Report 4203

L SHIP RESEARCH AND DEVELOPMENT CENTER
Bethesda, Maryland 20034

THE ROLE OF SMALL SPECIMENS AND WELDED STRUCTURAL ELEMENTS IN THE EVALUATION OF LOW-CYCLE FATIGUE OF SUBMARINE HULLS

by

Oles Lomacky

[redacted]

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STRUCTURES DEPARTMENT
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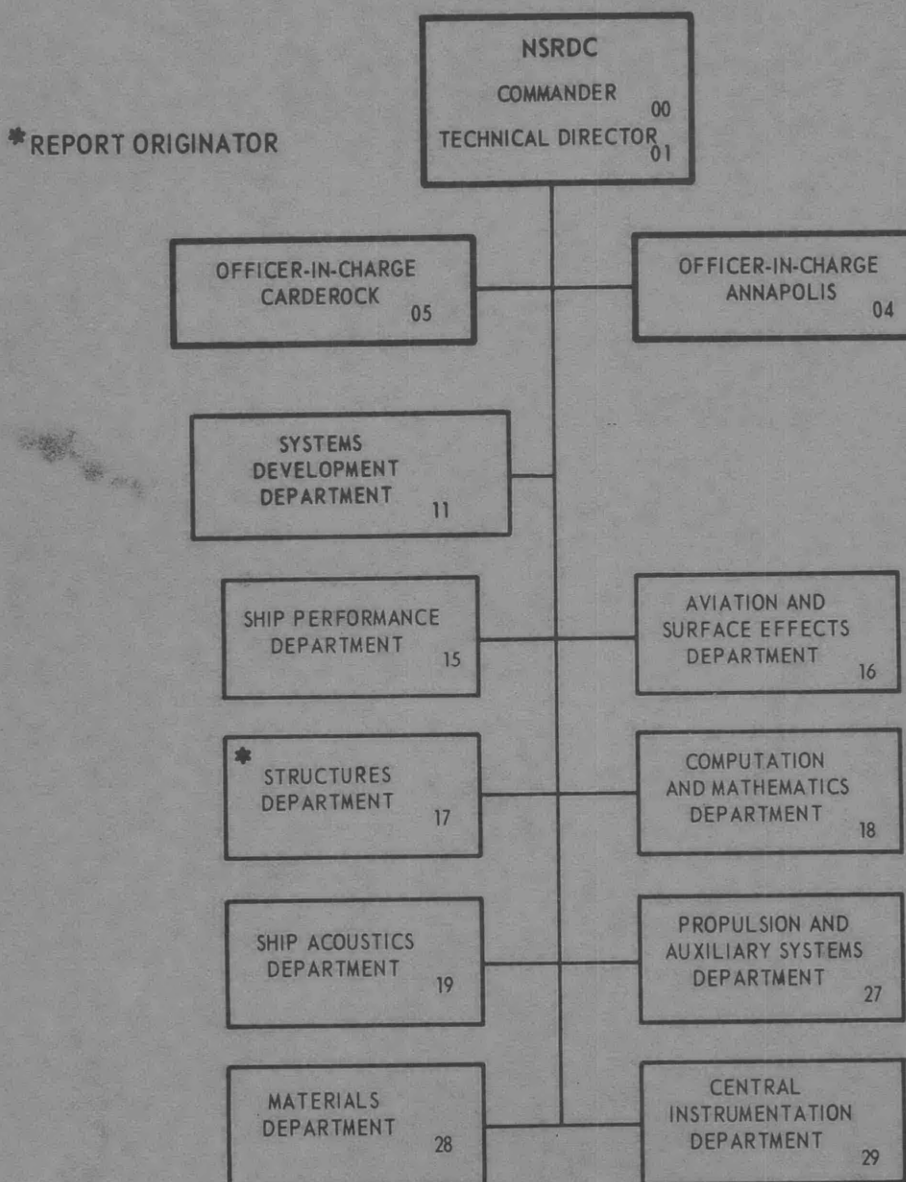

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ABSTRACT

Low cycle fatigue may be one of the controlling considerations in the utilization of new high strength materials in submarine hulls. This report outlines a program of experimental studies aimed at providing information germane to various aspects of structural fatigue evaluation.

The specimens described range from simple materials characterization types to complex butt and T-weldment structural elements. Materials of interest are HY-130, Ti-100, and HY-180. The report includes a discussion of the relation between various facets of analytical modeling of structural fatigue and testing goals for specific specimens.

ADMINISTRATIVE INFORMATION

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BACKGROUND

Naval Ship Research and Development Center (NSRDC) is pursuing the development of procedures for analyzing low-cycle fatigue of submarine hulls; the potential seriousness of low-cycle fatigue problems for high strength metal structures for future naval vehicles has recently been emphasized by Sorkin et al. (1972).*

A brief review of the "fail safe" design rationale underlying the development of analytical procedures is summarized below in order to establish the necessary frame of reference.

The most significant parameter both for the selection of material and for determination of surveillance procedures is damage accumulation, particularly during the first stage of fatigue life when cracks are relatively shallow with respect to shell thickness. The emphasis in design is on the minimization of crack initiation. This is in contrast to the alternate S-N curve approach where life is identified as cracking through the

*References are listed in alphabetical order beginning on page 71 entire thickness. The key premise in the "fail safe" design is that *in addition* to crack initiation, a limited amount of stable growth may be unavoidable and that such growth can be described in terms of loading and material data. It must be assumed that this crack growth occurs in welded joints of new high strength material loaded to realistic stress levels. It also follows that the structural integrity of the hull depends on rational surveillance and repair policies to preclude the growth of preexisting or newly initiated cracks to undesirable sizes. In this context undesirable crack size need not imply catastrophic failure following the next cycle. Instead, such crack sizes may be associated with a preestablished percentage of shell thickness well within the limits of crack growth prediction capabilities.

The probabilistic nature of structural fatigue is explicitly recognized in the formulation of combined mechanical-probabilistic models (Ang, 1972) for crack initiation and growth. Such models will permit the inclusion of statistical confidence levels in the prediction statements on fatigue performance. The implementation of such an approach clearly requires information on the range as well as on the mean values of important load, material, and fabrication variables. As a consequence, close coordination among material characterization, fabrication, inspection, loading history description, structural analysis, and service monitoring becomes a research need.

INTRODUCTION

This report is written in keeping with the spirit of an interdisciplinary approach to low-cycle fatigue. The aim is to provide general guidelines to the materials community regarding the type of information that is considered to be most useful not only for screening materials but also for the development and validation of analytical procedures. Although the ultimate application to submarine hulls has been emphasized, it is felt that the underlying rationale and the majority of the recommended specimens are equally applicable to high-performance surface ships.

A comprehensive approach to structural fatigue evaluation includes three closely related phases: (1) determination of the general suitability of a proposed new hull material, (2) development of fatigue design procedures, and (3) formulation of surveillance and maintenance guidelines. Materials of interest are HY-130, Ti-100, and HY-180. Ti-100 and HY-180 are currently considered largely in terms of the first phase, and the focus in the HY-130 program is on the development of fatigue design procedures.

Figure 1 provides a schematic framework for a discussion of the role of the experimental program outlined in this report within a comprehensive fatigue evaluation scheme.

The first phase of fatigue validation depends heavily on the testing of small-scale specimens and structural elements that contain weldments. Here, the emphasis is on screening of materials and joining procedures. Testing procedures are traditionally geared to the rapid generation of S-N curves, and no attempt is made to discriminate between crack initiation, stable crack growth, and terminal unstable growth (fracture). For the purpose of semiquantitative material/weldment comparisons, such distinctions may justifiably appear to be of only academic interest. However, for the purpose of the second phase aimed at the development of fatigue design procedures, the usefulness of a specific S-N curve depends largely on the extent to which N can be identified with macrocrack initiation, attainment of specific crack size, or fracture. This means that if small specimens are to provide a quantitative data base for fatigue analysis methodology, their testing and reporting procedures should be brought into accord with the recommendations contained in this report.

The specimens described in the section on baseline data serve a dual purpose. On one hand, they are intended to provide information on several facets of fatigue performance for screening/comparison purposes. On the other hand, such specimens can and ought to be used to provide a data base for the subsequent development of quantitative analytical methods.

Interim fatigue analysis procedures depend on the concurrent work in the analytical modeling, baseline, and experimental data provided by specimens listed in Tables 1 and 2. It is worth emphasizing that such specimens constitute the first--although by no means the last--step in the validation of analytical modeling. Assuming that testing programs for large-scale models include thorough stress analysis and fatigue damage (crack initiation and growth) monitoring of important details, such a program will play an essential role in the verification of interim analytical procedures. In the

TABLE 1 - BASELINE SPECIMENS

Specimen Type		Testing Conditions									Testing Goals						
General Description	Figure	Fluctuating Load	Fluctuating Deflection	Sustained Load	Sustained Deflection	Rising Load	Sustained K_I	Controlled ΔK_I	Air Environment	Saltwater Environment	Static Stress-Strain Response	Cyclic Stress-Strain Response	Creep or Stress Relaxation	Fracture	Crack Initiation	Crack Propagation	Comments
Smooth Round Bar Specimens	2, 5, 9		X	X	X	X			X		X	X	X	X	X		
Plane Strain Tensile	3					X								X			
Hollow Cylinder	10	X				X					X	X	X				Biaxiality effects on yield surface are of primary interest
Cantilever Plate	11		X						X	X					X		
Cruciform Plate	14, 18	X	X						X						X	X	Biaxiality effects on crack initiation are of primary interest
Tapered Double Cantilever Beam (TDCB)	17					X	X	X	X	X				X		X	May be modified for K_{Ic} or K_{Iscc} testing
Part-Through Crack Plate (PTC)	17	X		X		X	X		X	X				X		X	May be used for K_{Ic} or K_{Iscc} testing

TABLE 2 - ANALYTICAL MODEL VALIDATION SPECIMENS

Specimen Type		Testing Conditions								Primary Testing Goals										
General Description	Figure	Constant Amplitude	Complex Loading	Deflection Control	Axial Load Control	Flexural Load Control	Flexural K_I Control	Air Environment	Saltwater Environment	Crack Initiation	Crack Propagation	Surface Cracking	Internal Cracking	Notch Sensitivity	Biaxiality	Large-Scale Yielding	Weldment Effects	Residual Stress or Prestrain	Statistical Aspects	Comments
Smooth Round Bar	5		x	x				x	x	x		x						x	x	Used to evaluate cumulative damage theories on crack initiation
Notched Round Bar	22	X	X		X			X	X	X		X		X				X		
Notched Welded Cantilever Plate	23	X	X	X				X	X	X		X		X			X		X	
Prestressed Notched Beam	24	X				X		X			X	X				X				Primary interest is crack growth under compressive loading
Notched Hollow Cylinder	10				X					X	X	X			X	X				Primary interest is the influence of biaxiality and large-scale yielding on crack growth
Tapered Double Cantilever Beam Specimen (TDCB)	17		X				X	X		X	X									Used to evaluate cumulative damage theories on crack propagation based on constant amplitude data
Part-Through Crack Specimen (PTC)	17		X								X	X				X				
T- and Butt-Weldments under Flexural Loadings	26	X	X			X		X	X	X	X	X					X		X	
Butt Weldments under Axial Loading	28	X	X					X		X	X		X							Weld surface grinding is required

process of arriving at the recommended fatigue analysis, procedures shown in Figure 1 as the last element on the fatigue evaluation chain may require modification and updating of interim analysis procedures. On the other hand, a rational approach to testing procedures and interpretation of test results of large-scale models constructed from high strength steels should utilize interim fatigue analysis procedures, and the experimental program outlined in this report plays an indispensable role in their development.

Tables 1 and 2 represent an attempt at rough classifications of the test specimens and a general description of the type of information sought. Detailed explanation of various facets is found in the remainder of the report. It should be noted that the majority of the specimens are already considered to be a part of the materials-weldment characterization program or have been tested at some time either at universities or naval laboratories. Admittedly, the choice of the specimen reflects to a considerable degree the structural engineering background of the author and his view of the state of the art in fatigue and fracture analysis (Lomacky and Vanderveldt, 1972). Consequently, it is entirely possible that some aspect of small specimen testing has either been overemphasized or overlooked.

Hopefully, the report will generate additional dialogue between the structures and materials communities and lead in turn to improved fatigue evaluation procedures.

BASELINE DATA

GENERAL CONSIDERATIONS

The basic information needed for an analysis of fatigue and fracture performance at notches and cracks in structural elements may be classified as: (1) stress-strain relations, particularly plastic flow and fracture properties as observed on smooth specimens; (2) crack initiation and crack propagation data; and (3) an evaluation of fracture toughness evaluation in terms of fracture mechanics parameters.

Before various aspects of materials characterization are considered in greater detail, three general comments on testing and reporting procedures are in order:

1. The relatively low cost of baseline specimens should permit conducting a sufficient number of repetitive experiments to provide at least an approximate statistical estimate of the degree of variability of the test results. Such information is particularly desirable for developing the structural reliability analysis for HY-130 hulls; consideration of statistical aspects for Ti-100 and HY-180 could be deferred until the choice of these materials is finalized.

2. Although raw experimental data and specifics of the testing procedure may be omitted in the final test report, such information should be available on request. This is particularly important in crack propagation and toughness testing because in many respects analysis of resultant data has not been completely standardized. For example, reports on crack propagation characteristics often contain only the plot of crack growth rate versus stress intensity factor and give no information on the computational procedures used to reduce the raw data (crack size versus the number of cycles). The choice of a specific calculation procedure may turn out to be a significant factor, as discussed in a recent report by Frank and Fisher (1971).

Finally, although the design procedure ordinarily presumes isotropic behavior, the test sampling should ensure that any pronounced dependence on loading directionality can be recognized. This is particularly true for crack growth rate and/or toughness testing.

BASIC MECHANICAL PROPERTIES

Uniaxial monotonic tension and compression properties deduced from the axial loading tests of smooth round bars of the type shown in Figure 2 are ordinarily the first to be obtained as a part of a characterization program. Conventional (engineering) stress-strain and true stress-strain curve properties should be determined on parent metal and weld metal specimens.* Conventional properties include elastic modulus, proportional

*Such specimens should be machined from the interior of weldments, analogous to the procedure described by Van der Zanden et al. (1972).

limit, 2-percent yield stress, ultimate tensile strength, percent reduction in area, and percent elongation in specified length. True stress-strain characteristics of interest include true fracture ductility, true fracture strength, strain hardening exponent, and strength coefficient. Since ductility as measured by the standard round bar specimen may not correspond to the lowest limit of ductility, it is suggested that the plane-strain ductility be obtained. This can be achieved by the specimen shown in Figure 3 and described by Clausing (1970).

The usefulness of the above information is not restricted to the analysis of the stress-strain response corresponding to the rising load part of the first loading cycle. For example, the values of ductility and strain hardening exponent may also permit an estimate of fracture toughness K_{Ic} in the absence of specific fracture mechanics test data (Kraft, 1964; Hahn and Rosenfield, 1968; and Barsom, 1971).

Since the material to be used in service is likely* to be deformed during fabrication, the effect of tensile or compressive prestrain (on the order of 1 to 5 percent) on basic mechanical properties should also be investigated.

The effects of cyclic strains on the deformation properties must be considered in low-cycle fatigue analysis. These effects can best be appraised by the generation of cyclic stress-strain curve and by performing a monotonic tensile test to fracture on a material with cyclic deformation history. The cyclic stress-strain curve is generally obtained by connecting the tips of the stable hysteresis loops from several companion** specimens as shown in Figure 4. The specimens are generally smooth round bars tested under the condition of completely reversed (zero mean strain) strain.

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*Current specifications (NAVSHIPS 0900-006-9010, Section 9.3.1) imply that elongation in excess of 12 percent is permitted during fabrication.

**Testing techniques have recently been developed which permit an accurate determination of the cyclic stress-strain curve from a single specimen (Landgraf et al., 1969). Analogous to the monotonic data, the cyclic stress strain curves should be obtained for both the parent metal and weldments.

As shown in Figure 4, the cyclic stress strain curve may be either above or below the static curve, depending on whether the material is cyclic hardening or softening type as influenced by previous heat treatment and cold-working. Recent work by Morrow and Kitagawa (1972) shows a comparison of cyclic and static stress-strain properties; see Figure 5. The data were obtained from an HY-130 specimen and illustrate the cyclic softening effect. It should be noted that the softening behavior is also associated with HY-80, 10 Ni steels, and 621-Ti (titanium alloy). Tables 3, 4, and 5 compare static and cyclic properties of these metals.

