing the yield strength of the steel at the expense of decreasing the ultimate to yield strength ratio is not good practice where notch sensitivity is an important consideration, unless improved metallurgical characteristics more than offset the loss in performance due to the decreased value of β .

Plotted on Fig. 4-2 are the results of tests reported by Thomas and Windenberg (1948) in the same form as Fig. 3-41, i.e. the normalized load ratio λ/β vs. the area ratio ρ ; also on the same figure is a curve for steel A1 at -40°C taken from Fig. 3-40. These data are for internally notched specimens with notch detail similar to detail "I" shown in Fig. 2-2, tested at 3°C and are for specimens of two different widths 6 in. and 12 in. The results quoted are for one of the steels investigated referred to as steel "E" having a β of about 1.9. The data of Thomas and Windenberg, extending over a broad range of area ratios of 0.25 to 0.97, confirm the shape of the curves obtained in this investigation. One of the data points for the 6 in. wide specimens falls on the Strength Cutoff Line. The effect of increasing the width of the specimen on decreasing the load attainable as established in Sec. 4.3 is evident from Fig. 4-2 where the curve from the wider specimens lies below that for the narrower ones.

Considering the normalized presentation of the relationship between the area ratio and the normalized load ratio for any temperature, the experimental points are found, by curve fitting, to be represented by two curves in addition to the

Strength Cutoff line which is presented by,

$$\lambda / \beta = \rho \quad (4.4)$$

Fig. 4-3 shows the curves established and on Fig's 4-4 and 4-5 experimental points are indicated against the curves obtained accordingly. Up to the intersection with the Strength Cutoff Line, the curves consist of two parts, a cubic parabola for $1.0 \geq \rho \geq 0.75$ and a straight line for $0.75 \geq \rho \geq c_0$ where c_0 represents the value of ρ where this line intersects the Strength Cutoff Line $\lambda / \beta = \rho$. The straight line portion is first established knowing the co-ordinates of an experimental point with $0.75 \geq \rho > c_0$ and taking a straight line through this point intercepting the x-axis at $\rho = -0.2$. Thus the y-axis intercept of this line is established as,

$$y_0 = \frac{1.2}{\rho + 0.2} \cdot \frac{\lambda}{\beta} \quad (4.5)$$

$$\frac{\lambda}{\beta} = \frac{y_0}{1.2} (\rho + 0.2) \quad (4.6)$$

$$= \frac{y_0}{6} (5\rho + 1) \quad (4.7)$$

A cubic parabola tangent to the straight line at $\rho = 0.75$ with the equation,

$$\frac{\lambda}{\beta} = \frac{y_0}{6} (5\rho + 1) + (1 - y_0) (4\rho - 3)^3 \quad (4.8)$$

is then established. This parabola will intersect the y-axis at $\lambda / \beta = 1.0$

From Fig's. 4-4 and 4-5 it is seen that the above empirical curve fits the experimental points well.

4.5 STRENGTH INTERACTION SURFACE

Curves relating the loads ratio λ to width and to area ratio, ρ , both with strength intercepts can, for a given temperature, thickness, and strain rate, be presented in the form of a Strength Interaction Surface as shown on Fig. 4-6, for steel A1 at a temperature of -60°C , a thickness of 1 in. and a strain rate of about 80 $\mu\text{e/sec}$. Consider, first of all, planes parallel to width - λ plane. The intersection of these planes with the Strength Interaction Surface gives curves for constant values of the area ratio relating the width to λ as given previously on Fig. 3-36 for example. As planes are chosen with smaller values of ρ , i.e. moving away from the width - λ plane, the load attainable for a given width decreases.

The curves of intersection of planes parallel to the ρ - λ plane with the Strength Interaction surface give the relationship between λ and ρ for a specimen of a given width. As planes are chosen at greater widths the curves of intersection with the Interaction Surface drop down as shown for example on Fig. 4-3 where the results of Thomas and Windenberg (1948) are plotted.

The Strength Cutoff Lines, previously plotted on curves relating λ to width and λ to ρ are now seen to lie in the Strength Cutoff Plane with the equation $\lambda = \beta \cdot \rho$. For constant values of ρ , as established in Sec. 3.4.2, λ is limited by the maximum load that could be carried by the net section and equals the ratio of the ultimate strength multiplied by the net area to the yield strength multiplied by the gross area. For a given width, as established in Sec. 3.4.1, the Strength Cutoff Line is given by the $\lambda = \beta \cdot \rho$ equation of the plane.

The major portion of the Strength Interaction Surface representing points determined experimentally by testing notched tension specimens, represents the limiting value of loads ratio λ obtainable for a particular width and area ratio, ρ , is called the Strength Col, taking the name applied to a depression in a mountain chain. On Fig. 4-6 experimental points, obtained in this investigation, are shown by open circles.

The intersection of the plane $\lambda = 1.0$ with the Strength Interaction Surface describes the relationship between the area ratio, ρ , and the width marking the limit at which specimens can attain the yield load prior to fracture.

In the following sections, 4.5.1 through 4.5.4, the effect of temperature, thickness, residual stresses and strain rate on the Strength Interaction Surface will be discussed.

4.5.1. Effect of Temperature

Figure 4-7, plotted on a Transparency overlying the data from Fig. 4-6, shows the Strength Interaction Surface for steel A1 under the same circumstances as for Fig. 4-6, i.e. for a thickness of 1 in. and a strain rate of 80 $\mu\text{e/sec.}$ except that it is plotted for a temperature of 0°C. The effect of an increase in temperature on the behaviour of specimens is readily apparent. The Strength Col for the higher temperatures is lifted upwards, and a greater portion of the total Strength Interaction Surface is determined by the Strength Cutoff Plane.

The upward lift of the Strength Col represents at any point the increased capacity of the specimen to carry load at the higher temperatures. Experimental points on the Strength Interaction Surface are shown by closed circles.

For a loads ratio of 1.0, the size of the defect now tolerable for a given width is increased over that at -60°C.

In both Fig's 4-6 and 4-7 the experimental points have been obtained for steel A1 for a number of widths, 3 in., 6 in., and 12 in., with an area ratio $\rho = 0.75$, and at a width of 6 in. for area ratios of 0.9, 0.75, 0.5, and 0.4. One additional experimental point with a width of 1.5 in., and an area ratio of 1.0 was available from the standard tensile tests.

4.5.2. Effect of Thickness

The Strength Interaction Surfaces plotted on Fig's 4-6 and 4-7 are for a thickness of 1 in. Fig 3-42 shows

that the load ratio, λ , decreases with increasing thickness for low ambient temperatures, but paralleling the behaviour noted for increasing width of specimen the effect of increasing thickness diminishes and the curves approach horizontal asymptotes.

The effect of increasing the thickness of specimens on the Strength Interaction Surface would therefore be expected to be a deepening of the Strength Col but little or no additional deepening would occur for thicknesses greater than 3 in. for steel A3.

4.5.3. Effect of Residual Stresses

Figure 3-10 shows that at relatively high temperatures, Temperatures at which the presence of the notches does not have an appreciable effect on the behaviour of the specimen, residual stresses have little effect. Thus, for Strength Interaction Surfaces at high temperatures it is expected that residual stresses would not have much effect.

As discussed in Sec. 3.4.6, it is postulated that at lower temperatures, with reduced ductility of the steel, the residual stresses would have a detrimental effect. It is, therefore, anticipated that the Strength Col would be deepened in the presence of residual stresses although no experimental evidence was obtained in this investigation because of the difficulties encountered in the preparation of the specimens as discussed previously.

4.5.4. Effect of Strain Rate

All the tests in this program were conducted at a strain rate of about 80 $\mu\text{e/sec}$. This strain rate was selected as being a likely strain rate to which structures such as bridges would be subjected due to live load in service. Numerous investigators, e.g. Barsom (1974), have shown that increasing strain rates increases the notch sensitivity for steel of the types used in this investigation. The Strength Interaction Surface, therefore, for tests conducted at higher strain rate would have a deeper Strength Col because, in effect, at higher strain rates the yield strength is increased and the value of ultimate to yield strength ratio is decreased.

4.6 CHARPY V-NOTCH TESTS

Even confining the comparison of the Charpy V-notch test results, as shown in Fig's 3-31 to 3-34, to the curves of load ratio vs. temperature obtained for one thickness and having one area ratio, ρ and one width $2b$, no correlation was developable between the load ratio, λ , and Charpy V-notch energy absorbed curves. In fact the Charpy tests place the steels in a different order of notch sensitivity. Moreover, in as much as the Charpy tests give one measure for a given steel, say the temperature of an absorbed energy level of 15 ft. lb. the results of the tests herein presented lead to an entire Interaction Surface at a given temperature, the

validity of Charpy V-notch energy absorbtion criterion to determine the serviceability of the steel is not seen to be of much value.

CHAPTER 5

PROPOSED DESIGN PROCEDURE TO PREVENT FRACTURE IN SERVICE

5.1 GENERAL

Based on the results of this investigation and the work of other investigators on the rate of fatigue crack growth, procedures are proposed, at least in general terms, to prevent fracture of structures made from medium strength steels in service due to the existence of flaws or defects. The application of the procedures in a particular instance would require certain test information to determine the Strength Interaction Surface, as in Fig. 4-6, at least within the area of concern. In service for a member with a crack or defect it would then be possible to determine that yielding would occur prior to fracture, or, if not, the likely failure load.

5.2 PROPOSED PROCEDURE

Given that Strength Interaction Surfaces can be developed for different steels, knowing the climatic data for the service environment of the structure and recognizing the maximum defect in the structure likely to be undetected, the designer selects the steel in consideration of such factors as temperature,

member dimensions, (thickness and width), rate of load application (strain rate), and residual stresses expected in the structure.

Assuming that flaws once present may grow through fatigue, at the initial design stage the critical flaw size, the flaw size greater than that which the member would no longer yield before fracture at the lowest operating temperature, can be estimated. However, should the crack size exceed this critical value the failure load would be determinable. In this case, though, the safety of the structure would be impaired below that normally accepted, as failure would occur before yielding. Moreover, the failure mode changes from the desirable one of yielding, giving warning, to the undesirable mode of sudden fracture. Added to the above, is the possible situation where through restraint or other unknown factors such as the settlement of a support of a continuous bridge, additional loads or strains are imposed upon the section with a flaw. For all these reasons, therefore, while a crack size greater than the critical value does not necessarily indicate that fracture will occur, it is highly desirable that if cracks exist they be smaller than the critical value.

Limiting the cracks to sizes smaller than the critical value would mean that the area of the Strength Interaction Surfaces that is of chief interest is that lying above the value of $\lambda = 1.0$. This points out that steels with large values of ultimate to yield strengths ratio are preferable, other things being equal, for applications in which fracture

through cracks, at low temperature operations is possible because the region of the Strength Interaction Surface above the value of $\lambda = 1.0$ is increased.

Provided cracks are detected, they would be allowed to grow from the initial size to sizes less than the critical value. Inspection intervals can be defined based on the expected rate of crack growth knowing the loading spectrum as follows. From Barsom (1973), the rate of crack growth per cycle of loading, da/dN , is given by,

$$\frac{da}{dN} = 3.6 \times 10^{-10} (\Delta K)^3 \quad (5.1)$$

for ferrite pearlite steels where ΔK is in units of ksi. in $^{\frac{1}{2}}$, and is determined from Paris and Sih (1965) as,

$$\Delta K = \Delta \sigma \cdot \phi(a, \frac{a}{b}) \quad (5.2)$$

where $\Delta \sigma$ as the stress range, and $\phi(a, \frac{a}{b})$ a function of crack size, and crack to width ratio where for an internal crack of size $2a$, and member width $2b$

$$\phi(a, \frac{a}{b}) = (\pi a)^{\frac{1}{2}} \cdot \left\{ \frac{2b}{\pi a} \cdot \left(\tan \frac{\pi a}{2b} + 0.1 \sin \frac{\pi a}{b} \right) \right\}^{\frac{1}{2}} \quad (5.3)$$

The use of linear elastic fracture mechanics, which is the basis of the above expressions for ΔK , is valid for predicting the crack growth because the stress range is likely to be considerably less than the yield value.

From the calculations for predicting the number of load cycles needed to provide the required fatigue cracks in the notches of Group I-R specimens, Sec. A.7 of Appendix 1, it is seen that Eq. 5.1 provides conservative estimates of the crack growth rates.

The structure should therefore be inspected at locations where cracks are likely to develop at sufficiently short intervals such that cracks of the critical size would not be left undetected. If the initial size of undetected flaw is relatively small then the inspection intervals could be longer.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1. SUMMARY

1. A series of 131 notched static tension tests on steel specimens were conducted to provide data on the load carrying capacity and behaviour of the specimens depending on the test temperature, width of specimen, depth of notch, and thickness of specimens.

2. A limited number of tests were conducted to investigate the effect of the root radius of the notch, the notch geometry, and residual stresses; as well, ancillary tests including static tension tests and Charpy V-notch tests were made.

3. Four transducers were designed and built for the investigation, two to measure lateral contraction at the root of the notch, one to measure the longitudinal strain, and a fourth to measure the notch opening displacement.

4. In each notched static tension test the data obtained included the specimen temperature and continuous records of the lateral contraction at the two notches, the longitudinal strain, and the notch opening displacement.

5. For each group of tests, to investigate a particular parameter such as the effect of width, the fracture-

yield load ratio, the lateral contraction and the notch opening displacement are plotted vs. temperature.

6. The test data show that the effect of increasing thickness is to decrease the load ratio attainable and that this effect is more pronounced at lower temperatures. However, there appears to be a limiting thickness for any temperature beyond which no further decrease in the load ratio is obtained.

7. The test data show that with increasing widths for any temperature the load ratio attainable decreases and becomes asymptotic to a limiting value for large widths. At the area ratios tested, and at low temperatures, relatively narrow widths must be used to reach a load ratio of one.

8. Because the maximum attainable load ratio is a function of the ultimate to yield strength ratio, β , steels of the type tested with higher values of β , other properties being similar, would provide better fracture performance, as they would be able to tolerate larger cracks at similar load ratios.

9. An empirical equation of the form,

$$P_f/P_y = \beta - c_1 \arctan c_2 b$$

has been developed to give the relationship between the load ratio and the width $2b$.

10. The test data show for any temperature that with decreasing values of the net to gross area ratio, ρ , (larger

defects), the load ratio attainable decreases. For decreasing temperature for a given area ratio, the load ratio attainable for lower values of the area ratio may be limited by a Strength Cutoff line.

11. As the temperature is decreased the tolerable defect, that which allows attainment of the load ratio of one, decreases in size.

12. The data show that steels with increased values of ultimate to yield strength ratio, other properties being equal, can tolerate larger defects.

13. An empirical relationship has been developed relating the load ratio and the area ratio.

14. A proposed design procedure to prevent fracture in service based on the Strength Interaction Surface and a mechanism for crack growth prediction is presented.

6.2. CONCLUSIONS

1. The concept of a Strength Interaction Surface relating for a given temperature, thickness, and strain rate has been developed to show the effect of area ratio and width on the load carrying capacity of a notched tension specimen.

2. The Strength Interaction Surface is comprised of two parts, a Strength Cutoff Plane controlled by the ultimate strength of the net area, and a major portion termed the Strength Col. The Strength Col lying below the Strength Cutoff Plane, and determined by tests, reflects the reduction in strength

due to the loss of ductility on the notched section.

3. The effect of a temperature increase (decrease) on the Strength Interaction Surface is to make the Strength Col shallower (deeper). The change in the load ratio at any point reflects the increase (decrease) in the load capacity as the temperature is increased (decreased).

4. The effect of increasing thickness on the Strength Interaction Surface would be to deepen the Strength Col. From the test data a limiting thickness appears to exist beyond which the Strength Col would cease to deepen.

5. Although experimental evidence is lacking it is expected that residual tensile stresses would deepen the Strength Col especially for low temperatures.

6. Based on the work of other investigators it is expected that, for steels of the type studied, increasing strain rate would deepen the Strength Col.

7. The test results show that a sawn notch with half width of 0.003 in. is as severe as a fatigue precracked notch of the same depth.

8. For the steels tested, for temperatures down to -60°C , the test data show there is no discernable difference in the fracture load reached between testing specimens with internal notches or with external notches.

9. It was shown, for steels of the type tested, that Linear Elastic Fracture Mechanics relationships do not adequately describe the relationship between the load carrying capacity, the crack size, and the plate width. This is ascribed to the

extensive plastic deformation occurring prior to and during fracture.

10. The validity of a Charpy V-notch energy absorption criterion to determine the serviceability of a structural steel member is not seen to be of much value because the serviceability is described by a series of Strength Interaction Surfaces not by a single point.

6.3 FURTHER RESEARCH

Further research should be directed toward the more complete development of the Strength Interaction Surfaces for different steels, different strain rates, different thicknesses, and a series of temperatures. The effect of residual stresses needs better definition.

APPENDIX 1

A.1 LATERAL CONTRACTION TRANSDUCERS

Two transducers of the double cantilever type, Fig. A-1, were designed and built to provide an electrical signal linearly corresponding to the lateral contraction at the notch roots. The transducers were designed for lateral contraction values of up to 0.25 in. taking into account such considerations as linearity better than 0.1% of full scale deflection, the adverse working environment of low temperatures and condensation, and ruggedness of construction. The 7075-T6 Aluminum alloy used in the cantilever arms was chosen because of its high yield strength to Young's modulus ratio, and the thickness of the arms was selected to allow about 4000 $\mu\epsilon$ at the mid-point of the strain gages without the maximum stress in the arms exceeding 67% of the yield strength at the design deflection of 0.30 in. The length of the arms was chosen to accommodate notch depths of up to 2.75 in.