It is desirable to conduct at least a limited number of such tests on weld metal specimens. Actually, as illustrated in Figure 6, the differences between the cyclic stress-strain response of parent metal and weldment may be quite small compared to the differences in static response.

The above information on cyclic stress-strain response was obtained under conditions of zero mean stress and strain, and it would be helpful to have information available on the phenomenon referred to as the mean stress relaxation. Studies on several materials have shown that under the condition of large-amplitude strain reversals about nonzero mean strain, significant mean stress relaxation may occur (Morrow et al., 1960 and Jhansale and Topper, 1971). This may be a significant factor for crack initiation sites at notches in submarine structural details with high initial (fabrication or load induced) tensile residual stresses. Figure 7 is an example of this phenomenon as observed by Morrow et al. (1960) on SAE 4340 steel in axial fatigue tests. The soft and hard conditions respectively correspond to yield stresses of approximately 123,000 and 222,000 psi. Note that for the material in the hard condition, mean stress relaxation is insignificant although as Morrow pointed out, generalizations to other materials may be unwarranted. An important application of the mean stress relaxation phenomenon may be in the generation of baseline crack initiation data in weldments. As will be elaborated on in connection with the generation of test data on crack propagation rates, the presence of unknown, initial residual stress clouds the interpretation of the test data. However, Figure 8 illustrates how an induced residual stress may be relieved by a plastic overstraining sequence, in this case 21 variable amplitude cycles.

TABLE 3 - MONOTONIC TENSILE PROPERTIES OF UNCYCLED SAMPLES

Property	HY-80	HY-130 (A)	HY-130 (B)	10 Ni	621-8 Ti[1]
0.2% Offset Yield Strength, ksi	92	143	141	171	111
Modulus of Elasticity E, ksi	29,800	28,800	29,500	27,400	17,500
Ultimate Tensile Strength S_u, ksi	112	150	146	205	118
True Fracture Strength σ_f, ksi[2]	228/191	271/229	262/222	337/286	152/142
True Fracture Ductility ϵ_f	1.14	1.05	1.04	1.04	0.39
Percent Reduction in Area %RA	68	65	65	65	32
Strength Coefficient K, ksi[4]	99/169[3]	168	166	307	148
Strain Hardening Exponent n[4]	0.012/0.132[3]	0.026	0.030	0.095	0.047

(1) Fracture occurred outside gage section.

(2) The first value is the load just before it suddenly decreased prior to fracture divided by the final area of the fractured specimen. The second value is corrected for triaxiality according to Bridgman.

(3) The first value represents the initial portion of the plastic strain-stress curve, i.e., for plastic strains up to 1 percent. The second value is for plastic strains from 1 to 10 percent

(4) These are used to relate monotonic strains to stresses (see footnote to Table 5 and replace n' by n and K' by K).

TABLE 4 - TENSILE FRACTURE PROPERTIES AFTER CYCLIC STRAINING

(Obtained by conducting a tension test after 1 1/2 blocks of incremental step testing)

Property	HY-80	HY-130(A)	HY-130(B)	10 Ni	621-8 Ti	Remarks
Ultimate Tensile Strength S_u, ksi	109	141	135	193	121	All metals necked except 621-8 Ti
True Fracture Strength σ_f, ksi*	218/184	283/237	253/212	314/266	151/143	*
True Fracture Ductility ε_f	1.10	1.15	1.09	1.05	0.34	---
Percent Reduction in Area %RA	67	68	66	65	29	---

*The first value is the load divided by the area at fracture. The second value is corrected for triaxiality of stress at the necked region using the Bridgman correction factor.

TABLE 5 - REPRESENTATIVE CYCLIC STRESS-STRAIN PROPERTIES

(Determined by averaging the cyclic stress-strain curves obtained during the increasing-decreasing block of incremental step tests at approximately half the fatigue life)

Property*	HY-80	HY-130(A)	HY-130(B)	10 Ni	621-8 Ti
Cyclic 0.2% Offset Yield Strength σ'_{ys}, ksi	73	112	110	150	95
Cyclic Strength Coefficient K', ksi	158	203	205	289	181
Cyclic Strain Hardening Exponent n'	0.12	0.095	0.10	0.10	0.10

*These properties may be used in the following equation for relating cyclic strain amplitude $\Delta\varepsilon/2$ to cyclic stress amplitude σ_a:

$$\Delta\varepsilon/2 = \sigma_a/E + (\sigma_a/K')^{1/n'}$$

The specimen can then by cycled to obtain baseline weldment data on cyclic stress-strain response and crack initiation as shown in Figure 6.

Creep and stress relaxation data in the temperature range of interest (20 to 150 F) have obvious importance for shell stability calculations; they may also be significant for crack propagation under sustained or cyclic loading, particularly with reference to titanium alloys. Figure 9 shows tensile creep relaxation test specimens used at NSRDC (Chu, 1969). Compressive creep data should also be obtained using suitable specimens designed to preclude buckling. Recent work by Krafft et al. (1972) points the way to eventual utilization of creep, monotonic and cyclic stress-strain, and general corrosion properties as generated on simple uniaxial specimens for the generation of crack growth data. Apart from providing a better understanding of the material behavior, such an approach would be more economical than the current practice of generating crack growth data from fracture mechanics specimens.

In design, stress biaxiality effects on plastic flow properties are ordinarily assumed to be related to uniaxial properties by the von Mises yield criterion. This is generally coupled with the use of isotropic hardening rule which ignores Baushinger effects. This is a convenient form for computer applications, but it may turn out to give an inaccurate representation of stress-strain response of materials under cyclic loading and creep conditions. Consequently, studies indicated in Misovec et al. (1972) but extended to cover loading-unloading and creep effects should prove useful for buckling analysis (particularly for Ti-100) as well as for fatigue. For this purpose, a specimen of the type shown in Figure 10 may be used. The introduction of a longitudinal or an axisymmetric notch may make the specimen useful for the study of biaxiality and large-scale yielding effects on crack initiation and growth in fatigue. This will be discussed further in connection with the analytical model validation studies.

CRACK INITIATION

The basic questions which need to be answered first concern the design of baseline specimens and the definition of crack initiation. The resolution of these questions depends on the manner in which baseline data are going to be used for fatigue predictions.

The rationale proposed for crack initiation analysis is as follows. First, smooth specimen data are obtained in the form of total strain range versus number of cycles to crack initiation. Second, the strain concentration factors for stress raisers at weldments are estimated and used to obtain the maximum strain range as a function of the applied strain range. Here, the stress raiser may refer to the external surface notch (in the form of weld undercut) or three-dimensional internal defects such as porosity or incomplete weld penetration. Finally, the crack initiation life at the stress raiser is assumed to be the same as for the smooth specimen for the same value of the strain (range). In this context, the crack initiation at a stress raiser would correspond conceptually to the same type of crack which one would detect in the laboratory specimen. Because of differences in detection capabilities, the size of the crack detectable in the laboratory specimen may not be detectable in a full-scale detail. Nonetheless, if crack initiation life corresponding to the formation of visual "laboratory detectable crack" can be anticipated, such information can be used in the crack propagation analysis to estimate the number of cycles required to develop larger, more readily detectable cracks in a full-scale detail.

In principle, the above approach is applicable to crack initiating from a subsurface, from three-dimensional defects, or from surface notches. Subsurface defects may be in the form of porosity or incomplete weld penetration; a typical surface notch is produced by the weld undercut. It is desirable however that the two types of baseline specimens be used; the information from such specimens will provide a good check on the generality of proposed analytical procedures.

The most appropriate baseline specimen for internal cracking problems is the smooth round bar represented in Figure 5 and tested under fully reversed axial strain control. Both base material and weldment specimens should be tested. As discussed earlier, a plastic prestraining sequence should be applied to weldment specimens in order to relieve initial residual stresses prior to constant amplitude strain cycling.

The most useful specimen for both weldment and base material characterizations of external cracking is the cantilever plate. The specimen was originally developed (Gross et al., 1953) to study the fatigue characteristics of the pressure vessel steels and is used extensively for crack initiation studies (Gross et al., 1953; Gross, 1963; and Boblenz and Rolfe, 1966 and 1967). Figure 11 shows a modified version featuring ground weldment. The specimen is cycled under fixed deflection control and results in a constant strain range cycling about zero mean strain at the specimen surfaces. During testing, the load should also be monitored since such data provide an indirect check on the cyclic stress-strain curves. Typically, the results are presented in terms of a log-log plot of the total strain range $\Delta\varepsilon_T$ versus Ni number of cycles to surface crack initiation Because of the presence of through-the-thickness linear strain gradient, one would expect such baseline data to be unconservative (due to the statistical volume effect) if used for axially strained members. However, this may be offset by the fact that the crack initiation predictions are to be applied to notches where strain gradients are likely to be much steeper than the linear strain gradients in the baseline specimen.

Crack initiation in the above specimen is defined rather arbitrarily as the appearance (visual inspection) of at least one crack of 3/16-in. length on the specimen surface. Work is underway at NSRDC to determine by sectioning of the specimen the range of crack depths and shapes corresponding to the above definition of crack initiation. It is noteworthy that despite the arbitrary nature of the above definition of crack initiation, preliminary results from another type of specimen indicate a fair amount of agreement. Specifically, Figure 12 contains HY-130 crack initiation data obtained from such a cantilever plate specimen and from a round bar specimen (shown in Figure 5) tested under axial strain control at the University of Illinois (Martin and Morrow, 1972). In the round bar specimen, crack initiation is identified with the occurrence of assymmetry in the stress-strain hysteresis loop, thus indicating only very indirectly the first appearance of a crack. Any generalizations would be unwarranted for the round bar specimens since only limited data are available. Clearly, more comparisons are needed for these two types of specimens. However, in view of the fact that crack initiation constitutes a major portion of the life of smooth specimens, it is tempting to speculate that a difference* in the definition of crack size corresponding to crack initiation is relatively insignificant.

The total strain range is felt to be the dominant parameter that influences crack initiation at notches. This motivates the use of a cantilever bend plate specimen (with and without a ground butt weld) as described above. There are, of course, other parameters which require at least an exploratory type of experimental study. We have already referred to the effects of strain gradient. Factors still to be discussed include environment, mean strain/prestrain, and strain biaxiality.

Environment effects refer specifically to the comparison of data in air and saltwater environments. Unfortunately, saltwater data on weldments appear to be extremely limited. As an example, the existing cantilever plate specimen data shown in Figure 13 for HY-130 weldments may suffice for qualitative comparisons to base material but not for any meaningful statistical interpretation.

It is expected that environmental effects may depend on testing frequency and wave form. Economic considerations may preclude testing at frequencies corresponding to the service conditions.** Nevertheless an attempt should be made to at least establish a trend with respect to these parameters. This problem also accentuates the need for the development of accelerated testing methods.

Although strain range is considered as the primary variable, mean strain effects*** should also be assessed. Here, the same type of cantilever baseline specimens can be used. Crooker and Lange (1967) have reported the

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*Admittedly, there are other differences between the two specimens which complicate interpretation of the results, e.g., difference in the through-the-thickness strain gradient and strain triaxiality.

**This aspect will be discussed more fully in connection with crack propagation characterizations.

***Note that we have used mean strain rather than mean stress. At structural discontinuities where significant cyclic plastic flow is expected to occur, mean stresses may shake down to zero.

effect of mean strain on surface crack propagation for a modified version of such a specimen. Alternately, the simpler (round bar) axial specimen shown in Figure 5 could be used.

Prestrain effects simulating the fabrication-induced "conditioning" of the material are not expected to be significantly detrimental except at lives in excess of 10^4 cycles. However, this assumption should be verified by conducting constant strain range tests following one cycle of prestrain on the order of ±1.5 percent. The same considerations for specimen selection apply as for the mean strain effect.

Finally, because of its width, the cantilever plate specimen features essentially a complete lateral restraint (plane strain conditions) at the midwidth of its surface. This is thought to be a fairly typical condition at notches. Nevertheless, it is conceivable that a condition of equibiaxial tensile strain could introduce higher "equivalent" strain* than is present in the cantilever plate specimen. Hence it is highly desirable to have an experimental investigation of the effect of strain biaxiality by means of a simple cruciform type specimen (Pascoe, 1969); see Figure 14.

CRACK PROPAGATION

General Considerations

Ideally one would like to be able to generate crack growth rate data analytically by using the information developed in the course of basic materials characterization or crack initiation tests described previously. Although a start has been made in that direction (Liu and Iino, 1969;

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*The equivalent strain is defined as

$$\varepsilon_e = \frac{\sqrt{2}}{3} \left[(\varepsilon_{11} - \varepsilon_{22})^2 + (\varepsilon_{33} - \varepsilon_{22})^2 + (\varepsilon_{33} - \varepsilon_{11})^2\right]^{1/2}$$

where ε_{11}, ε_{22}, ε_{33} refer to the principal strain components.

Tomkins et al., 1969; and Krafft, 1972) one is forced for the present to obtain crack growth data directly from precracked specimen tests. The correlating parameter for this case is the stress intensity factor range ΔK_I which can be used within certain limitations (see Lomacky and Vanderveldt, 1972) to correlate crack growth rates observed in laboratory specimens with the crack growth rates in full-scale structural details.

The acquisition of baseline crack growth data should be limited to base metal unless specialized techniques* are followed to relieve initial residual stresses. This may seem surprising in view of the previous discussion concerning the desirability of specimens containing ground weldments as a baseline crack initiation data. However, such difference in the approach may be rationalized by reference to the difference in roles of residual stress in crack initiation as compared with crack propagation phenomena. If it is agreed that crack initiation on a microstructural level is governed primarily by shear on favorably oriented slip planes, then the most important macroscopic variable is the total strain range. Initial residual tensile stress is reflected only through the mean strain effect; this may or may not be important depending on the particular life range. On the other hand, for crack propagation analysis in compressively loaded weldments, initial residual stress affects not only the mean stress level but also the tensile (opening) portion of the stress intensity factor range which is thought to be the primary cause of crack growth. Although the significance of the compressive part of the stress intensity factor curve (as will be discussed later) is not well understood,** it is nevertheless clear that in any crack propagation studies conducted on weldments, the residual stresses may vary between tension and compression through the thickness of the specimen. It follows that the results from a specific "baseline" welded specimen

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*As, for example, the use of a plastic prestraining sequence discussed in connection with Figure 8.

**It is expected, however, that treating the compressive part of the load cycle as fully effective may lead to excessively conservative results.

may be strongly biased by the peculiarities of a specific residual stress field gradients and maximum surface values. This is particularly true in situations where the residual stress is compressive; in this case, the crack growth rates measured in the heat-affected zone (H.A.Z.) may be significantly lower than in the base metal. Where the residual stress is tensile, it may be anticipated that the differences in growth rates between weldments and base metal are likely to be less pronounced; in this case, only the mean stress (and not the stress range) is affected by the presence of the initial residual stress.

In view of the above, crack growth rates obtained from a specific welded specimen cannot be used as baseline data. However, because of the relative insensitivity of crack growth rates in low-cycle fatigue to microstructure (specifically to such differences as may exist between base metal, H.A.Z., and weld metal), it is felt that crack growth data obtained from base metal can be used to the first approximation for a conservative prediction of growth rates in weld metal and heat-affected zones.* The conservative aspect is introduced by making simplifying assumptions with respect to the magnitude and through-the-thickness gradients of the initial residual stress.

The effect of overall cyclic prestraining on crack propagation rates in base materials is worthy of separate investigation. It could turn out that at sufficiently high cyclic stress levels, previous cyclic damage to the material could produce a higher crack propagation rate than would otherwise be observed.

Service loading history features a variety of combinations of fluctuating and steady stress components as well as a variety of frequency

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*Studies of crack growth in base materials, weldments, and heat-affected zones have shown either that the growth rates fall within a fairly narrow scatter band (Maddox, 1969 and Dowse and Richards, 1971) or that the growth rates in base metal were significantly higher than the growth in the weld metal (Clark and Kim, 1970 and Parry et al., 1971) and heat-affected zone (Parry et al., 1971). Lower growth rates in weld metal and heat-affected zones were attributed by Parry et al. to the presence of favorable residual stress; Clark and Kim suggested that in addition to the residual stress effect, metallurgical differences between weld and base metal may also be a significant factor.

and wave forms. For the purpose of cumulative damage analysis, it is necessary to consider the possibility of crack growth under sustained loading tests; the aim is to establish the "threshold" level of stress intensity factors (corresponding to "critical" crack size-stress combinations) below which no crack growth is expected to occur, at least within the time interval of interest. If the maximum tolerable crack sizes (governing frequency of inspection and repair intervals) are selected in such a way that these thresholds are not exceeded, then the problem of growth under sustained loading can be excluded from further design considerations. In this sense, the threshold values can be regarded as a measure of maximum crack tolerance of the structure. Consequently, we shall defer discussion on the growth under sustained loading until the section on fracture toughness. In what follows we shall first discuss various aspects of testing for crack growth under constant amplitude cycling and assume that the maximum stress-crack-size combinations are kept below such critical (threshold) values.