The 500 Ohm strain gages used were of the high precision open face type. The cement used to mount the strain gages was of the heat and pressure curing type with an operating temperature range down to -75°C . Silicon Rubber gage coating was used to protect the gage because of its good low temperature behaviour, and the excellent mechanical protection to the gage.

These transducers are used by placing the pointed hardened set screws in small indentations made in the specimen, by

means of a center punch, and predeflecting the arms using the set screws. The initial signal obtained from the full strain gage bridge is then zeroed and the inward movement of the arms produces an unbalanced potential across the strain gage bridge. By appropriate calibration of the bridge output, the lateral contraction of the specimen could be obtained.

A special device was made for the calibration of these transducers, as well as the other transducers used in this investigation, by means of two dial gauges with 0.0001 in resolution and a Voltmeter with a 0.01 mV resolution. Linearity of the output for both transducers was found to be better than 0.5% of full scale output corresponding to the range of 0.00 to 0.250 in. lateral contraction.

A.2 NOTCH OPENING DISPLACEMENT TRANSDUCERS

Figure A-2 shows the double cantilever type transducer designed and built for the measurement and recording of notch opening displacement. The transducer was designed for maximum deflection of 0.30 in. and a usable range of 0.25 in. The same factors as for the design of the lateral contraction transducers were taken into consideration in the design of this transducer.

The transducer is used by clipping to two knife edges, 0.100 in. high, cemented to the specimen edge on both sides of the notch cut. The initial output of the full bridge is zeroed and the deflection of the arms with the opening of the

notch edge gives rise to unbalanced potential across the bridge. By calibration of the output the notch opening could be measured. Such calibration indicated that linearity better than 0.5% of full scale output corresponding to the range of 0.0 to 0.20 in. notch opening displacement was obtained.

A.3 LONGITUDINAL STRAIN TRANSDUCER

A transducer of the double cantilever type, shown in Fig. A-3, was designed and built to provide an economical means of recording longitudinal strains on the gross section of the notched static tension tests. This transducer was designed for recording strains of up to 15%, or an extension of 0.225 in. on the 1.50 in. gauge length used. The same design considerations as for the two previously described transducers were taken into account.

This transducer is mounted onto the specimen, as shown in Fig. A-2, by means of two knife edge assemblies tightened around two 1 in. long stubs of 1/4 in. drill rod tack welded on the specimen surface along the centerline of the specimen. These drill rod stubs were located 1.50 in. apart with a tolerance of ± 0.05 in. by means of a special jig made up for this purpose. One of the knife edge assemblies was designed to provide movements to allow the installation, preloading, and finally the removal of the transducer at the completion of the test. The calibration of the transducer

established the output linearity at about 0.5%, however, the $\pm 3.3\%$ error in placing the drill rod stubs meant that the recorded strains had a basic error of at least 3.3%. This accuracy was more than ample for the intended use of the strain records.

A.4 SIGNAL CONDITIONING BOX

To control the excitation and provide a balancing unit for the full bridge strain gages used on the four double cantilever type transducers, two for lateral contraction, one for notch opening displacement, and one for longitudinal strain, a four channel signal conditioning box was designed and built. The circuitry used on a typical channel is shown in Fig. A-4.

By the use of this signal conditioner, the excitation to each transducer was adjusted to provide outputs that would match the input voltage scale used on each X-Y recorder so as to obtain optimum resolution and range.

A.5 THERMOCOUPLE MOUNTING

To simplify the mounting of the thermocouples to the specimen, for tests below room temperature, the set-up shown in Fig. A-5 was provided where a $1\frac{1}{2}$ in. spring paper clip was used to press down the thermocouple to the specimen surface through a rubber and copper shield. The rubber strip provided

insulation from the atmosphere surrounding the thermocouple while the copper strip increased the effective contact area with the specimen. This arrangement proved quite satisfactory considering the accuracy required ($\pm 2^{\circ}\text{C}$). Larger spring clips were used for specimens thicker than 1 in.

A.6 REFRIGERATION AND INSULATION

The simplification of the cooling of the specimens for tests below room temperature was an important consideration in the test set-up. It was found that placing 3/4 in. dry ice slabs directly on the specimen and wrapping the assembly in insulation until the temperature of the specimen reached a few degrees below the test temperature was the most economical in expense, effort involved in the set-up of a test, and the time required to carry out a test. Caution was needed in judging the length of time needed for the dry ice to remain in contact with the specimen to avoid overcooled spots and excessive temperature gradients. Fig. A-6 shows typical relative locations and sizes of the dry ice slabs. It was established, by mapping a few specimens for temperature variations with time after the removal of the dry ice slabs, that after 10 to 15 min. of the removal of the dry ice the difference in temperature between any two points on the specimen was within $2^{\circ} - 3^{\circ}\text{C}$. This difference is within the accuracy sought for temperature control and measurement.

To insulate the notched static tension test specimens the arrangement shown in Fig. A-7 was found to be quite satisfactory. In the initial cooling stage the dry ice slabs were placed between the foam rubber and the specimen. After removing the dry ice, the specimen was rewrapped immediately. Foam rubber covered openings were provided for placing the various transducers.

A.7 FATIGUE PRECRACKING OF NOTCHES

One of the two notches for group I-R Specimens was prepared with 0.05 in. long fatigue cracks at the end of a 0.70 in. long sawn notch, Fig. 2-2 detail "F". These notches were precracked, using a 100 kip MTS hydraulic loading frame with electronic feedback load control, at the Structures and Materials Laboratory of the National Aeronautical Establishment.

The specimens were loaded in axial tension with an eccentricity of 3.00 in. The load varied sinusoidally from a minimum of 1 kip to a maximum of 11 kips at the rate of 5 cycles per second. This results in a nominal stress at the root of the notch of about 8.3 ksi or about 18% the yield strength. The average number of cycles needed to develop the first detectable crack was about 50,000 cycles. Crack inspection was made by two means, the first by use of an ultrasonic crack detector and the second by use of surface replicas made for the notch tip vicinity. The average number of cycles to develop

the 0.050 in. crack was found to be 245,000 cycles. This figure is approximately two and half times the number of cycles as predicted by equation 5.1 as follows.

From Paris and Sih (1965), the stress intensity range ΔK corresponding to the load range ΔP for eccentric tension on the specimen with a single edge notch is calculated from

$$\Delta K = \Delta P (a \pi)^{\frac{1}{2}} \phi(a/b) + \frac{6.e}{2b(2b-2)^{\frac{3}{2}}} \psi(a/2b)$$

where a , the notch depth; $2b$, the specimen width, and e , the load eccentricity. The two functions $\phi(a/b)$ and $\psi(a/2b)$ have the values 1.23, and 0.55 respectively for the specimen width of 6 in. and initial notch depth of 0.7 in. Thus for load range, ΔP , of 10 kips, it is found that the initial ΔK value is

$$\Delta K = 11.2 \text{ ksi.in}^{\frac{1}{2}}$$

and from Eq. 5.1,

$$\begin{aligned} \frac{da}{dN} &= 3.6 \times 10^{-10} \times (11.2)^3 \\ &= 5.06 \times 10^{-7} \text{ in/cycle} \end{aligned}$$

from this initial da/dN , the number of cycles needed to develop a 0.050 in. long crack is approximately 99,000 cycles.

STEEL	GRADE	CHEMICAL ANALYSIS*							Yld. Str. ksi	Ult. Str. ksi	%Elong. in 8"
		C	Mn	P	S	Si	N ₂	Ni			
CSA G40.8 Spec.	A	0.24	0.8/1.55	0.035	0.050	0.38	0.008	-			20
		0.21	0.85/1.5	0.030	0.045	0.35	0.008	-	36	65-85	
	B	0.22	0.8/1.55	0.035	0.050	0.13/.38	0.008	-			18
		0.19	0.85/1.5	0.030	0.045	0.15/.35	0.008	-			
A1 B A3 C	B	0.18	1.31	0.006	0.024	0.20	0.005	-	52	75	27
		0.21	-	<.005	0.015	0.18	-	0.014			
	B	0.17	1.23	0.007	0.015	0.23	0.005	-	42	68	28
		0.19	-	<.005	0.011	0.17	-	0.014			
	B	0.18	1.31	0.006	0.024	0.20	0.005	-	46	73	30
		0.21	-	<.005	0.015	0.18	-	0.014			
	A	0.18	1.42	0.009	0.017	0.03	-	-	48	70	32
		0.20	-	<.005	0.007	0.08	-	0.020			

* Upper line indicates Heat analysis, lower line indicates product analysis.