Crack Growth Rate Characterization

The type of information that is typically sought is shown schematically in Figure 15 on log-log plot. The ordinate represents the crack growth rate expressed as da/dN (inches per cycles) and the abscissa is the range of stress intensity factor ΔK_I. Several values of crack depth (a) - applied stress range ($\Delta\sigma_\infty$) combinations corresponding roughly to the range of ΔK_I between 10 and 100 ksi $\sqrt{in.}$ are also shown.*

Before discussing in greater detail how the above information is to be generated, several general features of the curve should be noted. Typically, the shape of the curve is sigmoidal with the central linear segment bounded by curves which appear to be asymptotic to vertical lines which represent a very low and a very high ΔK_I value. For reasons to be discussed below, only the central portion of the curve corresponding typically to growth rates between 10^{-6} and 10^{-4} in./cycle is of interest to the

*For this calculation, we assumed a long shallow flaw for which $\Delta K_I = 1.1\ \Delta\sigma_\infty \sqrt{\pi a}$ where $\Delta\sigma_\infty$ is the applied stress range.

designer. In any experimental program the upper and lower transition points corresponding to the departure from linear behavior need to be at least approximately defined to permit an assessment of the range of validity of the curves fitted to the data in the central region. For some materials interpretations of the results obtained from an electron fractography study (Bates and Clark, 1968) of fracture surfaces may be quite useful for this purpose as well as to elucidate fracture mechanics and crack growth under complex loading (McMillan and Hertzberg, 1968). Consequently, the study of the degree of correlation between macroscopic and microscopic growth rates should be included as a part of the materials characterization program. Here, the macroscopic growth rate is obtained from the visual observations of the crack front; the microscopic growth rate is calculated from the striation spacings obtained from fractographic examinations.

The lower asymptote corresponds conceptually to the threshold values; ideally, cracks will not propagate for values of ΔK_I lower than the threshold ΔK_I analogous to the concept of endurance limit in high-cycle fatigue. Unfortunately, there are two factors which mitigate against the usefulness of this concept for low-cycle fatigue analysis of weldments. First, the determination of threshold values requires an extremely painstaking experimental procedure. Second, such threshold values for weldments are likely to be extremely low; values as low as $\Delta K_I = 2$ ksi $\sqrt{\text{in.}}$ have been reported for weldments in mild steels (Frank, 1971). This may be due to the sensitivity of the threshold values to high mean stresses (Paris et al., 1971) which, in turn, may depend strongly on the highly indeterminable, initial residual stresses. The upper portion of the curve corresponds to the transition to the accelerated growth; this situation should be avoided in service by appropriate maintenance procedures requiring repair of cracks before the transition region is reached.

Figure 15 represents an idealized situation featuring one-to-one correspondence between the growth rate and the stress intensity factor range. Actual data for a specific material exhibit scatter, for example, as shown in Figure 16 for HY-130.* In general scatter may be due to any

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*This represents preliminary compilation of data at Naval Research Laboratory (NRL) by Crooker and Krause. Work is currently underway both at NRL and NSRDC to evaluate the effect of mean stress and applied stress/yield stress ratio.

combination of the following factors: (1) specimen geometry and thickness, (2) mean stress effect, (3) ratio of applied stress to yield stress, (4) chance variations in material and testing procedures, (5) stress biaxiality, and (6) environmental effects, specifically the saltwater environment. Fortunately, at least for HY-130 steel, the dependence on the first factor is relatively minor in contrast to the situation which may be expected in fracture toughness characterizations.

Economic considerations ordinarily preclude the generation of baseline data in saltwater at the cyclic frequencies of interest. Consequently, as in the case of crack initiation characterizations, it is proposed that the baseline data by obtained in air and that the trends due to the environmental effects be established by a limited number of tests.

Deferring the discussion of saltwater effects, let us now consider some of the specific aspects that need to be considered in the generation of baseline data in air. Typically, what is needed is a plot (similar to that shown in Figure 16) which includes an assessment of the effects of the first four factors listed above.

Concerning the specimen type, it is recommended that at least for zero to tension loading, duplicate data be generated from tapered double cantilever beam (TDCB) and part-through crack (PTC) specimens shown in Figure 17. Such an approach is beneficial for several reasons. Good agreement of the data (as for example in Figure 16) obtained from diverse specimens stengthens the validity of ΔK_I as a correlation parameter. Further, each specimen has special advantages. Thus, the TDCB specimen permits direct observation* of crack depth as well as rapid generation and analysis of data under constant ΔK_I control. If the initial notch geometry and number of cycles to crack initiation are recorded, such a specimen can also serve as a useful source of crack initiation data. On the other hand, the PTC specimen is more representative of the type of cracks found in structural details. Further, when combined with sectioning of selected PTC

*Making some allowance for the crack curvature which may occur in the thickness direction of the plate.

specimens, such an experimental program may be used for much needed statistical assessment of current NDT capabilities (Packman, 1968). Finally, a PTC specimen offers advantages for the study of biaxiality and large-scale plasticity effects to be discussed below.

The generation of baseline data has been described above for zero to maximum tension cycling and small-scale yielding conditions. A separate investigation is needed to permit an assessment of mean stress and large-scale plasticity effects, in other words, of what may be considered extremes in the conventional laboratory testing conditions. This is important because such extremes in laboratory testing may, in fact, be fairly common under service conditions and thus put to a severe test the validity of a simple da/dN versus ΔK_I relationship obtained under specific laboratory testing conditions.

Studies of mean stress effect should include high positive and negative R ratios.* High positive R ratios simulate the conditions of high tensile residual stress and shallow depth submergence. By contrast, high negative R ratios simulate deep submergence and low tensile residual stress. Although exceptions have been noted (Griffith et al., 1971) the general effect of increasing positive R ratios is to increase the growth rate at a given ΔK_I. It is often assumed that for negative R values, the crack is *fully* closed** during the compressive portion of the load cycle and that only the tensile part of the load should be considered as effective in the sense of promoting crack growth. This implies that for the same positive ΔK_I,*** growth rates for negative R ratios can be expected to be the same as for R = 0 data. Unfortunately, this assumption is not borne

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*$R = (K_I)_{min}/(K_I)_{max}$ where $(K_I)_{max}$ and $(K_I)_{min}$ are respectively the maximum and minimum stress intensity factors of the cycle.

**Judging from the experimental studies conducted by Bowles (1970), this assumption is not valid, at least for some materials. Similar studies for materials of interest to the Navy should be very helpful in providing needed information on this aspect of the problem.

***For negative R ratios, K_I would be computed only from that fraction of the stress range which corresponds to the tensile portion of the cycle.

out, at least for some high strength materials. Specifically, Crooker (1971) reports a 50-percent increase in fatigue growth rates due to tension-compression (R = -1) cycling for 9Ni-4Co-0.20C and HY-80 steels as well as for Ti-6Al-4V titanium alloy. More recent work on HY-130 (reports in preparation by Crooker and Krause at NRL and DeYoung at NSRDC) also indicates an effect of the compressive part of the load cycle. Hence, one can expect an increase of growth rate with increasing negative R ratios although this effect may be rather slight in comparison with the effect of increasing positive R ratios.

Plasticity effects are best studied by means of PTC specimen with very shallow flaws. High R and low ΔK_I values would result in very large *monotonic* plastic zones; low R and high ΔK_I values would produce large monotonic *and* cyclic plastic zones. Such extremes may be thought of as simulating the service conditions in early portion of the fatigue life of submarine pressure hull detail with the first corresponding to very shallow and the second to very deep submergences.

Stress biaxiality may influence crack propagation rates at least for some materials as shown in the recent experimental work of Kibler and Roberts (1970). Specifically, results on 6061-T4 and 6061-T6 aluminum sheets obtained on the specimen shown in Figure 17 indicated a distinct shift in crack growth rate data depending on the magnitude of tensile load parallel to the crack. The tests were limited to biaxial tension loading; this led to growth rates that were lower than for the uniaxial case for the same value of the fluctuating stress component normal to the crack face. One can conjecture that biaxial tension-compression may produce the opposite effect, i.e., higher growth rates. For this reason it is recommended that biaxial test data be obtained for materials of interest by means of a specimen similar to that shown in Figure 18.

Environmental effects on crack propagation are likely to depend very strongly not only on the type of environment but also on testing frequency (Gallagher, 1970; Barsom et al., 1971; and Ryder and Gallagher, 1972). Temperature (Ryder and Gallagher, 1972) and wave form (Barsom, 1971) constitute two additional variables. The general expectation is that the growth rate in saltwater is higher than in air and that the difference should increase with decreasing frequency and increasing temperature. Test frequency effects are illustrated in Figure 19 for HY-130 steel in simulated saltwater environment (3 1/2 percent NaCl solution). At the highest testing frequency of 2.5 Hz (2.5 cps), the results approach the results obtained in air (not shown on Figure 19); in general the air data were relatively unaffected by test frequency.* It is worth noting that the frequency of 0.05 Hz is roughly within the range that may be used for large-scale model testing but that the lowest frequency (0.005 Hz) is still two orders of magnitude higher than the loading rate that can be expected in service.**

In view of the above, it is clear that generation of baseline air data is not sufficient and that an assessment of saltwater effects at frequencies relevant to large-scale model testing programs and service conditions is essential. Obviously, testing at extremely low frequencies for the full range of ΔK_I is economically impractical. An alternative approach is to obtain baseline data in air (analogous to the information presented in Figure 18) and then to study the saltwater effects at several ΔK_I levels. The objective of such testing should be to estimate the frequency range at which the environmental effect reaches an upper limit with respect to the air data.*** It is also worth exploring a possible connection between such upper limits observed in low frequency cyclic tests and tests aimed at the determination of K_{Iscc} threshold values (to be discussed later) under sustained loading. Further, as mentioned earlier, the effects of wave form, hold time, and temperature merit additional consideration.

The usual procedure for simulating saltwater in the laboratory is to use 3.5 percent NaCl solution. This solution may be changed frequently in

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*With the possible exception of extremely high frequencies where inertial effects may become important.

**This may be on the order of one submergence cycle per day.

***For example in the study of HY-80 steel, Gallagher (1970) found that the upper limit occurred at 0.01 Hz for high ΔK_c and at 0.1 Hz for low ΔK_I. Ryder and Gallagher (1972) speculate that the limit for HY-130 steel may be reached at frequencies below 0.001 Hz.

order to maintain the pH and the salt concentration at a specific level. What needs to be established is the extent to which such simulation represents the range of variation in the electrochemical potential and pH in natural seawater and pressure tanks and, more specifically, the effects of such variations (including the effect of marine life) on stress corrosion cracking.

FRACTURE TOUGHNESS

General Considerations

Our concern so far has been with the generation of baseline data to be used for the analysis of crack initiation and stable growth. We will now discuss the type of basic information needed for a design estimate of the significance of crack sizes. For example, we may wish to compare for a specific number of load cycles or elapsed time in service the crack size predicted from crack initiation/propagation analysis with several alternative measures of the "critical" crack size. Alternately, we may wish to assess the design severity of cracks discovered during routine surveillance. Here, one might consider several toughness measures deduced from laboratory testing on precracked specimens--generally under the conditions of rising tensile load. Before such measures are discussed in greater detail, two general observations ought to be made. The first concerns the relevance of tensile load data to compressively loaded submarine structures; the second concerns the possibility of estimating "critical crack" size from considerations other than fracture toughness testing.

Tensile load results are relevant because localized tensile restraint can be introduced in a compressively loaded pressure hull during fabrication procedures. Consequently a crack that grows in fatigue could--at least in theory--become unstable as a result of interaction of crack depth and residual tensile stress field. Also, secondary structures attached to the hull may be subjected to applied tensile stress while the primary hull is undergoing submergence loading.

"Critical" crack size may be defined by considerations other than the results of toughness testing. From this point of view, maximum acceptable crack sizes can be defined in a way which would preclude the possibility that such cracks become unstable, i.e., leading to fast fracture on the very next load cycle. One may choose to define depths larger than a specific small percentage of shell thickness simply as an undesirable event to be avoided either because of ensuing "fast" growth rates (requiring excessive frequency of inspections) or because of increased uncertainties inherent in the mathematical analysis of deep flaws. This approach seems particularly attractive for tough materials such as HY-80, HY-130, Ti-100, and HY-180. Specifically, in the case of HY-130 steel, the transition from slow to accelerated growth (greater than 10^{-4} in./cycle) takes place at $\Delta K_I = 100$ ksi $\sqrt{in.}$ as shown in Figure 15. Assuming the design stress as 80 percent of static yield, we would then restrict the maximum permissible crack depth for the design life of the detail to about 0.25 in. Of course for this approach to be feasible, the da/dN plot should be obtained for ΔK_I values which are sufficiently high to identify the onset of transition regions.

If what constitutes a catastrophic crack size in service is determined on the basis of fracture toughness indices for steels of interest obtained from laboratory testing, the result is likely to be highly imprecise. The limitations of linear elastic fracture mechanics coupled with uncertainties regarding the state of residual tensile stress and degree of stress triaxiality are likely to play a significant role even though the same factors play a relatively minor role in crack propagation. On the other hand, alternative measures of toughness based on elastic-plastic fracture mechanics are still in the development stage. Fortunately, a great deal of precision may not be necessary in view of the fact that--at least conceptually--the linear-elastic fracture mechanics approach does provide a lower bound on fracture toughness under conditions of contained plasticity. Let us assume, for example, that it can be anticipated on the basis of an admittedly crude linear fracture mechanics analysis and over-conservative toughness data that even the development of a through-the-thickness flaw in the external pressure hull will not lead to rupture for a given material. This, in fact, is likely to be the case for materials of interest for submarine hull application although not enough data are available in weldments to reach the same conclusion. In such a case, there does not appear to be much point in pursuing refinements in analysis and testing procedures aimed at the determination of the *length* of the through-the-thickness flaws which could eventually lead to fracture in the form of unstable crack propagation. In general, what does need to be established is that linear elastic-fracture mechanical provides an *acceptable* degree of conservativeness for a specified material and structural detail. However, this problem is more likely to be resolved by design optimization, tradeoff studies, and cost of surveillance/repair policies than by material characterization tests. Likewise great precision is not required in the screening type materials comparison; as indicated in Figure 1, this stage in fatigue evaluation precedes the development of design procedures.

In what follows we shall discuss several toughness indices which--at least in principle--can be used directly in design. This means that they can be expressed in terms of combinations of permissible crack size and applied stress. We shall restrict the discussion to quasi-static aspects of toughness; the dynamic aspects of toughness are outside the scope of this report. It should be noted in passing that the dynamic aspects include not only *initiation* of crack extension under external dynamic loading but also crack arrest aspects under static loading. As a consequence, crack arrest toughness values for baseplate material may be needed to appraise the possibility of crack arrest following unstable propagation of cracks initiated in embrittled weld regions.

Fracture Toughness in Air, K_{Ic}

The choice of fracture indices may include (1) plane strain fracture toughness K_{Ic},* (2) plane stress fracture toughness K_c, (3) critical crack opening displacement COD, (4) critical value of J integral, and (5) R-curve characterization. The choice appears to be fairly wide, but for reasons to be discussed later, K_{Ic} is by far the most useful design parameter for submarine hull application despite its considerable limitations.

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*As specified in the ASTM requirements (STP 410, 1966) for plane strain K_{Ic} testing.

Although K_{Ic} testing has been standardized and related to such energy-based measures as the Charpy and dynamic tear tests (Pellini, 1969, and Corten and Sailors, 1971), alternate indices intended to extend fracture mechanics into the large-scale yielding domain are still within the developmental stage. Recent interest in the J integral concept (Begley and Landes, 1971 and Rice et al., 1972) stems to a great extent from the possibility that K_{Ic} can be determined from small-scale specimen tests where restrictions can be relaxed on the amount of crack tip plasticity in relation to crack size and principal specimen dimensions. Its practicality as a *design* parameter for surface cracks in complex details is still unexplored. The same is true of the COD concept presently under intensive development in England; see proceedings of the symposium sponsored by the Atomic Energy Authority on fracture toughness concepts. Here the aim is to provide a means of characterization and selection for those materials and weldments which exhibit significant plastic deformation before fracture. The application of either the COD or J integral concept in design would require further development of (simplified) elastoplastic analysis techniques; presently these are largely limited to two-dimensional crack problems and would require an application of numerical methods for complex configurations.

Concerning the K_c concept, it should be recognized that plane stress fracture toughness is a mathematical fiction which can be approached only in the foil thickness range. In practice, fracture toughness K_c must be obtained from full-thickness specimen testing; pending further developments in three-dimensional fracture analysis, the interpretation of such values in design where flaw configuration and plate thickness may differ from laboratory conditions is now largely a matter of conjecture.

The indices mentioned so far are concerned with predicting onset of crack *initiation** under sustained loading. The R-curve concept (Pellini

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*In fact this constitutes a limitation of such indices for tough materials since the onset of crack initiation is not immediately followed by load instability. The very difficulty of determining the onset of crack initiation in thick specimens may also be particularly troublesome for J integral development.

and Judy, 1970) admits a more realistic approach to ductile fracture because it makes provision for some stable crack growth under sustained loading *preceding* general fracture instability. However, as in the case of K_c determination, R-curves must be generated for specific plate thicknesses. Further, the design implementation of such an approach (requiring a fairly complex structural analysis) appears presently to be feasible only for thin plates with through-the-thickness flaws.

In view of the above limitations of J integral, COD, K_c, and R-curves for quantitative *design* application to submarine hulls, it is imperative to reexamine two objections which may be raised against the use of the K_{Ic} concept for tough hull materials of current interest.

First, there is the obvious difficulty of measuring K_{Ic} for such materials with reasonably sized specimens. However, the development of J integral concepts, COD, or the recently introduced equivalent energy concept (Witt and Mager, 1973) is encouraging for the determination of valid K_{Ic} from undersized specimens. Also, it may be possible to estimate K_{Ic} from the knowledge of basic mechanical properties (Krafft, 1964; Hahn and Rosenfield, 1968; and Barsom, 1971).

Second, the applicability of linear elastic fracture mechanics may be a questionable tool for predicting fracture based on small flaws in tough materials. This is because such cracks may be surrounded by plastic zones which are by no means insignificant in terms of their relationship to crack size and shell thickness dimensions. In fact, this condition resembles the test conditions for K_{Ic} determination from specimens with insufficient in-plane dimensions; as pointed out by Novak (1972), such specimens underestimate the true K_{Ic} value. On the other hand, the *possibility* of limited ductility in welded details due to specific conditions of mechanical constraint, previous embrittlement* resulting from

*The deleterious effect of prestraining has already been demonstrated for the notch behavior of normally tough mild steel (Mylonas and Kobayashi, 1969 and Mylonas and Beaulieu, 1969).

fabrication procedures, etc. cannot be entirely ruled out. What is important is that, conceptually, K_{Ic} denotes the lower bound of fracture toughness. This means that for a specified design stress, the estimate of critical crack sizes will be conservative provided that such cracks are located at the areas of high strain concentration, i.e., in the regions of highly localized plasticity. This also assumes that K_{Ic} values are generated for base metal and metal/weld combinations on the basis of tests which include an appraisal of possible embrittlement mechanisms resulting from fabrication processes.

Finally, it is worth noting additional aspects of the K_{Ic} determination for design use as contrasted to the determination of valid K_{Ic} for material comparisons. Normally, the fatigue precracking stress is kept fairly low in specimen preparation in order to avoid biasing effects on K_{Ic}. For low-cycle fatigue analysis, however, a knowledge of K_{Ic} as influenced by previous fabrication and loading history is required in order to determine the crack size which will terminate fatigue life. Hence there is need for a separate determination of K_{Ic} with and without initial prestrain for base material and weldments although, admittedly, the biasing effect of the initial residual stress may affect weldment results. Second, an appraisal of the effect of *high* cyclic precracking stresses should be studied. This effect may turn out to be important in cyclically softening materials (Miller and Morton, 1971). Possibly some of this information could be culled from the testing program for da/dN versus ΔK_I determination by judicious design of the crack propagation specimen, the recording of critical crack size, and fractographic observations of fracture surfaces.

Fracture Toughness in Saltwater, K_{Iscc}

The parameters of primary interest are K_{Ih} and K_{Iscc}. Both refer to the plane strain toughness as measured on the precracked specimens in a saltwater environment. In addition, an applied electric potential is used for K_{Ih} determination to promote crack tip hydrogen embrittlement in susceptible steels. For materials which are susceptible to stress corrosion and/or hydrogen embrittlement, K_{Iscc} or K_{Ih} may be significantly lower than K_{Ic} obtained in an air environment.

It should be emphasized that the onset of crack growth under sustained loading is not synonomous with catastrophic crack extension. In fact, crack initiation and subsequent growth in welded structural details may be followed by crack arrest. This may occur because of a change in material properties and/or residual stresses at the crack tip in the course of crack extension. Nonetheless, the occurrence of stress-corrosion cracking should be avoided if for no other reason than to preclude undesirable acceleration of fatigue cracking. Such accelerated fatigue growth may result from coupling (Wei and Landes, 1969 and Gallagher, 1970) of sustained load and fatigue cracking where the maximum stress intensity of the cycle is above the K_{Iscc} limit.

In what follows we shall discuss several aspects of K_{Iscc} testing. Similar considerations also apply to the determination of K_{Ih}.

Conceptually, K_{Iscc} corresponds to a specific combination of crack size and applied stress below which crack extension under sustained loading will not occur.* Unfortunately, in contrast to the determination of K_{Ic}, the testing procedures for K_{Iscc} are yet to be standardized with respect to three primary variables: geometrical, time, and environmental effects.

The satisfaction of plane strain conditions for geometrical effects is considered to be at least as important as in the use of K_{Ic} determination. Depending on the inplane and thickness specimen dimensions, the apparent K_{Iscc} may underestimate or overestimate the intrinsic value. In a recent paper, Novak (1972) has outlined a tentative procedure for estimating the measurement capacities of a particular specimen geometry for obtaining a valid K_{Iscc}.

The situation is no less complex for time effects (Wei et al., 1971). Most of the reported data were obtained for testing times of less than 10,000 hr, and occasionally the tests are terminated before 100 hr. It is known, however, that short testing times may mask incubation (crack initiation) effects (Wei et al., 1971). Obviously for submarine applications where economic inspection intervals may be on the order of 5 yr, conclusions drawn from the results of short-time laboratory tests may promote a false sense of security. For this reason, K_{Iscc} test results should preferably be accompanied by crack growth kinetics data (Wei et al., 1971) indicating

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*At least, no growth is expected within the specified testing time.

the rate of crack growth da/dt (crack extension per unit time interval) as a function of the initial stress intensity factor K_I. An example of this type of data is shown in Figure 20.

Environmental considerations concerning the simulation of saltwater in laboratory testing for fatigue crack growth rates, as discussed on page 24, apply equally to the determination of K_{Iscc}.

Finally, the effect of plastic prestraining on the K_{Iscc} of Ti-100 should be explored; Novak (1972) has studied this effect for HY-80, HY-130, and HY-180.

Creep Effects

Cracking under constant load in nonaggressive environments at room temperature has been attributed to creeplike deformation processes at the crack tip. Landes (1970) recently noted this type of behavior in AISI 4340, H-11 tool steel, and 18Ni (300) maraging steels tested in a dry argon environment; a previous reference to this topic is contained in Johnson and Paris (1968). It was first believed that this type of growth is confined to conditions approaching plane stress as would be the case for through cracks in thin plates. However, more recent work (Crooker and Griffis, 1972) indicates that the possibility of crack growth under sustained loading in air environment exists also for part-through crack specimens* where the conditions at the crack tip approach plane strain. This finding may have serious implications for submarine hulls constructed from materials which exhibit this type of growth even under plane strain conditions.

Figure 21 presents the data obtained by Crooker and Griffis (1972). The initial stress intensity factor K_{Ii} is plotted against the time to failure under constant load. Data are shown from both part-through-crack (PTC) and single-edge notched (SEN) bend specimens. The following observations are of particular interest. First, there was a strong influence of

*Admittedly, environmental effects cannot be ruled out since the tests have been conducted in air and not in an inert environment such as used in the Landes (1970) tests.

specimen geometry and/or anisotropy. Here, anisotropy was introduced by the difference in the orientation of crack plane with respect to the rolling directions between PTC and SEN specimens. Second, there was a significant degradation in toughness compared to that measured under rising load at time t = 0. Finally, the authors state that the threshold value of K_{Ic} represented by the horizontal portion of the curve was only an apparent threshold because some crack extension occurred in every specimen although final fracture was not reached in every test.

Clearly, further investigation of the above phenomena is needed at least for titanium alloys. A comparison of the above threshold values with the K_{Iscc} values measured under stress corrosion cracking would be of interest. For plane stress conditions, Landes (1970) formulated a model based on the Krafft ligament instability concept and uniaxial creep data (Krafft, 1964; Krafft, 1967; and Krafft et al., 1972) which predicted results in good agreement with his experimental data on AISI 4340 steel. However, plane strain conditions were more representative of the type of cracks found in pressure hulls and so the applicability of the Landes work is rather uncertain.

DATA FOR ANALYTICAL MODEL VALIDATION

GENERAL CONSIDERATIONS

The first part of the report dealt with the acquisition of baseline data. Such data may be sufficient for material screening purposes and a crude estimation of the fatigue performance of full-scale hulls. However, because of the multiplicity and interplay of factors that must be considered in a large-scale hull model, it is preferable to *start* the validation (and, where necessary, a modification) of many detailed aspects of the analytical approach on simplified specimens and structural elements. Here, the level of complexity can be gradually increased in terms of the specimen geometry, fabrication, or loading history. The effect of important parameters can be accentuated if not entirely isolated; this should permit an assessment of the degree of oversimplification that results from the application of specific baseline data and specific simplifications inherent in analytical modeling.

The specimens to be tested to analytical model validation (Table 2) cover a wide spectrum of specimen geometry and loading conditions. On one end of the spectrum, we consider smooth and round bar specimens tested under complex loading for the primary purpose of eliciting information on the degree of applicability of crack initiation data under constant amplitude. On the other end, we consider full-thickness weldments where most of the complexities present in the complete hull can be studied. Admittedly, the ability to cover the full range of restraint stresses, fabrication-induced cracking or embrittlement, and loading history representative of a full-scale hull is obviously limited even with such complex specimens.

Table 2 indicates that in several instances diverse specimens are proposed to obtain information on some specific facet of fatigue. Where this occurs, the table implies options in the choice of specimens. However it must be emphasized that although testing of diverse specimens is not essential, it is nevertheless very desirable for the purpose of checking specimen independence and hence the generality of the analytical approach.

For pupose of the subsequent discussion, it will be found convenient to group the specimens listed in Table 2 according to the following scheme: (1) smooth and round bars under axial loading, (2) notched, welded cantilever plates, (3) fracture mechanics specimens under complex loading, (4) notched beams and cylindrical tubes, (5) T-fillet welded beams, and (6) butt-welded beams and plates. We shall now examine some of the specific aspects of each group with reference to the testing goals and general features of specimen design and testing procedure. Within that context, we shall also discuss the interrelationship between various specimens and relevant baseline information (described in the first part of the report) to be used in the interpretation of the test results.

ROUND BARS

This group is comprised of the smooth bar shown in Figure 5 and two types of notched bars shown in Figure 22.

As indicated in Table 2, the primary purpose of the smooth specimens is to obtain data for a preliminary evaluation of several approaches to cumulative damage (as, for example, the Miner rule) with respect to crack initiation. Prestraining effects leading to initial residual stresses should also be studied. The low cost of these specimens should permit a sufficient number of tests for subsequent statistical interpretations of the results. Relevant baseline data (discussed in the first part of the report) are obtained from (1) cyclic stress-strain curves, (2) constant strain amplitude crack initiation, and (3) mean strain effect and stress relaxation. The testing should be conducted under deflection control with the strain-time spectra analogous to the stress-time spectra shown later in Figure 25 in connection with the crack propagation studies under complex loading.

The two types of round notched bar shown in Figure 22 reflect different testing objectives and consequently their size and testing conditions differ.

The primary purpose of the Type 1 specimen tested under deflection control is to provide a checkpoint on the notch strain analysis and ample data on notch sensitivity relating to crack initiation under constant amplitude. The specimen represents a modification of that shown in Figure 5 in the form of axisymmetric, circumferential notches of varying geometry. Notch geometry is controlled by root radius ρ and notch depth h. The bluntest notch should be designed to permit placement of strain gages in the longitudinal and circumferential directions and the monitoring of local strain history until cyclic stabilization occurs. Visual observation of crack initiation should be accompanied by sectioning of a number of specimens for an estimate of the size of the initiated crack. Relevant baseline data are the same as for smooth bar specimens discussed above. In addition, the smooth bar data should elucidate notched bar test results under complex loading conditions.

The primary purpose of the Type 2 specimen is to obtain data on crack propagation phenomena under compressive *load* fluctuations in the presence of high residual tensile stresses resulting from cyclic notch plasticity. A secondary objective is to obtain crack initiation data for comparison with results obtained on a much smaller specimen represented by Type 1 tested under different strain control conditions. Specimen dimensions correspond to those tested by Pickett et al. (1964) for the study of crack initiation and growth phenomena in HY-80 under compressive loading. As in the case of the cited study, compressive preloading should be introduced in some specimens and their biaxial notch strain histories monitored. In addition to the desired data on crack initiation and propagation, information should be sought concerning at least the magnitude of surface residual stresses to be compared to theoretical predictions. Relevant baseline data include the data listed for Type 1 as well as the crack propagation information obtained from fracture mechanics specimens.

CANTILEVER PLATES

Specimens in this group represent various modifications of the baseline cantilever specimen shown in Figure 11. These modifications are of two types.

The first modification is in the form of a full-width machined notch across the top surface of the specimen. Both welded and unwelded specimens are to be modified in this fashion; the location of notches in welded specimens is to be varied between the center of the weld and the edge of the heat affected zone. Figure 23 shows an example of a welded specimen with a notch located in the center of the weld. Notch acuity is varied by varying root radius ρ and notch depth h.

The second modification is in the form of a simulated "natural" weld profile also shown in Figure 23. These specimens should be fabricated in such a way that the weld profile parameters (ρ, θ, h) slightly violate the allowable maximum (or minimum) values provided by current welding specifications. Tests are to be conducted under controlled deflection (either constant amplitude or complex loading) and should include saltwater as well as air environments.

As indicated in Table 2, the primary purpose of cantilever plate specimens is to enable an assessment of the influence of notch sensitivity on surface crack initiation. Consequently, the general testing goals (and relevant baseline information to be used for the interpretation of test results) resemble those associated with notched round bars. However, because of the presence of the weld, notched cantilever plates clearly represent more complex specimens; hence a discussion of the justification for such specimens is presented below.

The main purpose of notched base material specimens is to obtain a verification of notch sensitivity estimates derived from round bar specimens tested in air under constant amplitude deflection control. It is anticipated that only few such specimens need to be tested. Specifically, the intent is to appraise the effect of the differences which might exist between round bar and cantilever plate specimens due to possible differences in notch strain gradients, surface strain triaxiality, and recording of the visual observations of surface crack initiation. The following aspects are considered essential to the interpretation of test results:

1. Prior to testing, notch profiles should be recorded.

2. Since an estimate of notch strain history is an essential element in the crack initiation analysis, efforts should be made to obtain such information by means of experimental analysis and to compare it to analytical predictions. Accordingly where geometry permits, notches should be instrumented with strain gages to record local strain history until stabilization. Alternately, the use of moire grids should be explored analogous to the current application of this method for fatigue research in the Soviet Union (see Shneydorovich, 1971).

3. Visual observation of crack initiation should be followed by specimen sectioning and recording of crack profiles.

The testing of specimens with notched weldments in saltwater and air environments is intended to provide information on the effects of weldment residual stresses and weldment/heat-affected zone material properties on notch sensitivity. The results will be compared with the predictions given by (unnotched) baseline specimen data. Regarding specific aspects of testing, procedures outlined in items (1) and (3) as discussed above should be employed in all tests. Notch instrumentation* for air-tested specimens should be employed for at least a limited number of specimens, particularly for those tested under complex deflection control.

*It is recognized that the useful fatigue life of the gage may be quite limited; however, it may be sufficient to record materials stabilization.

The intent of using specimens with a simulated "natural profile" is to provide surface crack initiation data in saltwater environment for welds without surface treatment. The data will be compared to predictions based on the information provided by smooth and notched (controlled) specimens. Testing should be terminated following formation of a crack that is detectable by visual observations; this should be followed by specimen sectioning and recording of weld profile and crack geometry. Both constant amplitude and complex loading histories should be studied.