TABLE 2-1 CHEMICAL AND MECHANICAL PROPERTIES OF STEELS USED.

TABLE 2-2

NOTCHED STATIC TENSION SPECIMEN GROUPS

Effect Investigated	Group	No. of Spec	Spec. Dimensions in x in	$\frac{A_n}{A_g}$	Notch Depth in	Notch Root Radius in	Notch Detail	Steel Used
Width	I-W	8	1x3	0.75	0.375	0.003	E	A1
	II-W	8	1x6	0.75	0.750	0.003	E	A1
	III-W	8	1x12	0.75	1.500	0.003	E	A1
	IV-W	8	1x18	0.75	2.250	0.003	E	B
	I-W-B	8	1x3	0.75	0.375	0.003	E	B
	I-W-C	8	1x3	0.75	0.375	0.003	E	C
Notch Depth	I-D	8	1x6	0.90	0.300	0.003	E	A1
	II-W	8	1x6	0.75	0.750	0.003	E	A1
	III-D	8	1x6	0.50	1.500	0.003	E	A1
	IV-D	8	1x6	0.40	1.800	0.003	E	A1
Thick-ness	I-T	8	1/2x6	0.75	0.750	0.003	E	A3
	II-T	8	1x6	0.75	0.750	0.003	E	A3
	III-T	8	2x6	0.75	0.750	0.003	E	A3
	IV-T	8	3x6	0.75	0.750	0.003	E	A3
Root Radius	I-R	8	1x6	0.75	0.750	Fatigued	F	A1
	II-W	8	1x6	0.75	0.750	0.003	E	A1
Notch Geom.	I-G	8	1x6	0.75	0.750	0.003	I	A1
	II-W	8	1x6	0.75	0.750	0.003	E	A1
Resid. Stres's	I-RS	3	1x6	0.75	0.750	0.003	I	A1
	II-W	8	1x6	0.75	0.750	0.003	E	A1

Notes:

- 1) A_n/A_g is nominal value of net to gross area ratio, ρ ;
- 2) Notch detail designation as per Fig. 2-2;
- 3) Steel designation as per Table 2-1.

GROUP: I-W
STEEL: A1

Nom. Width: 3.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .750; Notch Root Radius: .003 in.

Specimen No	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A_n in.	A_{g_2} in.	A_n/A_g	P_y kip	σ_y ksi	P_f kip	σ_f ksi	P_f/P_y	lcyn in.	lcy in.	lcf in.	ndyn in.	ndy in.	ndf in.	
33	2.16	2.99	.724	133 115	44.5 53.2	157	72.7	1.22	.003 .004	.027 .030	.087 .119	.004	.040	.150	24
38	2.20	3.01	.731	136 118	45.2 53.6	161	73.2	1.22	.003 .003	.046 .124	.149 .124	.003	.041	.115	9
37	2.22	3.02	.735	138 124	45.7 55.9	164	73.9	1.21	.002 .002	.031 .025	.12 .087	.002	.038	.099	-2
40	2.22	3.02	.735	142 126	47.0 56.8	165	74.3	1.19	.002 .002	.054 .028	.146 .097	.003	.040	.132	-22
34	2.19	2.99	.732	138 125	46.2 57.0	161	70.3	1.20	.003 out	.021 of order	.051	.003	.042	.087	-38
39	2.23	3.02	.738	147 134	48.7 60.0	150	67.3	1.04	out .004	of order .039	.042	.005	.054	.056	-50
30	2.19	2.99	.734	- 133	50.0 60.6	147	63.8	1.05	.003 .003	- -	.035 .030	.004	-	.041	-60
31	2.23	3.01	.741	150 136	49.8 61.0	166	74.4	1.12	.002 .003	.022 .027	.046 .043	.004	.044	.066	-44

TABLE • 3-1

GROUP: II-W
STEEL: A1

Nom. Width: 6.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .750 ; Notch Root Radius: .003 in.

Specimen No	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A_{n_2} in.	A_{g_2} in.	A_n/A_g	P_y kip	σ_y ksi	P_f kip	σ_f ksi	P_f/P_y	l_{cy} in.	l_{cy} in.	l_{cf} in.	ndyn in.	ndy in.	ndf in.	
47	4.44	6.02	.737	269 235	46.3 52.9	292	65.8	1.11	.004 .007	.089 .109	.110 .151	.008	.130	.160	21
59	4.58	6.11	.749	283 237	46.3 51.8	310	67.8	1.10	.005 .006	.070 .078	.110 .115	.008	.106	.20	11
32	4.37	5.92	.738	270 228	45.6 52.2	288	65.9	1.08	.006 .005	.083 .095	.094 .180	.007	.124	.200	1
25	4.55	6.11	.745	283 242	46.3 53.2	298	65.5	1.06	.006 .006	.090 .086	.108 .109	.007	.115	.145	-9
29	4.48	6.01	.745	277 233	46.1 52.0	296	66.2	1.08	.006 .006	.086 .092	.096 .168	.007	.107	.166	-21
6	4.43	5.97	.741	- 246	48.9 55.6	262	59.2	.91	.006 .006	- -	.036 .029	.009	-	.038	-34
44	4.51	6.07	.743	- 265	51.6 58.7	285	63.2	.92	.005 .005	- -	.035 .036	.007	-	.051	-45
16	4.38	5.96	.735	- 270	54.0 61.6	275	62.8	.87	.006 .007	- -	.033 .028	.010	-	.04	-61

TABLE 3-2

GROUP: III-W
STEEL: A1

Nom. Width: 12.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .750 ; Notch Root Radius: .003 in.

Specimen No	X-Section Areas			Loads and Stresses						Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A _n ² in.	A _g ₂ in.	A _n /A _g	P _y kip	σ _y ksi	P _f kip	σ _f ksi	P _f /P _y	l _{cyn} in.	l _{cy} in.	l _{cf} in.	ndyn in.	ndy in.	ndf in.		
1	8.94	11.94	.746	485 387	40.6 43.3	485	54.4	1.01	.009 .009	- -	.103 .100	.013	-	.239	23	
5	8.84	11.92	.742	493 383	41.4 43.3	501	56.7	1.03	.010 .012	- -	.139 >.20	.016	-	.225	9	
2	8.87	11.90	.745	- 408	42.5 46.0	505	56.9	1.01	.007 .010	- -	.097 >.20	.016	-	>.2	-1	
3	8.73	11.97	.729	- 420	45.1 48.1	516	59.1	.98	.009 .008	- -	.094 .098	.014	-	>.2	-15	
8	8.89	11.96	.743	- 448	46.9 50.4	480	54.0	.86	.010 -	- -	.05 -	.016	-	.087	-22	
6	8.90	11.97	.743	- 451	47.6 50.7	470	52.8	.83	.011 .010	- -	.035 .022	.016	-	.037	-28	
4	8.83	11.97	.738	- 449	47.6 50.8	470	53.2	.84	.011 .010	- -	.044 .037	.017	-	.07	-47	
7	8.94	11.93	.749	- 504	52.8 56.4	508	56.8	.81	.012 -	- -	.017 -	.019	-	.026	-57	

TABLE 3-3

GROUP: IV-W
STEEL: B

Nom. Width: 18.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .750; Notch Root Radius: .003 in.

Specimen No	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open. Displ.			Test Temp. $^{\circ}$ C
	A_{n_2} in.	A_{g_2} in.	A_n/A_g	P_y kip	σ_y ksi	P_f kip	σ_f ksi	P_f/P_y	lcyn in.	lcy in.	lcf in.	ndyn in.	ndy in.	ndf in.	
1	13.58	18.20	.746	591	41.0 43.5	739	54.5	1.00	.012	-	n.a.	.023	-	>.2	23
7	13.56	18.42	.751	636	43.4 46.0	756	54.7	.95	.015	-	n.a.	.026	-	>.2	8
8	13.68	18.22	.751	670	46.2 49.0	783	57.3	.93	.012	-	n.a.	.022	-	>.2	-2
4	13.62	18.17	.750	690	47.7 50.6	790	58.0	.91	.012	-	n.a.	.02	-	>.2	-13
6	13.6	18.15	.750	696	48.5 51.2	764	56.2	.87	.020	-	>.2	.027	-	>.2	-24
3	13.7	18.25	.750	724	50.0 52.8	773	56.4	.85	.009	-	.088	.020	-	.20	-34
5	13.62	18.16	.750	735	51.0 54.0	761	55.9	.82	.012	-	.096	.025	-	.135	-49
2	13.24	18.15	.730	766	54.8 57.9	782	59.1	.81	.016	-	.055	.026	-	.045	-59

GROUP: I-W-B
STEEL: B

Nom. Width: 3.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .750; Notch Root Radius: .003 in.