PRESTRESSED BEAMS AND HOLLOW CYLINDERS

The primary purpose of these specimens is to investigate the effects of (1) coupling of initial residual tensile stress and applied compressive load fluctuation, (2) applied stress biaxiality, and (3) large-scale yielding. In situations where the above factors are accentuated, such studies should elucidate the extent to which fatigue behavior can still be predicted from baseline data. Specific details concerning specimen design and testing procedures are discussed below.

The proposed* notched beam specimen shown in Figure 24 is intended specifically for the study of facet (1) as listed above. The test results are to be compared to those obtained for Type 2 round notched bar. The outer fibers of the specimens are preloaded by flexure into the plastic range. Upon unloading, self-equilibrating stresses of varying size (tension or compression) and intensity are introduced. An example of such a residual stress pattern is shown in Figure 24. Such patterns can be calculated from the deformation history of the bar and baseline stress-strain response data. It should also be feasible to obtain at least an approximate check of such calculations by hole drilling methods of surface residual stress measurement. Following preloading, shallow notches are to be cut into the surface of the beam. Prior to notching operations, strain gages are to be located near the

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*This type of specimen fabricated from HY-180 steel has been tested at NSRDC although the results are yet unpublished.

notch location to monitor relaxation strains resulting from the cutting operation. Cyclic tension is to be applied to one group of specimens and cyclic compression flexural loading to the other. The number of cycles to crack initiation (extension from the blunt notch), crack growth increments, and relaxation strains ahead of the crack tip and on top surface of the specimen are to be recorded during testing. After the crack has propagated a sufficient distance to obtain reliable information on growth rate, the testing should be terminated, residual stresses measured by the hole drilling method, and the specimens sectioned to indicate crack profiles. For corrosion-sensitive materials it may be desirable to run some tests in a saltwater environment at the crack tip and to terminate the tests when the crack has arrested or unstable crack propagation has occurred.

Cylindrical tube specimens similar to the specimen shown in Figure 10 were used by Crosby et al. (1969) to study biaxiality effects on fatigue. The specimen allows considerable flexibility in the choice of load biaxiality and applied stress/yield stress ratios. It is suggested that both smooth and notched specimens be used. The notched specimens would feature either axisymmetric (circumferential) or longitudinal notches under constant amplitude loading.

Smooth specimens should be tested until fracture occurs under various biaxial (tension-tension or tension-compression) loading conditions. This phase of the study essentially parallels the work of Crosby. The number and size of cracks as observed on the specimen surface should be recorded as a function of the number of load cycles. Periodic introduction of dye penetrants and sectioning of the specimen after testing should provide information on the through-the-thickness crack propagation mode. The information obtained from this phase of the study should prove very useful for the development of analytical probabilistic models. Interpretation of the test results for the "dominant" flaw* which leads to fracture should be feasible by utilizing the baseline specimen data as well as the data provided by the notched cylindrical specimens discussed below.

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*This refers to the flaw which eventually leads to fracture.

The primary purpose of testing notched cylindrical specimens is to provide information on crack propagation under biaxial loading and/or large-scale yielding effects.* Biaxial loading ratios should be the same as those selected for smooth specimen studies with the tensile component normal to the crack plane. In addition to crack propagation aspects, useful information can be obtained on the influence of notch sensitivity on crack initiation under biaxial loading. Adequate strain gage instrumentation should be provided in the vicinity of notches to permit an assessment of elastic-plastic computer analyses currently under development. As in the case of smooth cylindrical specimens, periodic application of dye penetrants and sectioning of the specimen following fracture could provide sufficient information on the rate of crack propagation through the wall thickness.

FRACTURE MECHANICS SPECIMENS

Let us assume that the load-time history can be reasonably idealized** as composed of a randomized sequence of sinusoidal load cycles, each featuring a varied combination of mean and fluctuating stress components. It should then be possible to obtain at least a conservative estimate of crack growth rates on the basis of cumulative damage rules; the simplest concept is the rule of linear damage addition. The accuracy of such estimates must then be demonstrated experimentally for each material and selected load spectra. In addition to accumulating information on crack size as a function of load cycles, the testing program may benefit by inclusion of fractographic studies of fracture surfaces as mentioned in connection with the baseline data acquisition.

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*This pertains to the condition where plastic zone sizes are large in comparison to the crack size and shell thickness. It is approached when the ratio of applied stress to yield stress is large.

**It would be preferable to work with continuous service submergence records. Such records would enable us to dispense with the simplifying notion of a "cycle." Instead, the actual load-time history could be simulated in laboratory testing analogous to the approach currently favored in many aerospace applications.

Fracture mechanics specimens shown in Figure 17 offer a natural starting point for the experimental validation of cumulative damage rules on crack propagation. Having previously discussed the salient features of these specimens in connection with the generation of baseline data, we shall now focus attention on the problem of selecting the load spectra.

On the premise that for the externally pressurized hull, the driving force for crack propagation is the residual tensile stress, the simplest types of load spectra to be studied are shown in Figure 25. For the sake of simplicity, only two level loadings are shown; the study of more than two levels should be deferred until the interrelationship between the two level loading variables (as discussed below) is better understood.

Figure 25 simulates an idealized service condition assuming that all submergences originate and culminate at the surface. The relevant variables are σ_y, k, σ_e, σ_s, and N_s. Here σ_y is the yield stress, k and m are positive constants ranging between zero and unity, σ_e and σ_s are respectively the largest and smallest stress ranges, and N_s is the number of σ_s cycles per block. In the extreme case where $\sigma_s = \sigma_e$, we obtain the constant amplitude testing condition which was characteristic for the large-scale HY-80 model testing program. Multilevel block loadings of this type would feature a variety of different stress levels σ_s and randomization within a block N_s for a given value of $k\sigma_y$. Here $k\sigma_y$ simulates residual stress; typically, the values of k may be selected to range between 0.5 and unity.

Figures 25b and 25c simulate the service condition of the majority of depth fluctuations that occur about some mean submergence level. Hence, in addition to the parameters listed for Figure 25a, we introduce $m\sigma_y$ (with m a positive constant) as representing the mean hydrostatically induced stress corresponding to mean depth submergence. In Figure 25b the maximum stress range σ_e is associated with surfacing and in Figure 25c with the submerging part of the cycle.

T-FILLET WELDMENTS

The specimens are shown schematically in Figure 26; butt-welded specimens are shown in the same figure and will be discussed later. Specimen dimensions correspond to those tested at the Naval Applied Science Laboratory (NASL) and at NSRDC during the past decade as recently summarized by Macco (1972). Flexure under constant load control is applied such that the fillet welds are stressed cyclically from zero to maximum tension. In beams, flexure is applied by a uniform bending machine; in plates, flexure results from uniform pressure applied generally to the lower surface of the specimen. The testing machines can also be adapted to spectrum cyclic-loading tests. In what follows we shall examine the objectives of the testing program and the salient features of the recommended testing procedure. Our interest is focussed on the initiation and early propagational stage of surface cracks. For this type of detail, internal flaw growth is not expected to control the fatigue life.

The specimens under consideration are more complex than any discussed so far and can justifiably be considered as structural elements since they contain at least the majority of complicating features associated with full-scale T-fillet weldments. The objective of such structural elements is to provide a comprehensive evaluation of analytical procedures which have evolved from the synthesis of data obtained on much simpler specimens. Where required, such procedures would be modified in light of the experimental data before being applied for estimates of the fatigue performance of full-scale or nearly full-scale details.

Consequently, the testing program should encompass weldments in ground and as-welded conditions, salt and air environments, constant amplitude, and complex loading history. It is also important that the welding process and weld quality control be representative of shipyard practice. The testing procedure should enable detection of any pronounced deviation from unavoidable simplifications introduced in the mathematical modeling pertaining to stress analysis, crack initiation, or early stage crack propagation. To this end, the following recommendations should be followed:

1. Contours of weld profiles should be obtained prior to testing. Information on weld toe geometry is of particular importance. It may be necessary to resort to sectioning and visual magnification techniques to characterize the variations in weld contours with special emphasis on toe undercut geometry.

2. At least for a limited number of specimens, strain gages in biaxial direction should be placed near and at some distance away from the weldment and monitored either until strain stabilization occurs or a definite tendency toward cyclically induced creep can be detected. For the plate specimens, it is also important to appraise the magnitude of strain variation in width direction. Strain gages should also be placed on the surface opposite the stiffener at least for a limited number of specimens. The purpose of these gages is to provide information concerning stress redistribution after sizable cracks have developed at the toe of the weld.

3. Crack initiation indications should be carefully monitored in terms of length and number and location of surface cracks as a function of load cycles. An example of this type of information is shown in Figure 27. Within the context of crack initiation and crack propagation (discussed below), shipyard inspection techniques should be employed and compared to laboratory techniques. Initiation definitions used for smaller baseline and analytical model validation specimens should be used in describing initiation for comparison purposes.

4. Crack propagation should be obtained both with respect to the surface length and through-the-thickness growth. Ultrasonic detection methods should be combined with ink staining techniques and sectioning of the specimens. The emphasis should be on the acquisition of data *prior to a 10-percent increase of deflection of the specimen.*

5. A few well-defined specimens should be tested with the fillet weld in compression. Here, the intent is to obtain information on the reasonableness of various assumptions made in the analysis with respect to the effects of initial residual tensile stress on crack initiation and early growth under compressive loading. It is recognized that crack arrest may occur long before the 10-percent increase of deflection is observed.

6. It is expected that the bulk of the data can be obtained from beam specimens. However, a limited testing program of more costly plate specimens is considered necessary to accomplish two additional testing objectives: data on crack arrays and data on the statistical size effect. Crack array data are required to validate the analytical modeling of the transition from multiple individual cracks to a single, continuous crack. Size effects may be responsible* for the generally poorer performance of plate specimens which are 32-in. wide as compared to the plate specimens which are 5-in. wide, as appears to be the case judging from the data presented in the summary by Macco. It is desirable to establish whether there is a trend due to size effects as a function of specimen width; if such trends can be established from structural element tests, projections to large-scale pressurized models would be simplified. To this end, the feasibility of supplementing the tests of 32-in.-wide plates with a small number of plates of greater width should be considered.

7. Finally, one facet of the testing program should be devoted to the appraisal of the thickness effect on crack initiation and propagation. This is motivated by the following consideration. Although no significant effects of thickness are to be expected for baseline specimen tested under uniform applied stress conditions, weldment introduces unknown through-the-thickness residual stress gradients which may significantly influence crack growth behavior for deep surface flaws. The testing of a limited number of "thin" and "thick" plates would be very helpful in assessing the accuracy of simplifying assumptions which have to be made in the analysis to obtain surface values and gradients of the initial residual stress. The thickness range of interest should encompass the thickness associated with cantilever plate specimens and maximum plate thickness associated with full-scale hull detail design.

*To some extent, such differences may be attributable to possible variations of strains across the specimen width; to detect pronounced variations, strain gages should be positioned as suggested in Item 2.

BUTT WELDMENTS

Fatigue cracking in T-weldments ordinarily originates at the weld toe; in butt weldments, the possibility of internal cracking must also be considered. Judging from Radziminski et al. (1970), initiation and growth of cracks may be expected from various types of internal defects in butt joint specimens under axial tension where weld reinforcement is removed. Such conditions may be realized at ground butt weldments when submarine secondary structures are subjected to applied tensile stress fluctuations, i.e., hard tanks. It is also possible that a propensity for internal cracking may exist even in compressively loaded butt weldments. This may be the case at the pressure hull inserts welded under conditions of high restraint since such restraints maximize the possibility of localized through-the-thickness residual tensile stresses and hydrogen embrittlement.

Once the possibility of internal cracking is recognized, then it follows that the testing program must not be limited to flexurally loaded specimens. At least a limited number of axially loaded specimens tests is necessary to reproduce the required stress at deep subsurface defects. In the interest of limiting the number of specimen types, a case can be made for dispensing entirely with flexural specimens in favor of axially loaded specimens for both surface and internal cracking studies. It is recognized however that for low-cycle fatigue life studies, flexural specimens may permit testing to higher stress levels because of the axial loading limitations of conventional testing machines. Also, flexural specimens offer an opportunity to compare in the same specimen surface crack initiation and early growth under compressive and tensile fiber stresses. Because of the above considerations, it is felt that both flexural and axial specimens could profitably be included in the testing program with an understanding that flexural specimens are suited only for surface cracking studies.

Flexural Fatigue Specimens

Recommended beam and plate butt-welded specimens are shown in Figure 26. The dimensions correspond to those used at NASL and NSRDC (Macco, 1972). The load control conditions are the same as for the previously described T-welded specimens.

The general testing aims are the same as for T-welded beam and plate specimens. This also applies to the testing procedures except for the modifications described below.

In the T-welded specimens, the emphasis is on obtaining crack initiation and crack growth data on the tensile face of the specimen; in most cases, this should also be the face containing the toe of the weld. It is recommended that an attempt should be made to obtain similar information on the compressive face, at least for beam specimens. As in the case of T-welded specimens tested with the weld toe in compression (see Item 5 on page 44), such data should be helpful in providing an indirect verification of the analytical modeling of fatigue under compressive loading. Further information on the effect of residual stress gradients and residual stress relaxation may be provided by interrupting the tests of some of the beam specimens which develop cracks on both tensile and compressive faces. The specimens should then be inverted in the testing machine in order to subject previously tensile fibers to cyclic compression; and testing is continued until fracture occurs.

Axial Fatigue Specimens

As stated earlier, subsurface crack initiation and growth in ground butt weldments may occur under applied tension *or* compression. Cracking may originate at a variety of subsurface weld defects, e.g., shrinkage cracks, voids, lack of fusion, and slag inclusions. These defects may occur at various positions within the weld thickness and may interact with one another. The description of such defects in terms of size and orientation may be very difficult by means of conventional test methods. Consequently, the task of developing appropriate analytical approaches appears to be much more formidable than for surface cracking.

Nevertheless despite the complications cited above, analytical modeling techniques for subsurface cracking in weldments have been proposed for both crack initiation (Forman, 1968, and Van der Zanden et al., 1972) and propagation (Harrison, 1969, and Radziminski et al., 1970) phases, and these merit further investigation. However, it is extremely important in this phase of the program to provide close coordination between specimen design, testing procedure, and analytical modeling so that various predictive techniques (ranging from localized strain concept through fracture mechanics and purely statistical methods) can be effectively evaluated. Consequently before discussing specific specimen types, general comments are in order regarding the application of fabrication and testing procedures to all specimens.

First, the specimens feature full-thickness weldments and should be fabricated by procedures which are within the range of current specifications and shipyard practice. Specifically, the welding procedures should be such that intentional weld defects are produced (Radziminski et al., 1970) which are just within or slightly exceed the current acceptance standards. Since it is the *internal* cracking problem that is being studied, it is important to minimize the possibility of crack initiation at the toe of the weld by removing overfill reinforcement and grinding the weld surface. In tensile-loaded specimens, failure can be defined as the penetration of the surface by a growing defect; in compressively loaded specimens, crack arrest may preclude such definition, and the tests should be terminated once substantial internal cracking develops.

Second, a combination of the latest techniques for nondestructive and destructive inspection should be employed to record initial defect distribution, crack initiation, crack growth rate, and terminal failure. A good illustration of this approach is contained in Radziminski et al. (1970) where ultrasonics, radiography, and inspection of fracture surfaces were used.

Finally, with the specimens cycled under load control, strain gages should be placed on the specimen surfaces to record data on cyclic stress-strain response until material stabilization occurs.

Bearing in mind the above general requirements, let us now consider the specific specimens to be used in the evaluation of subsurface cracking. These are shown schematically in Figure 28 and are discussed in detail below.

The specimen shown in Figure 28a represents the type tested by Radziminski et al. (1970) under zero to tension and complete reversal load control. Specimen dimensions were as follows: L = 4'-0, 2 in. $\leq w \leq$ 4 in. and $1/2 \leq t \leq 1\ 1/2$ in. It is recommended that the testing of such specimens be conducted under zero to tension load control and that the specimen thickness be at least 1 1/2 in. Net section stress should be such that within the range of acceptable (as falling within the limits of weld quality control specifications) defect sizes, the range of ΔK_I from 10 to 100 ksi $\sqrt{in}$ is covered. It is also desirable to vary the test width w in order to obtain information on the statistical size effect.