Specimen	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A_{n_2} in.	A_{g_2} in.	A_n/A_g	P_y kip	σ_y ksi	P_f kip	σ_f ksi	P_f/P_y	lcyn in.	lcy in.	lcf in.	ndyn in.	ndy in.	ndf in.	
5	2.28	3.05	.746	137 122	44.9 53.6	155	68.1	1.14	.003 .002	.033 .030	.049 .100	out of order			22
7	2.24	3.05	.736	142 123	46.4 54.9	155	69.4	1.12	.003 .003	.036 .041	.090 .059	.005	.052	.063	7
3.	2.23	3.05	.731	138 124	45.2 55.6	160	72.0	1.20	.002 .002	.036 .029	.085 .079	.003	.045	.134	-2
8	2.28	3.04	.750	143 131	47.0 57.8	165	72.0	1.16	.003 .003	.036 .035	.114 .054	.005	.053	.072	-13
2	2.23	3.04	.733	147 132	48.4 59.3	161	72.1	1.18	.003 .004	.042 .060	.056 .150	.004	.060	.140	-23
1	2.27	3.03	.750	147 136	48.5 59.8	166	73.0	1.13	.003 .004	.040 .032	.087 .043	.005	.048	.060	-33
4.	2.27	3.04	.746	157 140	51.6 61.7	166	72.9	1.06	.002 .003	.060 .056	.110 .062	.005	.078	.083	-43
6.	2.21	3.03	.728	156 141	51.5 63.8	170	77.1	1.12	.003 out	.054 of order	.076	.004	.063	.125	-56

TABLE 3-5

GROUP: I-W-C

STEEL: C

Nom. Width: 3.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .750 ; Notch Root Radius: .003 in.

Specimen No	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open Displ.			Test Temp. °C
	A_{n2} in.	A_{g2} in.	A_n/A_g	P_y kip	σ_y ksi	P_f kip	σ_f ksi	P_f/P_y	lcyn in.	lcy in.	lcf in.	ndyn in.	ndy in.	ndf in.	
101	2.23	3.12	.715	131 112	42.0 50.2	170	76.2	1.36	.002 .003	.035 .038	.142 .140	.003	.043	.138	22
89	2.21	3.07	.721	136 119	44.1 53.8	175	79.1	1.34	.003 .002	.026 .034	.100 .148	.003	.053	.188	7
52	2.27	3.12	.729	135 119	43.3 52.4	178	78.3	1.36	.002 .003	.026 .031	.112 .134	.004	.048	.195	-1
103	2.21	3.07	.721	138 124	44.8 56.0	182	82.2	1.38	.002 .003	.030 .045	.106 .190	.003	.048	.175	-13
80	2.21	3.09	.717	143 127	46.3 57.4	155	70.5	1.13	.002 .003	.034 .053	.042 .064	.003	.056	.068	-25
55	2.24	3.08	.728	149 134	47.9 59.8	155	69.2	1.08	.002 .003	.037 .039	.041 .042	.005	.058	.064	-34
83	2.23	3.08	.724	153 136	49.7 61.0	164	73.6	1.11	.003 .002	.042 .038	.052 .042	.004	.061	.068	-47
41	2.30	3.08	.747	157 145	50.9 63.1	166	72.3	1.07	.002 .002	.040 .047	.044 .055	.003	.057	.066	-59

TABLE 3-6

GROUP: I-D

STEEL: A1

Nom. Width: 6.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .900 ; Notch Root Radius: .003 in.

Specimen No	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A_{n_2} in.	A_{g_2} in.	A_n/A_g	P_y kip	σ_y ksi	P_f kip	σ_f ksi	P_f/P_y	lcyn in.	lcy in.	lcf in.	ndyn in.	ndy in.	ndf in.	
12	5.33	6.01	.887	270 244	44.9 45.8	366	68.7	1.38	.005 .004	.024 .028	.090 .115	.005	.038	.173	21
42	5.38	6.12	.879	277 260	45.3 48.3	360	66.9	1.33	.003 .004	.029 .029	.094 .103	.005	.046	.164	9
9	5.38	6.13	.878	281 255	45.8 47.4	365	67.8	1.33	.004 .006	.029 .061	.116 .169	.005	.041	.115	-3
45	5.32	6.09	.874	295 265	48.4 49.8	370	69.5	1.29	.003 .004	.032 .035	.102 .109	.005	.053	.20	-12
14	5.26	6.03	.873	291 270	48.3 51.3	360	68.4	1.28	.004 .004	.028 .034	.094 .107	.006	.049	.138	-21
2.	5.36	6.02	.890	291 220	48.3 50.4	361	67.4	1.26	.003 .004	.023 .023	.100 .094	.004	.035	.118	-36
10	5.35	6.12	.870	301 288	49.2 53.8	342	63.9	1.17	.003 .003	.028 .024	.057 .043	.005	.040	.068	-44
4	5.28	6.05	.873	293	52.2 55.5	307	58.1	1.00	.003 .004	- -	.016 .013	.006	-	.015	-68

TABLE 3-7

a4

GROUP: III-D

STEEL: A1

Nom. Width: 6.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .500; Notch Root Radius: .003 in.

Specimen No	X-Section Areas			Loads and Stresses				Lateral Contract.			Notch Open. Displ.			Test Temp. $^{\circ}$ C
	A_{n2} in.	A_{g2} in.	A_n/A_g	R_y kip	σ_y ksi	P_f kip	σ_f ksi	P_f/P_y	l_{cyn} in.	l_{cy} in.	l_{cf} in.	ndyn in.	ndf in.	
36	2.96	5.99	.493	155	45.8 52.4	220	74.3	.81	.004 .004	-	.110 .106	.007	.140	21
53	2.99	6.08	.492	154	46.2 51.5	218	72.9	.79	.003 .004	-	.120 .126	.008	.168	9
68	2.95	6.04	.488	157	46.0 53.2	216	73.2	.80	.004 .004	-	.076 .072	.007	.092	-1
19	3.05	6.15	.496	162	46.7 53.1	214	70.2	.75	.005 .004	-	.146 .146	.009	.092	-13
21	2.98	6.13	.486	154	48.0 51.7	202	67.8	.70	.003 .005	-	>.2 >.2	.010	.150	-23
27	3.00	6.11	.491	162	48.0 54.0	208	69.3	.72	.003 .004	-	.064 .07	.010	.090	-36
46	2.83	6.04	.468	168	50.5 59.4	203	71.7	.71	.004 .009	-	.035 .068	.010	.045	-47
18	3.00	6.09	.493	168	52.0 56.0	201	66.8 32.9	.64	.004 .005	-	.036 .034	.010	.038	-56

TABLE 3-8

2

OF/DE

2

GROUP: IV-D
STEEL: A1

Nom. Width: 6.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .400 ; Notch Root Radius: .003 in.

Specimen	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A_n , in.	A_g , in.	A_n/A_g	P_y kip	σ_y ksi	P_f kip	σ_f ksi	P_f/P_y	lcyn in.	lcy in.	lcf in.	ndyn in.	ndy in.	ndf in.	
26	2.45	6.11	.401	114	45.5 46.5	170	69.4	.61	.004 .003	-	.100 .099	.005	-	.104	21
5.	2.39	6.00	.398	127	46.4 53.1	184	77.0	.66	.003 .004	-	.110 .122	.008	-	.137	9
49	2.31	6.00	.385	120	46.4 51.9	179	77.3	.67	.002 .005	-	.120 .115	.010	-	.142	-1
15	2.38	6.02	.396	130	47.0 54.6	189	79.4	.68	.005 .002	-	.123 .141	.004	-	.124	-11
24	2.40	6.04	.398	132	48.0 55.0	178	74.0	.62	.008 .002	-	.120 .060	.003	-	.071	-24
41	2.41	6.09	.397	135	49.0 56.0	195	80.9	.66	.005 .002	-	.107 .100	.006	-	.117	-35
23	2.38	6.06	.393	142	50.4 60.0	164	68.9	.55	.003 .004	-	.027 .030	.010	-	.034	-48
28	2.32	6.08	.381	140	51.2 60.3	168	72.4	.57	.004 .004	-	.036 .052	.007	-	.035	-56

TABLE 3-9

GROUP: I-T
STEEL: A3

Nom. Width: 6.00 in; Nom. Thickness: .500 in; Nom. A_n/A_g : .750 ; Notch Root Radius: .003 in.

Specimen No.	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A_n , in.	A_{g_2} , in.	A_n/A_g	P_y , kip	σ_y , ksi	P_f , kip	σ_f , ksi	P_f/P_y	lcyn, in.	lcy, in.	lcf, in.	ndyn, in.	ndy, in.	ndf, in.	
12	2.08	2.77	.752	104 81	37.6 39.4	123	58.9	1.18	.003 .003	.032 .033	.095 .081	.007	.057	.20	24
14	2.18	2.91	.748	105 85	36.0 39.0	131	60.1	1.25	.004 .002	.029 .027	.074 .104	.004	.038	.122	9
16	2.02	2.72	.740	100 79	36.7 39.2	119	59.0	1.21	.004 .003	.039 .031	.112 .15	.006	.052	>.2	-1
17	2.11	2.84	.742	112 85	39.4 41.2	134	63.5	1.21	.002 .004	.027 .029	.083 .100	.007	.052	.152	-12
10	2.09	2.86	.731	111 88	38.8 42.1	127	60.5	1.17	.004 .003	.039 .101	.100 .101	.005	.069	.152	-23
11	2.18	2.89	.753	118 93	40.8 42.8	125	57.5	1.06	.004 .004	.046 .037	.059 .050	.006	.068	.088	-34
15	2.26	3.03	.748	120 98	39.6 44.2	132	58.1	1.10	.003 .008	.027 .060	.056 .127	.008	.055	.103	-44
13	2.40	3.20	.751	- 117.	42.8 48.7	136	56.6	.99	.004 .003	- -	.038 .035	.006	-	.067	-57

TABLE 3-10

GROUP: II-T

STEEL: A3

Nom. Width: 6.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .750 ; Notch Root Radius: .003 in.

Specimen No	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A_n in.	A_{g_2} in.	A_n/A_g	P_y kip	σ_y ksi	P_f kip	σ_f ksi	P_f/P_y	lcyn in.	lcy in.	lcf in.	ndyn in.	ndy in.	ndf in.	
1	4.51	6.02	.748	232 205	38.5 45.5	289	64.2	1.25	.004 .003	.024 .021	.20 .093	.006	.031	.132	24
2	4.49	6.01	.747	215 180	35.8 40.1	269	59.9	1.26	.003 .005	.027 .035	.079 .152	.008	.050	.191	9
3	4.55	6.07	.750	232 193	38.2 42.4	273	59.9	1.18	.004 .004	.026 .032	.069 .094	.007	.051	.125	-3
5	4.49	6.03	.745	240 196	39.8 37.0	253	56.2	1.06	.005 .004	.039 .070	.053 .086	.005	.062	.073	-24
6	4.57	6.10	.748	230 196	37.7 42.9	242	52.9	1.05	.003 .005	.065 .037	.083 .046	.008	.058	.072	-33
9	4.25	5.86	.725	- 198	41.3 46.6	225	53.0	.96	.003 .004	- -	.023 .032	.008	-	.043	-44
8	4.44	5.94	.747	- 216	43.2 48.7	236	53.1	.92	.006 .003	- -	.029 .025	.006	-	.026	-50
7	4.37	5.85	.746	- 205	41.8 47.0	227	52.0	.93	.004 .004	- -	.031 .030	.006	-	.037	-55

TABLE 3-11

GROUP: III-T
STEEL: A3

Notch Width: 6.00 in; Nom. Thickness: 2.00 in; Nom. A_n/A_g : .750 ; Notch Root Radius: .003 in.

Section No.	X-Section Areas			Loads and Stresses							Lateral Contract.			Notch Open. Displ.			Test Temp. ° C
	A _{n₂} in.	A _{g₂} in.	A _n /A _g	P _y kip	σ _y ksi	P _f kip	σ _f ksi	P _f /P _y	lcyn in.	lcy in.	lcf in.	ndyn in.	ndy in.	ndf in.			
1	8.62	11.72	.735	390 320	33.3 37.1	480	557	1.26	.004 .004	.037 .036	.119 .116	.005	.059	.149	23		
2	8.78	11.84	.742	410 340	34.6 38.7	528	60.1	1.30	.004 .004	.028 .031	.113 .115	.005	.050	.225	6		
5	8.85	11.96	.740	410 320	34.3 36.2	505	57.1	1.25	.004 .005	.039 .035	.106 .093	.005	.062	.222	-2		
3	8.70	11.80	.738	420 350	35.6 40.2	462	53.2	1.12	.006 .006	.043 .042	.070 .074	.005	.062	.100	-13		
4	8.78	11.90	.738	418 345	35.1 39.3	462	52.6	1.12	.002 .004	.031 .029	.060 .051	.005	.050	.092	-23		
8	8.80	11.82	.745	- 350	36.0 39.8	411	46.7	.97	.004 .004	- -	.031 .030	.007	-	.048	-29		
6	8.74	11.80	.741	- 360	37.2 41.2	420	48.0	.97	.003 .004	- -	.030 .030	.005	-	.047	-44		
7	8.78	11.88	.739	- 390	40.0 44.4	414	47.1	.88	.004 .004	- -	.022 .028	.006	-	.035	-54		

TABLE 3-12

GROUP: IV-T

STEEL: A3

Nom. Width: 6.00 in; Nom. Thickness: 3.00 in; Nom. A_n/A_g : .750 ; Notch Root Radius: .003 in.

Section No	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A_n , in.	A_g , in.	A_n/A_g	P_y kip	σ_y ksi	P_f kip	σ_f ksi	P_f/P_y	lcyn in.	lcy in.	lcf in.	ndyn in.	ndy in.	ndf in.	
16	18.0	13.42	.746	610 537	22.9 40.0	783	58.3	1.29	.004	.036	.136	.006	.056	>20	23
14	18.05	13.34	.739	665 540	36.8 40.5	685	51.3	1.05	.004	.039	.046	.005	.057	.067	11
15	18.00	13.42	.746	553	33.5 41.4	598	44.6	1.00	.004	-	.015	.005	-	.022	12
13	18.09	13.16	.728	620 530	34.3 40.3	785	59.7	1.30	.004	.031	.125	.005	.046	.158	1
12	18.09	13.50	.746	660 555	36.5 41.1	718	53.2	1.09	.005	.040	.065	.007	.058	.087	-15
10	17.99	13.25	.736	580	39.0 43.8	621	46.9	.90	.005 .005	-	.028 .029	.007	-	.040	-34
11	18.02	13.34	.740	600	41.0 45.0	648	48.6	.89	.006 .006	-	.024 .016	.006	-	.023	-43
9	17.99	13.10	.728	675	45.5 51.5	677	51.7	.85	.007 .008	-	.011 .014	.007	-	.011	-61

TABLE 3-13

GROUP: I-R
STEEL: A1

Nom. Width: 6.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .750 ; Notch Root Radius: Fatigued

Specimen No	X-Section Areas			Loads and Stresses					Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A_n , in.	A_g , in.	A_n/A_g	P_y , kip	σ_y , ksi	P_f , kip	σ_f , ksi	P_f/P_y	lcyn, in.	lcy, in.	lcf, in.	ndyn, in.	ndy, in.	ndf, in.	
77	4.50	6.00	.750	268 220	44.7 48.9	284	63.1	1.06	.004 .005	.052 .073	.079 .089	.008	.101	.190	23
66	4.57	6.07	.753	278 230	45.8 50.3	292	63.9	1.05	out of order .006	of order .080	--	.009	.141	--	7
76	4.51	6.01	.750	278 226	46.2 50.1	301	66.7	1.08	.005 .005	.072 .076	.107 --	.009	.110	--	-1
80	4.36	5.93	.735	285 228	48.0 50.4	298	68.3	1.07	.008 .006	.128 .082	.158 --	.008	.150	--	-14
69	4.52	6.06	.746	288 235	47.5 52.0	308	68.1	1.08	.006 .005	.076 .074	.122 --	.008	.113	--	-23
67	4.53	6.05	.749	-- 250	48.5 54.7	297	65.6	1.01	.008 .004	-- --	.140 .066	.008	--	.130	-35
43	4.43	6.02	.736	-- 250	50.0 56.4	268	60.5	.91	.008 .005	-- --	.025 .015	.009	--	.018	-44
79	4.42	5.97	.741	-- --	53.0 --	257	58.1	.82	-- --	-- --	.004 .004	--	--	.012	-56

TABLE 3-14

GROUP: I-G

STEEL: A1

Nom. Width: 6.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .750 ; Notch Root Radius: .003 in.

Specimen	X-Section Areas			Loads and Stresses						Lateral Contract.			Notch Open. Displ.			Test Temp. °C
	A_n , in.	A_g , in.	A_n/A_g	P_y , kip	σ_y , ksi	P_f , kip	σ_f , ksi	P_f/P_y	P_f/P_y	lcyn, in.	lcy, in.	lcf, in.	ndyn, in.	ndy, in.	ndf, in.	
65	4.40	6.01	.737	268 195	44.6 44.3	298	67.7	1.13		.002 .002	.048 .049	.117 .108	.005	.086	> .20	22
55	4.34	6.08	.713	284 203	46.7 46.8	299	69.0	1.11		.002 .002	.090 .067	-	.005	.146	-	8
75	4.36	6.03	.738	280 203	46.4 46.6	307	69.0	1.12		.002 .002	.094 .085	> .20 .170	.005	.103	-	0
58	4.53	6.13	.738	289 215	47.1 47.5	317	70.1	1.12		.002 .002	.057 .055	.103 .096	.006	.099	.180	-12
11	4.56	6.10	.747	294 222	48.2 48.7	294	64.5	1.00		.002 .002	.058 .058	.059 .059	.005	.096	.100	-23
57	4.52	6.07	.745	285 223	49.3 49.3	285	63.1	.96		.002 .002	-	.042 .038	.006	-	.067	1
22	4.51	6.07	.742	285 223	49.4 49.4	285	63.2	.96		.002 .002	-	.043 .044	.005	-	.072	-46
35	4.55	6.08	.748	272 250	54.9 54.9	272	59.8	.82		.002 .003	-	.023 .022	.006	-	.035	-56

TABLE 3-15

GROUP: I-RS

STEEL: A1

Nom. Width: 6.00 in; Nom. Thickness: 1.00 in; Nom. A_n/A_g : .750; Notch Root Radius: .003 in.