In the past, transverse butt weldments have received most of the attention, but the possibility of cracking at longitudinal butt weldments which are stressed in the direction parallel to the axis of the weld should also be taken into account. This may be of special concern if initial transverse cracking were to develop as a consequence of hydrogen embrittlement. Consequently, specimens of the type shown in Figure 28b (discussed in Gurney, 1968) are needed to provide information on fatigue cracking in longitudinal weldments. These specimens should be tested under zero to maximum tension load control. The specimen thickness t should be at least 1 1/2 in. and the length L should be varied to provide information on the statistical aspects. Width w should be controlled by the requirement that the applied tension stresses should encompass the range of ΔK_I values indicated above.

Now focus attention on specimens tested under axial compressive loading. As mentioned earlier, internal cracking under compressive loading appears likely only in the presence of high initial restraint tensile stress. This consideration motivates the choice of "knuckle" and/or patch weld specimens shown in Figures 28c and 28d. High through-the-thickness initial tensile stress is introduced in both specimens by means of specific fabrication procedures.

The "knuckle" specimen was developed at NSRDC (Wiggs, 1969) primarily for the study of surface cracking at weld undertoes. A controlled value of tensile restraint stress is introduced into the midsection d. This is accomplished by first welding the outer edges of the specimen and then completing the weld while the specimen is under predetermined compressive load. Load eccentricity e is varied by varying the transition angle (typically, α varies between 5 to 10 deg), thereby permitting controlled variation of the ratio of bending to membrane stresses. However, if the scope of the studies is limited to internal cracking, the angle should be set equal to zero. Specimen thickness should be at least 1 1/2 in. Length L, chosen with regard to buckling considerations and ultrasonics inspection requirements, ranges typically between 8 to 12 times the thickness. Specimen width w is on the order to 5 to 10 times the thickness and should be determined by applied stress range required to encompass the range of K_I values from 10 to 100 ksi $\sqrt{in.}$

The patch-welded specimen shown in Figure 28d is intended to simulate fairly common conditions at inserts in submarine pressure hull. With t_I chosen as representative of hull thickness, the dimensions D, t_2, A, and L should be chosen to maximize the radial restraint during fabrication. This will involve some experimentation with trial specimen designs combined with strain gage instrumentation during fabrication. Angle θ should be chosen in conformance with fabrication specifications. Because of stress concentration introduced by the transition section, surface cracking may precede internal cracking despite weld surface grinding. If this should occur, the surface should be repaired and cycling continued until sufficient data are accumulated on internal flaw initiation and growth.

SUMMARY AND CONCLUSION

This report examines the vital role of small-scale specimens and welded structural elements in the process of evaluating low-cycle fatigue of submarine hulls. Small-scale specimens range from smooth round bars to cruciform-type plates; structural elements include nearly full-thickness beams and plates featuring T or butt welds. The major elements of the report are summarized below.

Although most of these specimens are not new, their significance has not been sufficiently explored in terms of overall fatigue evaluation. Consequently, in the introduction we examine the relation between experimental studies discussed in the main body of the report to materials screening, analytical modeling, large-scale model testing, and fatigue analysis methodology. Tentative classification of the specimens as falling into baseline or analytical model validation category is introduced.

Baseline specimens are envisioned as serving a dual purpose. First, they provide information on certain phenomenological aspects needed for material screening purposes. Second, they can also provide information for the development of analytical methods. However, this can be accomplished only if an attempt is made to discriminate between the three phases of the fatigue process, i.e., crack initiation, stable crack growth, and terminal fracture.

Next, baseline specimens are discussed in detail with reference to configurations and testing objectives. Specifically, information is sought on basic mechanical properties (static and cyclic), crack initiation, stable crack growth, and toughness characteristics related to design. Although total strain range is felt to be the most appropriate parameter for characterizing crack initiation, stable crack growth is best described by the range of stress intensity factor. Merits of various toughness measures that bear on the design estimation of the unacceptable crack size that may be developed in service are also discussed.

Finally, we review those specimens and structural elements which because of the complexity introduced by variable amplitude loading, presence of machined notches, and/or untreated weldments lend themselves readily as a first check on the validity of analytical procedures. In the experimental studies of this type, individual parameters which immensely complicate the planning and subsequent interpretations of large-scale model tests can be isolated and accentuated to provide a check on the reasonableness of simplifications inherent in the analysis. This not only necessitates a *variety* of specimens but also careful planning of the experimental procedures in accordance with the recommendations contained in the report.

ACKNOWLEDGMENTS

The author is indebted to Mr. A. J. Wiggs for many helpful discussions concerning the text. He is also grateful to Dr. B. Ellingwood for the regression analysis of HY-130 fatigue data on the cantilever plate specimen.

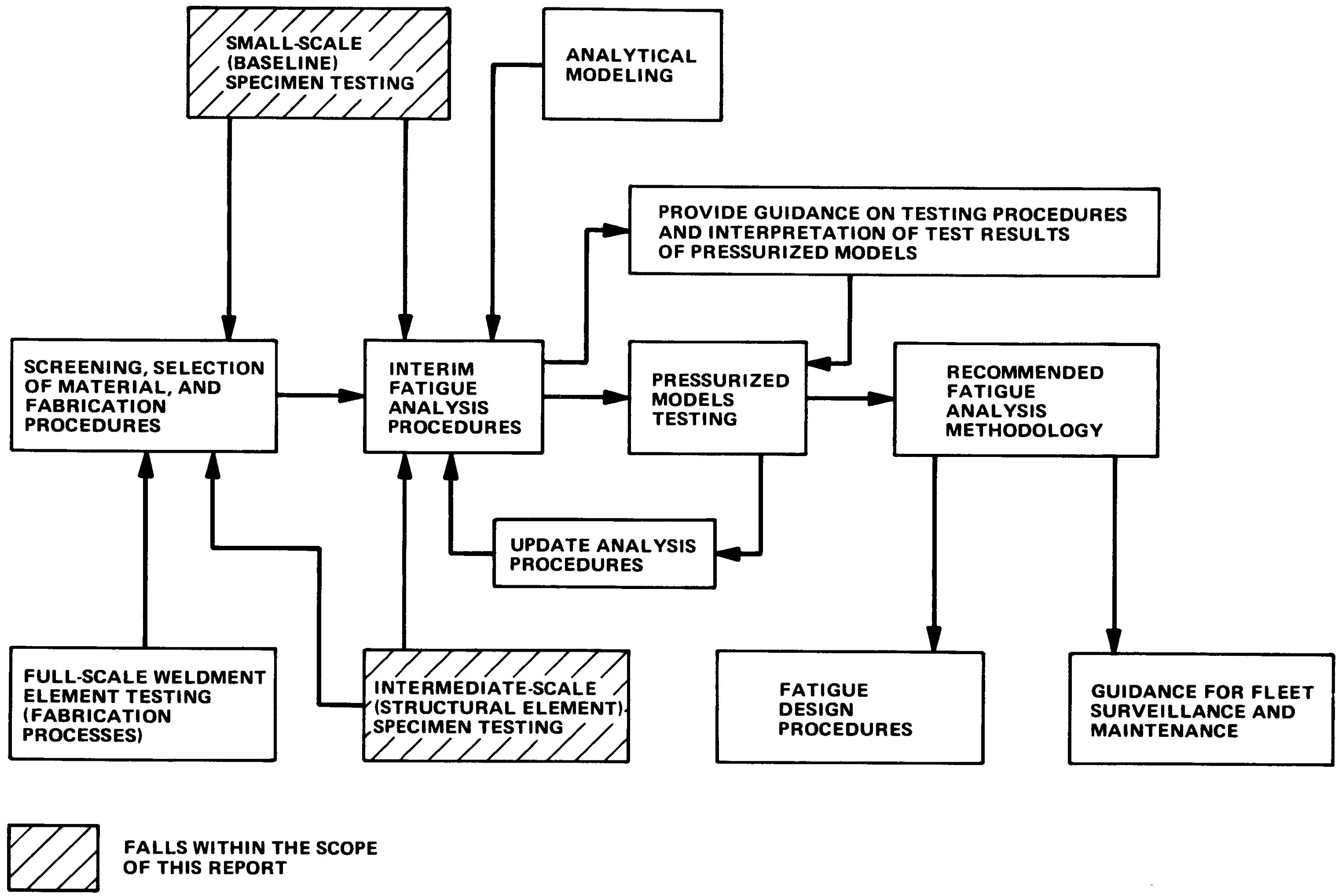


Figure 1 - Key Elements in the Evaluation of Low-Cycle Fatigue of Submarine Pressure Hulls

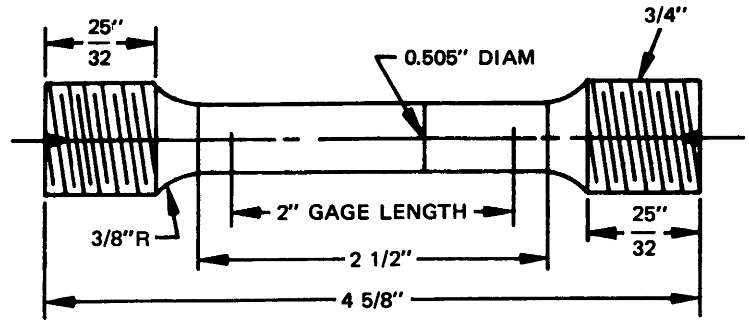


Figure 2 - Standard NSRDC 0.505-Inch Tensile Specimen

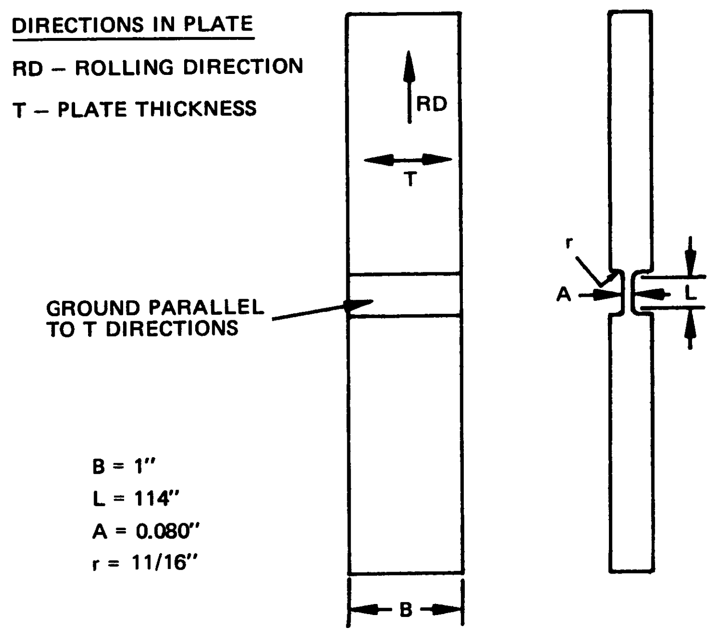


Figure 3 - Plane Strain Tension Specimen

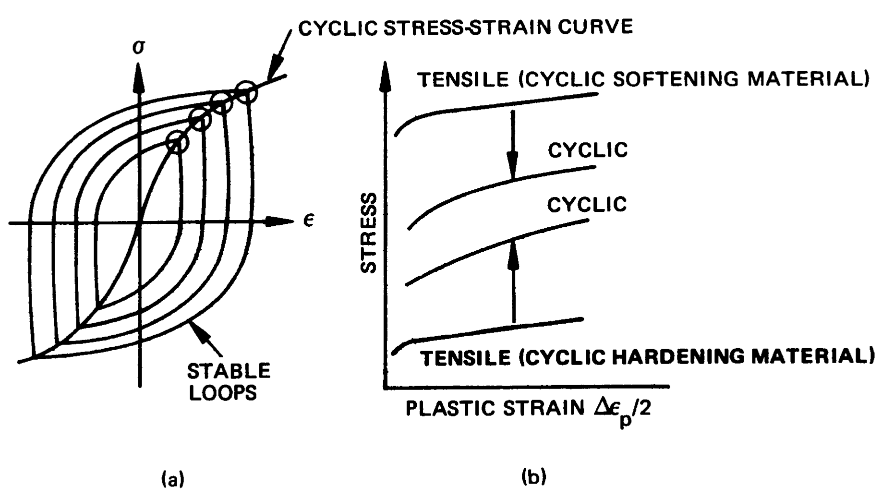


Figure 4 - Schematic Illustration of Cyclic Stress-Strain Curves

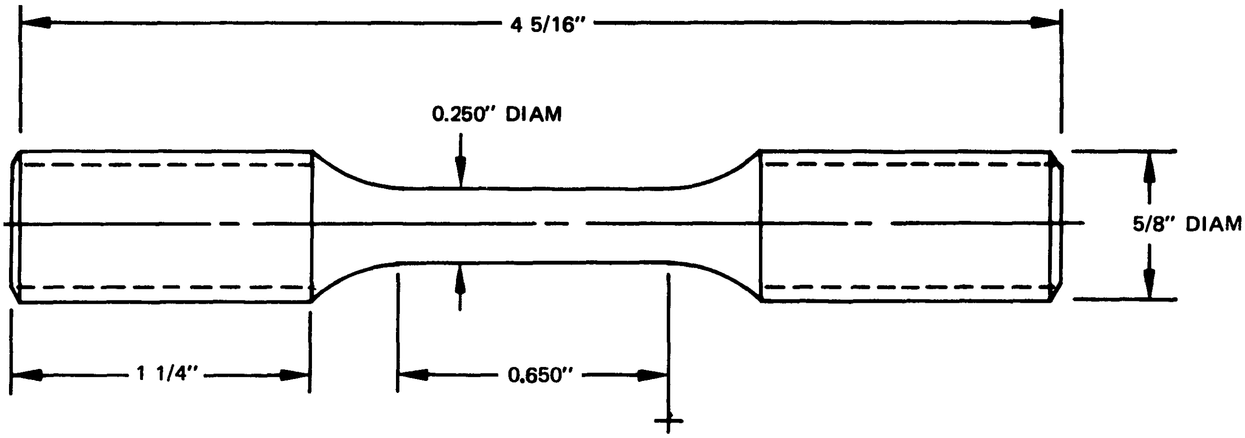


Figure 5a - Specimen

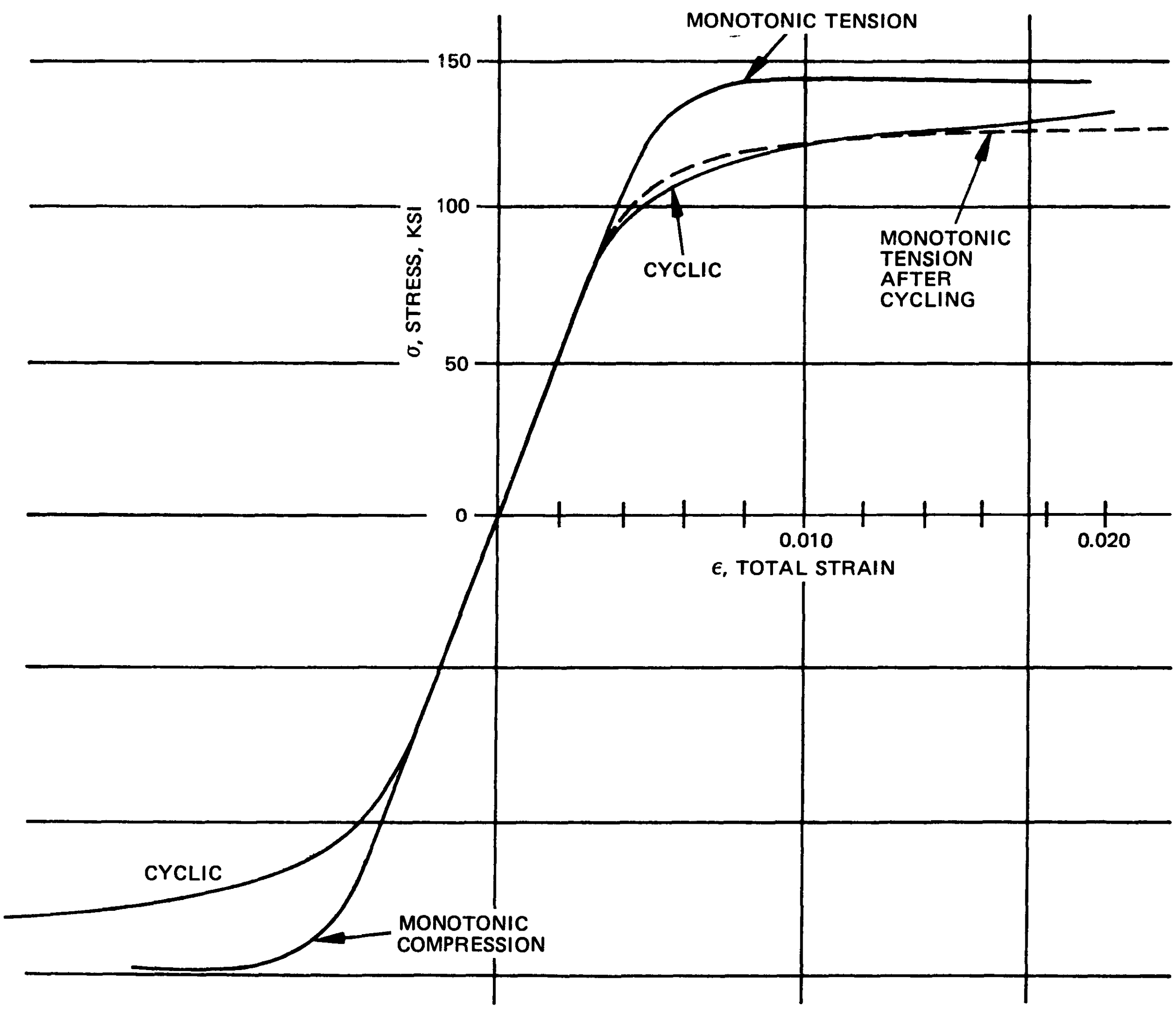


Figure 5b - Stress-Strain Curves

'igure 5 - Comparison of Monotonic and Cyclic Stress-Strain Curves for HY-130

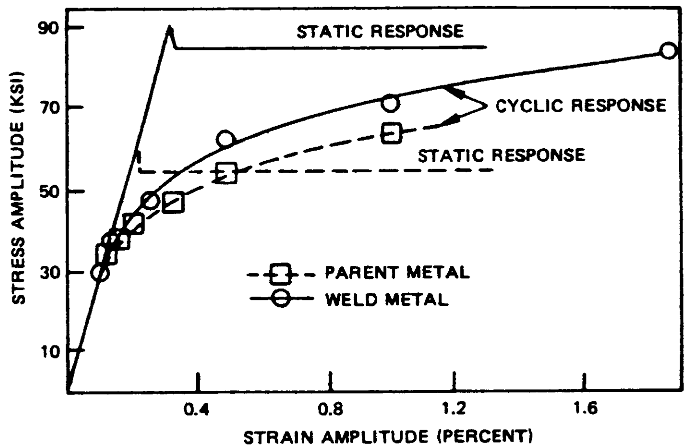


Figure 6 - Static and Cyclic Stress-Strain Response of Parent (CSAG 640.12 Structural Steel) and as Deposited Weld Metals