Specimen No	X-Section Areas			Loads and Stresses						Lateral Contract.				Notch Open. Displ.			Test Temp. ° C
	A _n , in.	A _g , in.	A _n /A _g	P _y kip	σ _y ksi	P _f kip	σ _f ksi	P _f /P _y	lcyn in.	lcy in.	lcf in.	ndyn in.	ndy in.	ndf in.			
50	4.62	6.13	.753	280 208	45.6 45.0	316	58.5	1.13	.002 .003	.044 .064	.104 .102	.007	.075	.182	7		
51	4.66	6.17	.755	287 215	46.5 46.0	320	68.7	1.11	.003 .003	.056 .058	.096 .097	.009	.085	.195	-7		
52	4.58	6.09	.751	292 216	48.0 47.0	310	67.7	1.06	.006 .002	.134 .068	> .2 .105	.008	.102	.195	-23		

TABLE 3-16

TABLE 3-17

STANDARD TENSILE TEST RESULTS FOR STEEL A1

Spec. No.	X-Sec.	Yield	Yield	Ult.	Ult.	Elong.	Elon.	Test Temp. °C
	Area	Load	Str.	Load	Str.	in 8"	in 8"	
	in ²	P _y kip	σ _y ksi	P _u kip	σ _u ksi	in		
22	1.49	66.0	44.3	107.0	71.8	2.04	25.5	22
4	1.51	67.5	44.8	115.0	76.3	2.07	25.9	22
7	1.51	66.5	44.0	113.5	75.2	2.06	25.8	22
43	1.50	64.5	43.0	107.0	71.3	n.a.	n.a.	22
26	1.48	63.5	43.0	104.5	70.7	2.12	26.5	22
1	1.50	66.0	44.0	108.0	72.0	2.15	26.9	22
28	1.46	63.5	43.5	104.0	71.3	1.99	24.9	4
19	1.49	69.0	46.5	113.0	76.1	2.05	25.6	0
24	1.46	69.0	47.3	112.0	76.8	2.18	27.3	-12
18	1.50	70.5	46.9	117.5	78.2	2.30	28.8	-23
17	1.51	71.5	47.3	120.5	79.6	2.05	25.6	-33
12	1.48	73.0	49.5	119.5	81.0	1.80	22.5	-44
11	1.51	76.0	50.5	122.0	82.7	n.a.	n.a.	-62

TABLE 3-18

STANDARD TENSILE TEST RESULTS FOR STEEL B

Spec. No.	X-Sec.	Yield	Yield	Ult.	Ult.	Elong.	%Elong.	Test
	Area	Load	Str.	Load	Str.	in	in	Temp.
	in	P_y kip	σ_y ksi	P_u kip	σ_u ksi	in	in	$^{\circ}\text{C}$
1	1.49	66.5	44.6	110.5	74.2	2.03	25.4	22
2	1.49	69.5	46.6	112.0	75.2	2.05	25.6	11
5	1.49	69.0	46.3	112.5	75.5	2.10	26.3	- 1
4	1.49	70.0	47.0	115.0	77.2	2.10	26.3	-12
6	1.49	73.5	49.3	117.0	78.5	2.10	26.3	-22
7	1.49	74.5	50.0	118.0	79.2	2.00	25.0	-32
8	1.49	76.5	51.3	121.5	81.5	2.03	25.4	-48
9	1.51	83.0	55.1	122.0	81.1	2.10	26.3	-53

TABLE 3-19

STANDARD TENSILE TEST RESULTS FOR STEEL A3

Spec. No.	X-Sec.	Yield	Yield	Ult.	Ult.	Elong.	%Elong.	Test Temp. °C
	Area	Load	Str.	load	Str.	in	in	
	in ²	P _y kip	σ _y ksi	P _u kip	σ _u ksi	8"	8"	
1	1.49	47.0	31.5	98.5	66.0	1.97	24.6	24
2	1.50	46.0	30.7	99.5	66.3	2.40	30.0	11
3	1.50	47.0	31.3	97.0	64.7	2.54	31.8	- 2
4	1.50	51.0	34.0	107.0	71.3	2.20	27.5	-12
5	1.49	49.5	33.3	106.5	71.7	2.00	25.0	-22
6	1.49	57.0	38.4	112.0	75.4	2.00	25.0	-32
7	1.49	52.5	35.3	107.0	72.0	n.a.	n.a.	-46
8	1.49	56.0	37.7	110.5	74.3	2.04	25.5	-59
9	1.51	55.0	36.5	108.5	72.1	1.74	21.8	-65

TABLE 3-20

FRACTURE - YIELD LOADS RATIO - TEMPERATURE
DATA FOR WIDTH EFFECT GROUPS

Steel	Group ¹	Width in	$\lambda = P_f / P_y$ in brackets $\lambda/\delta = (P_f/P_y) / (\sigma_u/\sigma_y)$ 0°C -20°C -40°C -60°C				$\sigma_u/\sigma_y =$ δ
A1	I-W	3	1.22 (0.74)	1.21 (0.74)	1.14 (0.69)	1.00 (0.61)	1.65
	II-W	6	1.09 (0.66)	1.05 (0.64)	0.95 (0.58)	0.84 (0.51)	
	III-W	12	1.01 (0.61)	0.93 (0.56)	0.84 (0.51)	0.76 (0.46)	
B	I-W-B	3	1.15 (0.69)	1.14 (0.69)	1.10 (0.66)	1.07 (0.64)	1.66
	IV-W	18	0.94 (0.57)	0.89 (0.54)	0.84 (0.51)	0.81 (0.49)	
C	I-W-C	3	1.35 (0.75)	1.28 (0.71)	1.12 (0.62)	0.99 (0.55)	1.80 ²
	Kus, & Leung (1970)	6	1.26 (0.70)	1.18 (0.66)	1.02 (0.57)	N/A	

✓
Notes:

- 1) All groups are 1 in. thick, with $\rho = 0.75$;
- 2) Data from Kus and Leung (1970).

TABLE 3-21

FRACTURE - YIELD LOADS RATIO - TEMPERATURE

DATA FOR NOTCH DEPTH EFFECT GROUPS

Steel	Group ¹	$A_n/A_g = \rho$	$\lambda = P_f / P_y$ in brackets $\lambda/\beta = (P_f/P_y) / (\sigma_u/\sigma_y)$				$\sigma_u/\sigma_y = \beta$
			0°C	-20°C	-40°C	-60°C	
Al	I-D	0.90	1.32 (0.80)	1.28 (0.78)	1.19 (0.72)	1.04 (0.65)	1.65
	II-W	0.75	1.09 (0.66)	1.05 (0.64)	0.95 (0.58)	0.84 (0.51)	
	III-D	0.50	0.80 (0.49)	0.75 (0.46)	0.69 (0.42)	0.62 (0.38)	
	IV-D	0.40	0.66 (0.40)	0.65 (0.39)	0.60 (0.36)	0.53 (0.32)	
C		0.791	1.37 (0.76)	1.27 (0.71)	1.06 (0.59)	N/A	1.80
	Kus, & Leung	0.750	1.26 (0.70)	1.18 (0.66)	1.02 (0.57)	N/A	
	(1970)	0.709	1.21 (0.67)	1.10 (0.64)	0.95 (0.53)	N/A	
		0.625	1.10 (0.61)	1.01 (0.56)	0.85 (0.47)	N/A	

Notes:

1) All groups are 1 in. thick x 6 in. wide

TABLE 3-22

FRACTURE - YIELD LOADS RATIO - TEMPERATURE
DATA FOR THICKNESS EFFECT GROUPS

Steel	Group ¹	Nom. Thick. in	$\lambda = P_f / P_y$ in brackets $\lambda/\beta = (P_f/P_y) / (\sigma_u/\sigma_y)$				$\sigma_u/\sigma_y =$ β
			0°C	-20°C	-40°C	-60°C	
A3	I-T	0.50	1.22 (0.59)	1.17 (0.57)	1.07 (0.52)	1.00 (0.47)	2.07
	II-T	1.00	1.21 (0.58)	1.10 (0.53)	0.98 (0.47)	0.91 (0.44)	
	III-T	2.00	1.25 (0.60)	1.11 (0.54)	0.95 (0.46)	0.88 (0.43)	
	IV-T	3.00	1.24 (0.60)	1.03 (0.50)	0.89 (0.43)	0.85 (0.41)	

Notes:

- 1) All groups are 6 in. wide with $\rho = 0.75$.