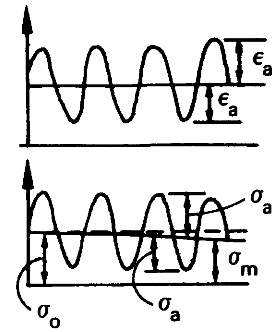


Figure 7a - Schematic of Test Condition

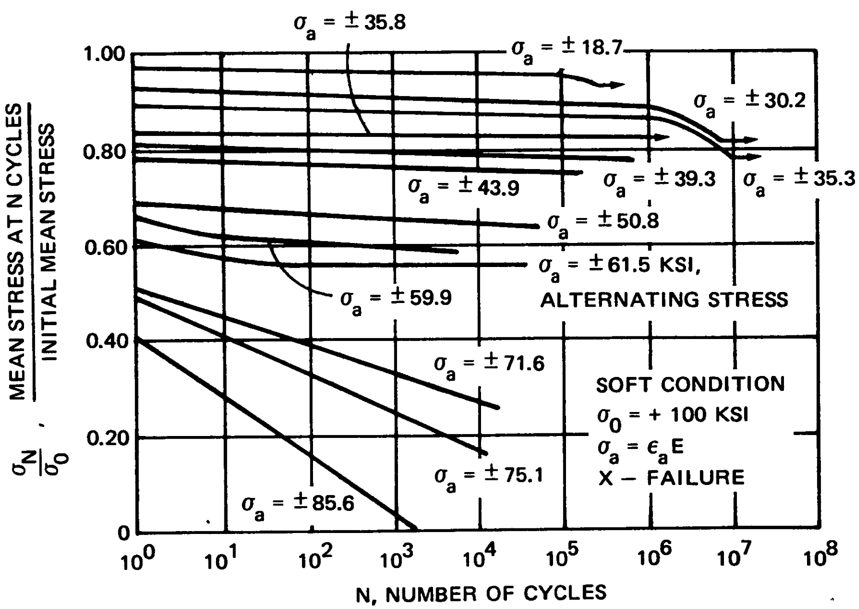


Figure 7b - Relaxation of Mean Stress of SAE 4340 Steel Corresponding to Soft Condition

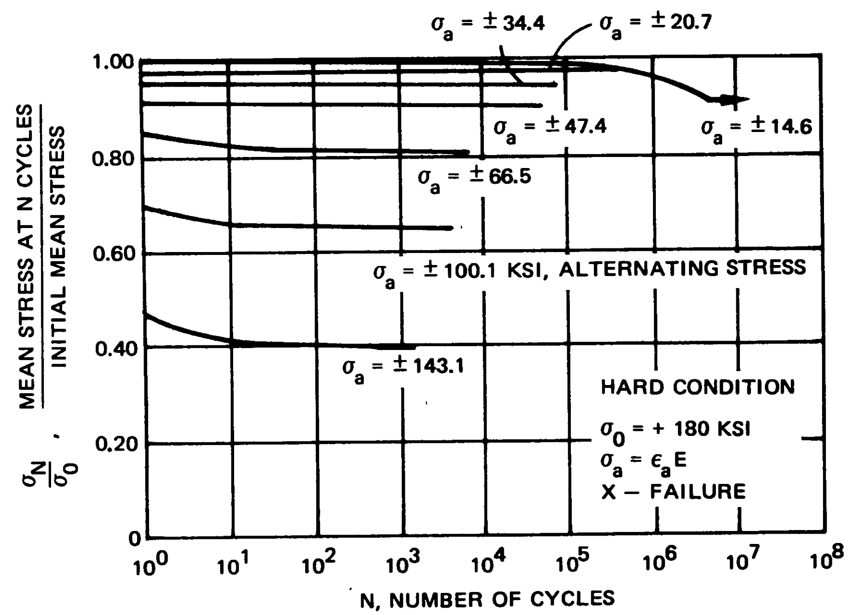


Figure 7c - Relaxation of Mean Stress of SAE 4340 Steel Corresponding to Hard Condition

Figure 7 - Illustration of Cycle Dependent Mean Stress Relaxation Effect

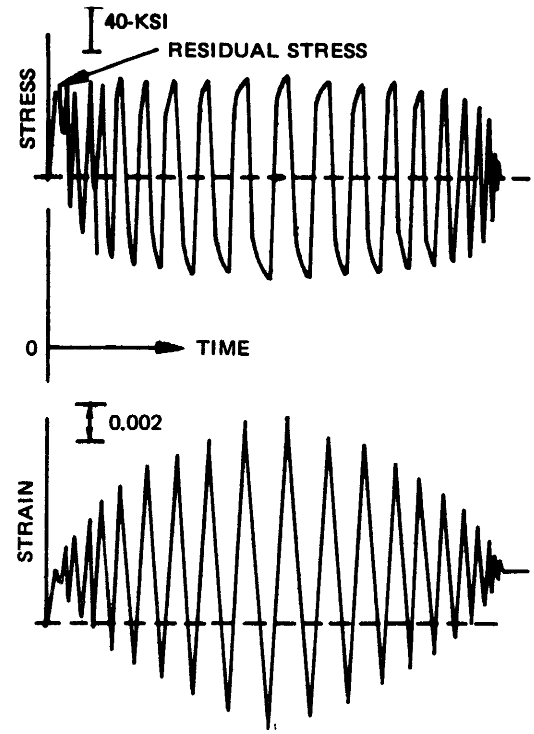


Figure 8 - Strain Controlled Overstraining Sequence Showing Relaxation of Mean Stress

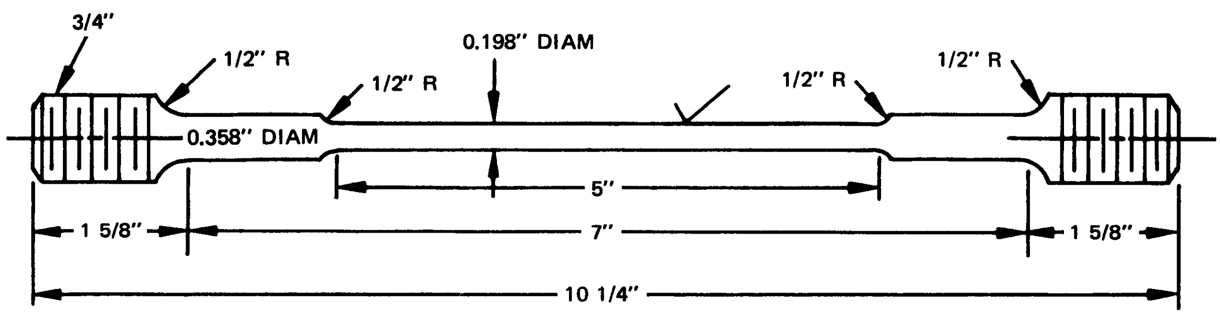


Figure 9a - Relaxation Test Specimen--Balwin Machine

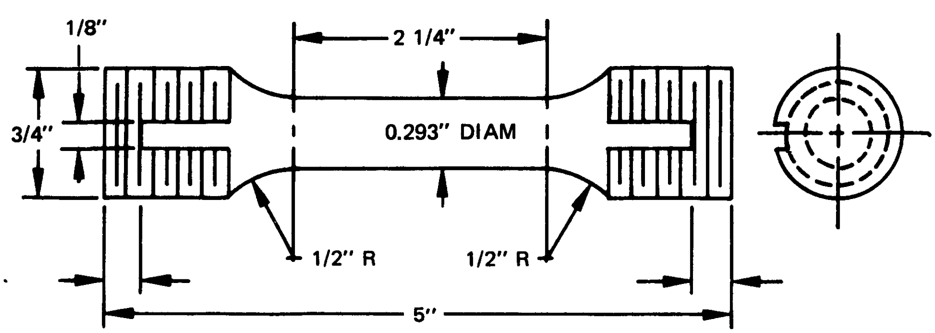


Figure 9b - Tensile Creep Specimen

Figure 9 - Creep and Stress Relaxation Specimens

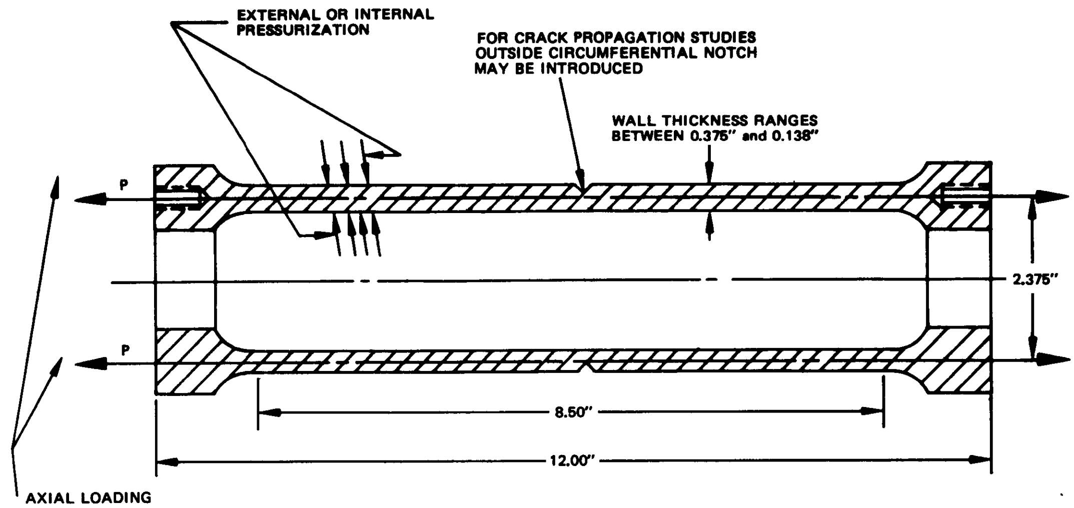


Figure 10 - Biaxial Test Specimen for Yield Surface Characterization
(From Misovec et al., 1972)