FIG.2-1 1 INCH THICK PLATE SPECIMENS

DOUBLE EDGE NOTCH

INTERNAL NOTCH

NOTCH DETAIL "E"

NOTCH DETAIL "F"

NOTCH DETAIL "I"

FIG.2-2 NOTCH DETAILS USED

FIG.2-3 SPECIMEN LAYOUT FOR 1 INCH PLATE, STEEL A1 AND B

GROUPS I-T AND II-T

GROUPS III-T AND IV-T

FIG. 2-4 THICKNESS EFFECT SPECIMENS

GROUPS I-T AND II-T

GROUPS III-T AND IV-T

FIG.2-5 SPECIMEN LAYOUT FOR 3 INCH PLATE, STEEL A3

FIG. 2-6 RESIDUAL STRESS EFFECT SPECIMEN

FIG. 2-7 STANDARD TENSILE SPECIMEN

FIG.2-8 CHARPY V-NOTCH SPECIMEN

FIG. 3-1 TYPICAL LOAD vs NOTCH ROOT LATERAL CONTRACTION RECORD

FIG. 3-2 TYPICAL LOAD vs NOTCH OPENING DISPLACEMENT RECORD

FIG. 3-3 LOAD vs NOTCH ROOT LATERAL CONTRACTION RECORD
FOR NONSYMMETRICALLY FAILING SPECIMEN

FIG. 3-4 WIDTH EFFECT ON FRACTURE-YIELD LOADS RATIO FOR STEEL A1

FIG. 3-5 WIDTH EFFECT ON FRACTURE-YIELD LOADS RATIO
FOR STEEL B

FIG.3-6 FRACTURE-YIELD LOADS RATIO FOR GROUP I-W-C

FIG. 3-7 NOTCH DEPTH EFFECT ON FRACTURE-YIELD LOADS RATIO

FIG. 3-8 THICKNESS EFFECT ON FRACTURE-YIELD LOADS RATIO FOR STEEL A3

FIG.3-9 NOTCH ROOT RADIUS EFFECT ON FRACTURE-YIELD LOADS RATIO

FIG. 3-10 NOTCH GEOMETRY AND RESIDUAL STRESS EFFECT
ON FRACTURE-YIELD LOADS RATIO

FIG. 3-11 WIDTH EFFECT ON NOTCH ROOT LATERAL CONTRACTION FOR STEEL A1

FIG.3-12 WIDTH EFFECT ON NOTCH ROOT LATERAL CONTRACTION FOR STEEL B

FIG. 3-13 NOTCH ROOT LATERAL CONTRACTION FOR GROUP 1-W-C

FIG.3-14 NOTCH DEPTH EFFECT ON NOTCH ROOT LATERAL CONTRACTION FOR STEEL A1

FIG.3-15 THICKNESS EFFECT ON NOTCH ROOT LATERAL CONTRACTION FOR STEEL A3

FIG. 3-16 NOTCH ROOT RADIUS EFFECT ON NOTCH ROOT LATERAL CONTRACTION

FIG. 3-17 NOTCH GEOMETRY AND RESIDUAL STRESS EFFECT
ON NOTCH ROOT LATERAL CONTRACTION

FIG.3-18 WIDTH EFFECT ON NOTCH OPENING DISPLACEMENT
FOR STEEL A1

FIG.3-19 WIDTH EFFECT ON NOTCH OPENING DISPLACEMENT
FOR STEEL B

FIG. 3-20 NOTCH DEPTH EFFECT ON NOTCH OPENING DISPLACEMENT
FOR STEEL A1

FIG. 3-21 THICKNESS EFFECT ON NOTCH OPENING DISPLACEMENT FOR STEEL A3

FIG. 3-22 NOTCH ROOT RADIUS EFFECT ON NOTCH OPENING DISPLACEMENT

FIG.3-23 NOTCH GEOMETRY AND RESIDUAL STRESS EFFECT
ON NOTCH OPENING DISPLACEMENT

FIG. 3-24 TYPICAL STRESS-STRAIN RECORD FOR STEEL A1 •

FIG.3-25 TYPICAL STRESS-STRAIN RECORD FOR STEEL B

FIG. 3-26 TYPICAL STRESS-STRAIN RECORD FOR STEEL A3

FIG. 3-27 YIELD AND ULTIMATE STRENGTH vs TEMPERATURE
FOR STEEL A1

FIG.3-28 YIELD AND ULTIMATE STRENGTH vs TEMPERATURE
FOR STEEL B

**FIG.3-29 YIELD AND ULTIMATE STRENGTH vs TEMPERATURE
FOR STEEL A3**

FIG.3-30 YIELD AND ULTIMATE STRENGTH vs TEMPERATURE
FOR STEEL C, KUS (1970)

FIG.3-31 CHARPY V-NOTCH ABSORBED ENERGY VARIATION WITH TEMPERATURE
FOR STEEL A1

FIG. 3-32 CHARPY V-NOTCH ABSORBED ENERGY VARIATION WITH TEMPERATURE
FOR STEEL B

FIG. 3-33 CHARPY V-NOTCH ABSORBED ENERGY VARIATION WITH TEMPERATURE
FOR STEEL A3

FIG.3-34 CHARPY V-NOTCH ABSORBED ENERGY VARIATION WITH TEMPERATURE
FOR STEEL C

FIG.3-35 HARDNESS PROFILE FOR STEEL A3

FIG.3-36 RESIDUAL STRESS PATTERN FOR SPECIMEN WITH WELD BEADS

FIG. 3-37 FRACTURE - YIELD LOADS RATIO vs SPECIMEN WIDTH
FOR STEEL A1

FIG.3-38 FRACTURE-YIELD LOADS RATIO vs SPECIMEN WIDTH
FOR STEEL B

FIG. 3-39 FRACTURE-YIELD LOADS RATIO vs SPECIMEN WIDTH
 FOR STEEL C

FIG.3-40 FRACTURE-YIELD LOADS RATIO vs NET-GROSS AREA RATIO
FOR STEEL A1

NORMALIZED FRACTURE-YIELD LOADS RATIO

- GROUPS I-D, II-W, III-D, AND IV-D
- STEEL C FROM KUS AND LEUNG (1970)
TABLE 3-21
- 0° C
 - △ -20° C
 - ▽ -40° C

FIG.3-41 NORMALIZED FRACTURE-YIELD LOADS RATIO
vs NET - GROSS AREA RATIO FOR STEEL C

FIG.3-42 FRACTURE-YIELD LOADS RATIO vs SPECIMEN THICKNESS
FOR STEEL A3

FIG. 4-1 EMPIRICAL FRACTURE-YIELD LOADS RATIO vs WIDTH RELATIONSHIP
FOR STEEL A1 AT -60°C

**FIG.4-2 NORMALIZED FRACTURE-YIELD LOADS RATIO
vs NET-GROSS AREA RATIO
FROM THOMAS AND WINDENBERG (1948)**

**FIG.4-3 EMPIRICAL FRACTURE-YIELD LOADS RATIO
vs. NET-GROSS AREA RATIO RELATIONSHIP**

FIG. 4-4 EMPIRICAL FRACTURE-YIELD LOADS RATIO vs NET-GROSS AREA RATIO
RELATIONSHIP FOR STEEL AI

FIG.4-5 EMPIRICAL FRACTURE-YIELD LOADS RATIO vs NET-GROSS AREA RATIO.
 RELATIONSHIP FOR STEEL TESTED BY THOMAS AND WINDENBERG (1948)

FIG. 4-6 STRENGTH INTERACTION SURFACE FOR STEEL A1 AT -60°C

FIG. 4-7 STRENGTH INTERACTION SURFACE FOR STEEL AT 0°C

• EXPERIMENTAL DATA
(TABLES 3-20 AND 3-21)

FIG. 4-7 STRENGTH INTERACTION SURFACE FOR STEEL A1 AT 0°C

FIG. A-2 NOTCH OPENING DISPLACEMENT TRANSDUCER

FIG.A-4 TRANSducer SIGNAL CONDITIONER

FIG.A-5 TYPICAL DETAIL FOR MOUNTING OF THERMOCOUPLES

FIG.A-6 TYPICAL DRY ICE SLAB LOCATION AND RELATIVE SIZE

**FIG.A-7. TYPICAL SPECIMEN INSULATION
FOR NOTCHED TENSION TESTS**

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