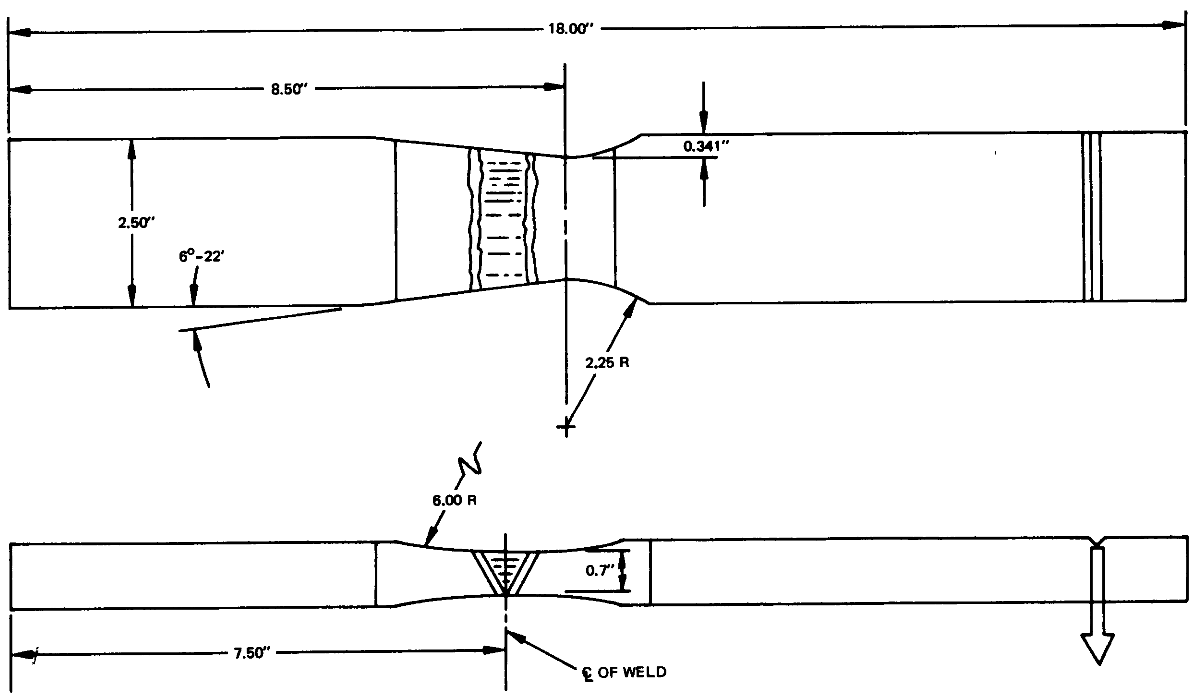


Figure 11 - Tapered Welded Low-Cycle Fatigue Specimen

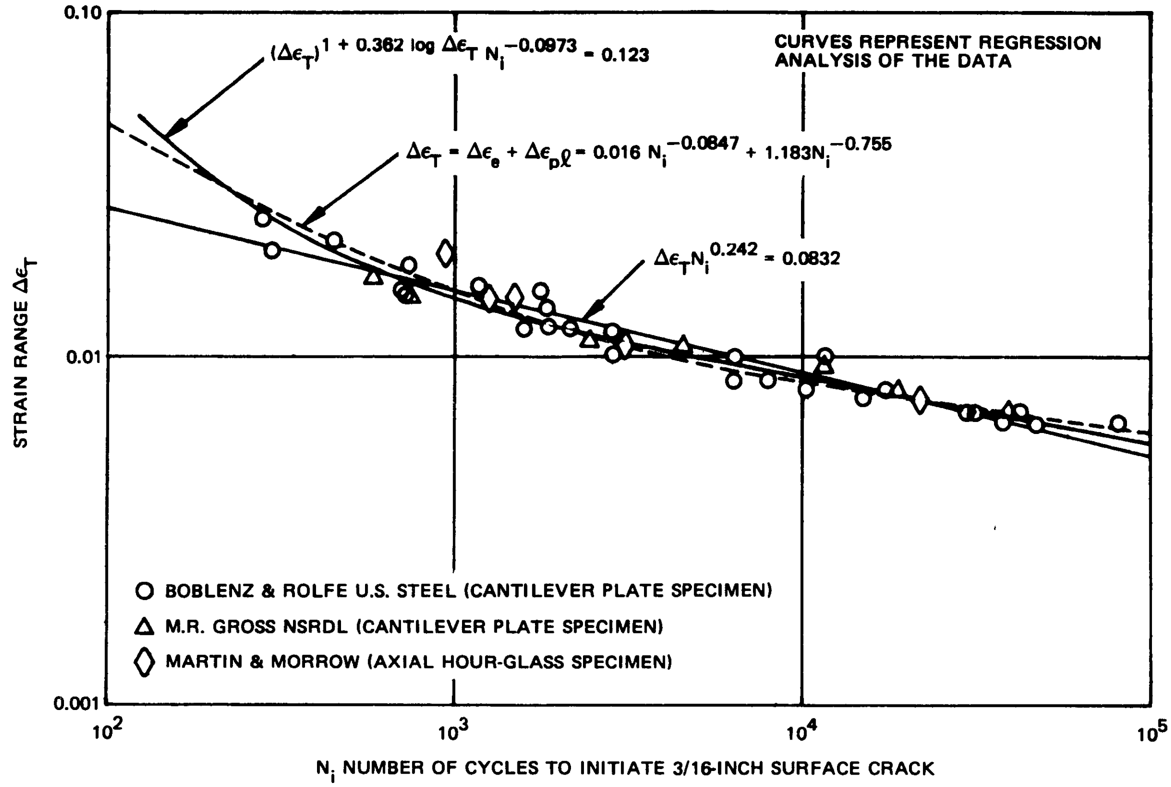


Figure 12 - Low-Cycle Fatigue Behavior of HY-130 Baseplate Material in Air

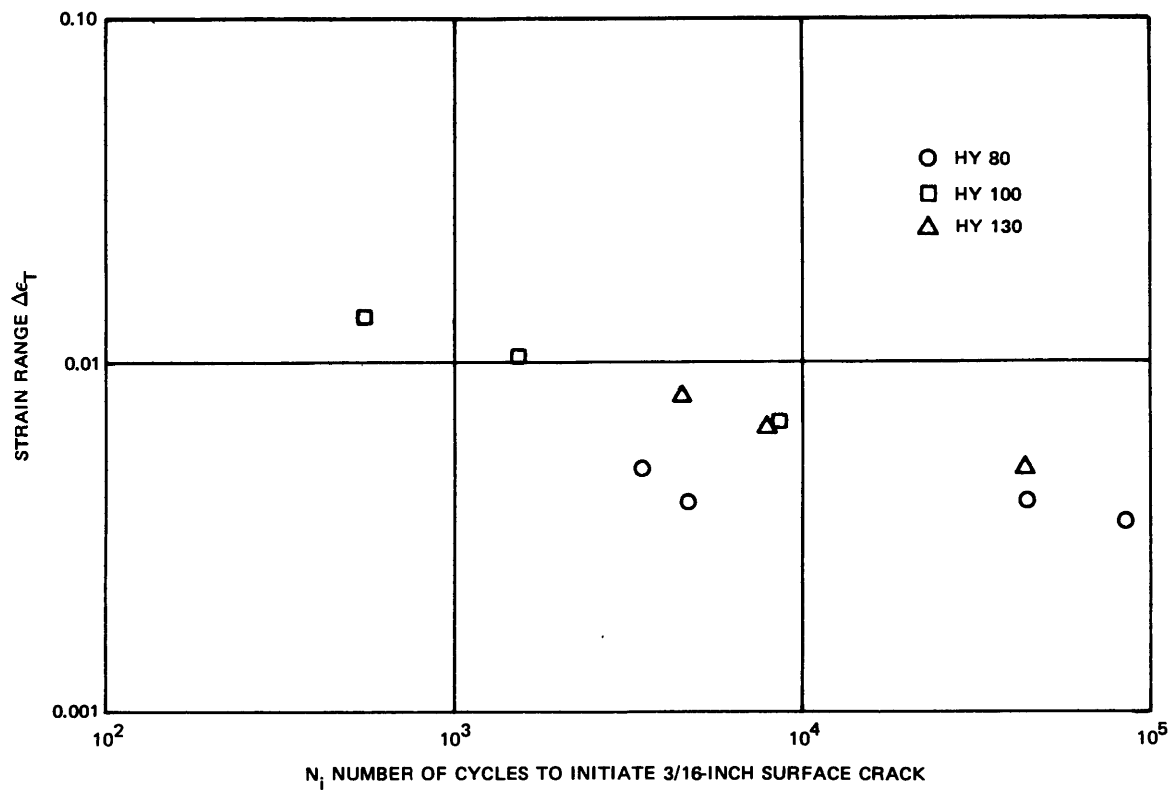


Figure 13 - Low-Cycle Fatigue Behavior of Weldments in Saltwater

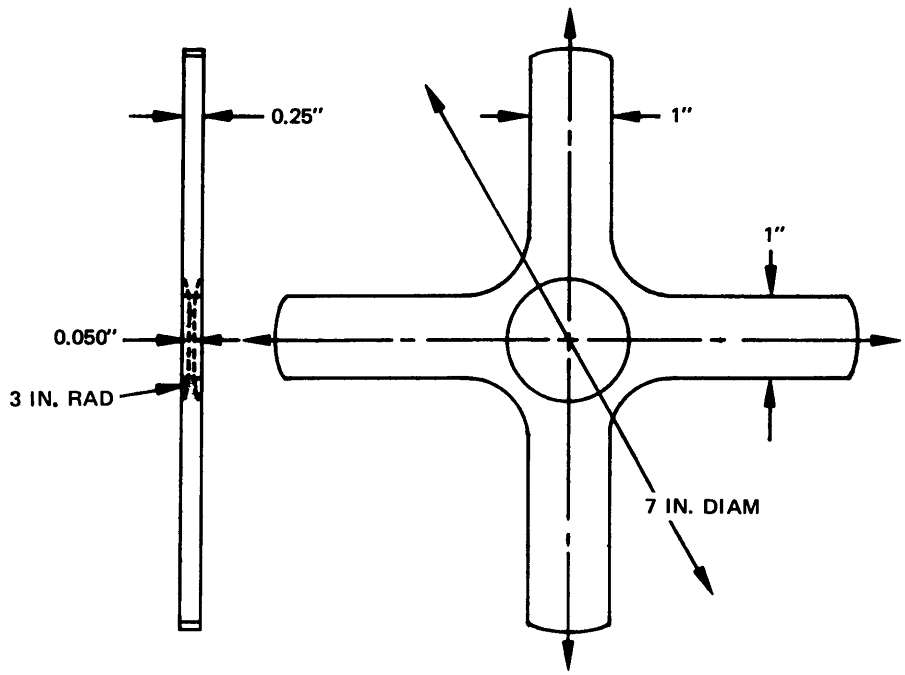
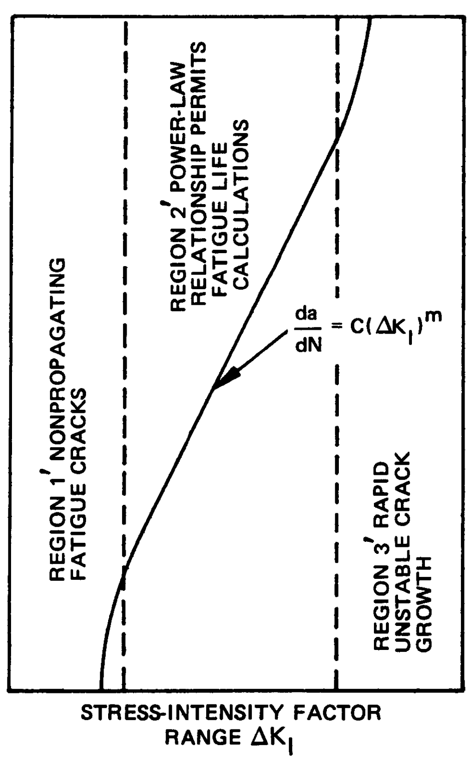
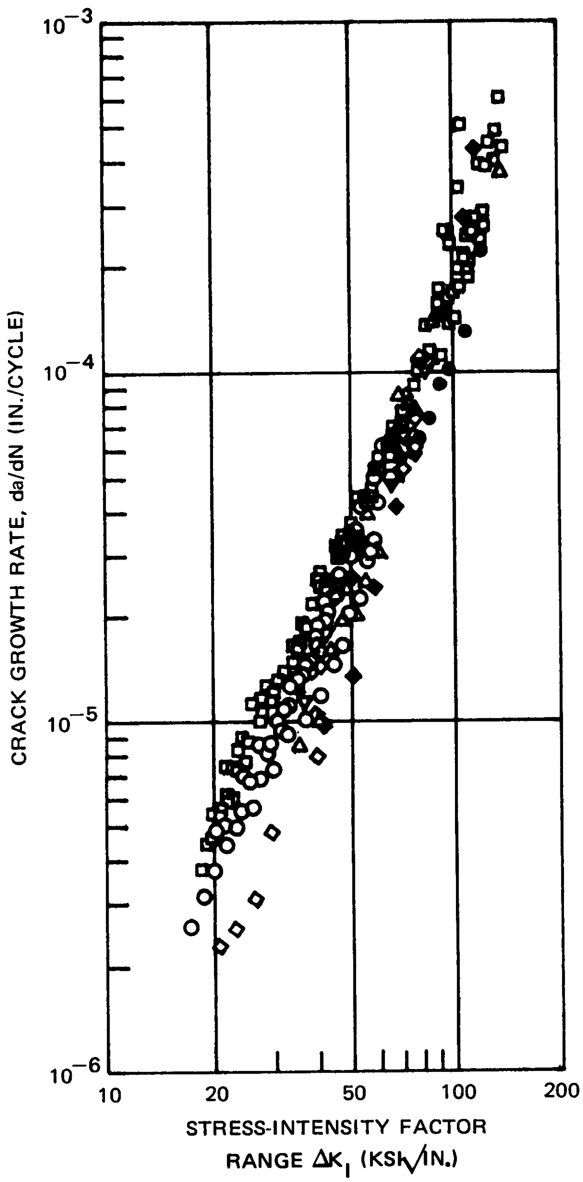


Figure 14 - Cruciform Specimen for Biaxial Crack Initiation Studies (From Pascoe, 1969)



ΔK	$\Delta\sigma_\infty$ KSI	a, IN.
15	35	0.05
	23	0.12
	16	0.25
20	46	0.05
	30	0.12
	21	0.25
50	115	0.05
	75	0.12
	52	0.25
100	150	0.12
	104	0.25
	73	0.50

Figure 15 - Fatigue Crack Growth Curve on Log-Log Coordinates (From Crooker and Lange, 1969)



SYMBOL	LABORATORY	SPECIMEN TYPE
○	NRL	PTC
●	NRL	CTC
◆	NSRDC	TDCB
△	NSRDC	SEC
▽	NSRDC	DEC
□	U.S. STEEL	WOL
◇	U. ILLINOIS	WOL

PTC – PART THROUGH CRACKED PLATE
CTC – CENTER CRACKED PLATE
TDCB – TAPERED DOUBLE CANTILEVER BEAM
SEC – SINGLE-EDGE CRACKED PLATE
DEC – DOUBLE-EDGE CRACKED PLATE
WOL – WEDGE OPENING LOAD BEAM SPECIMEN

Figure 16 - Growth Rate Scatter for HY-130-Air Data

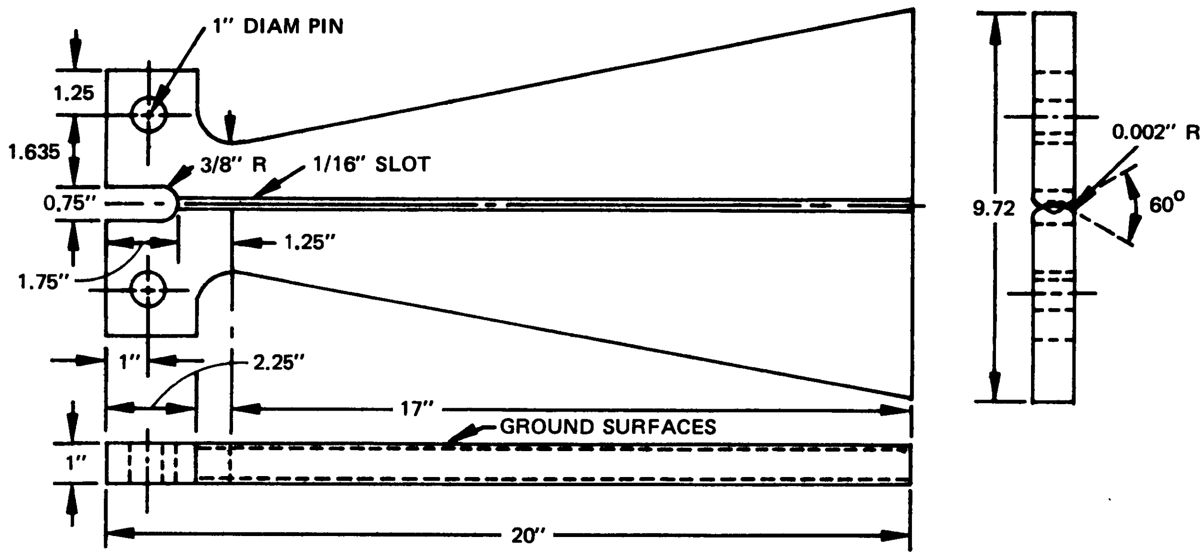


Figure 17a - Tapered Double Cantilever Beam Specimen

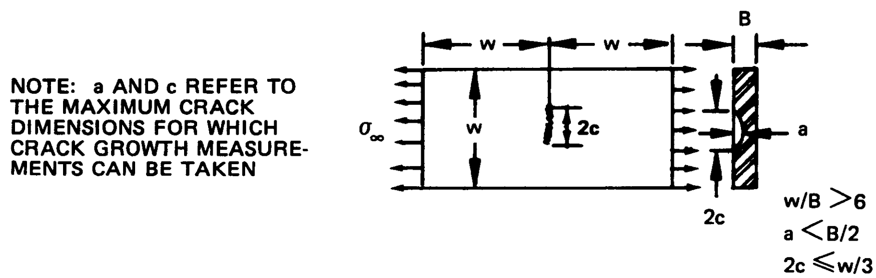


Figure 17b - Part-Through Crack Specimen

Figure 17 - Recommended Specimens for Crack Growth Characterization Studies

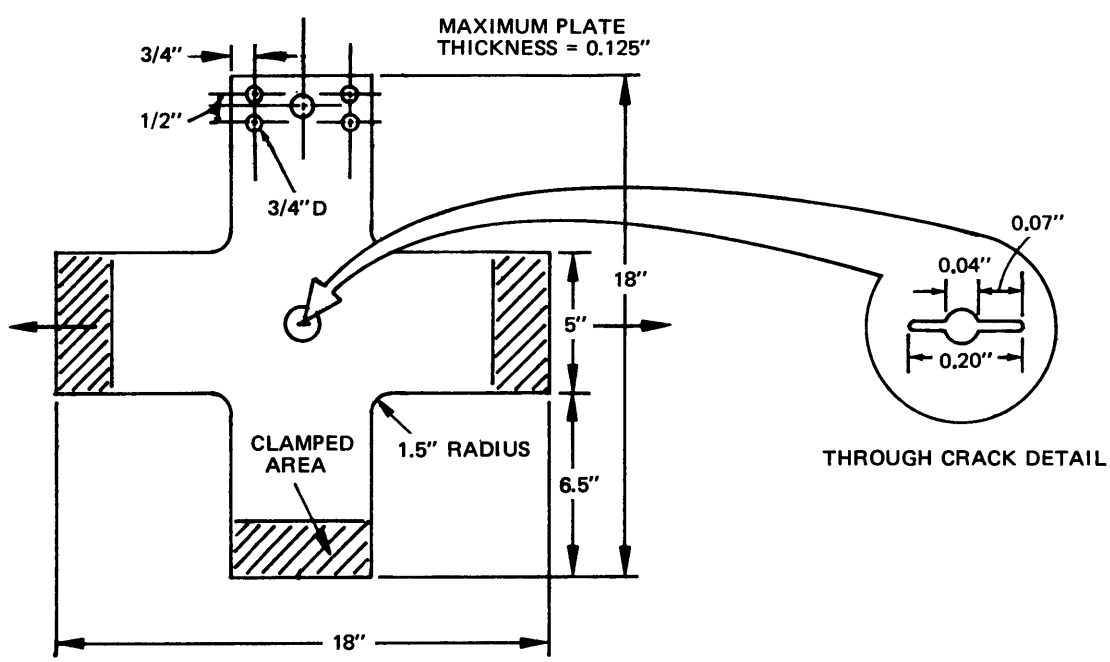


Figure 18 - Cruciform Specimen for Biaxial Crack Propagation Studies

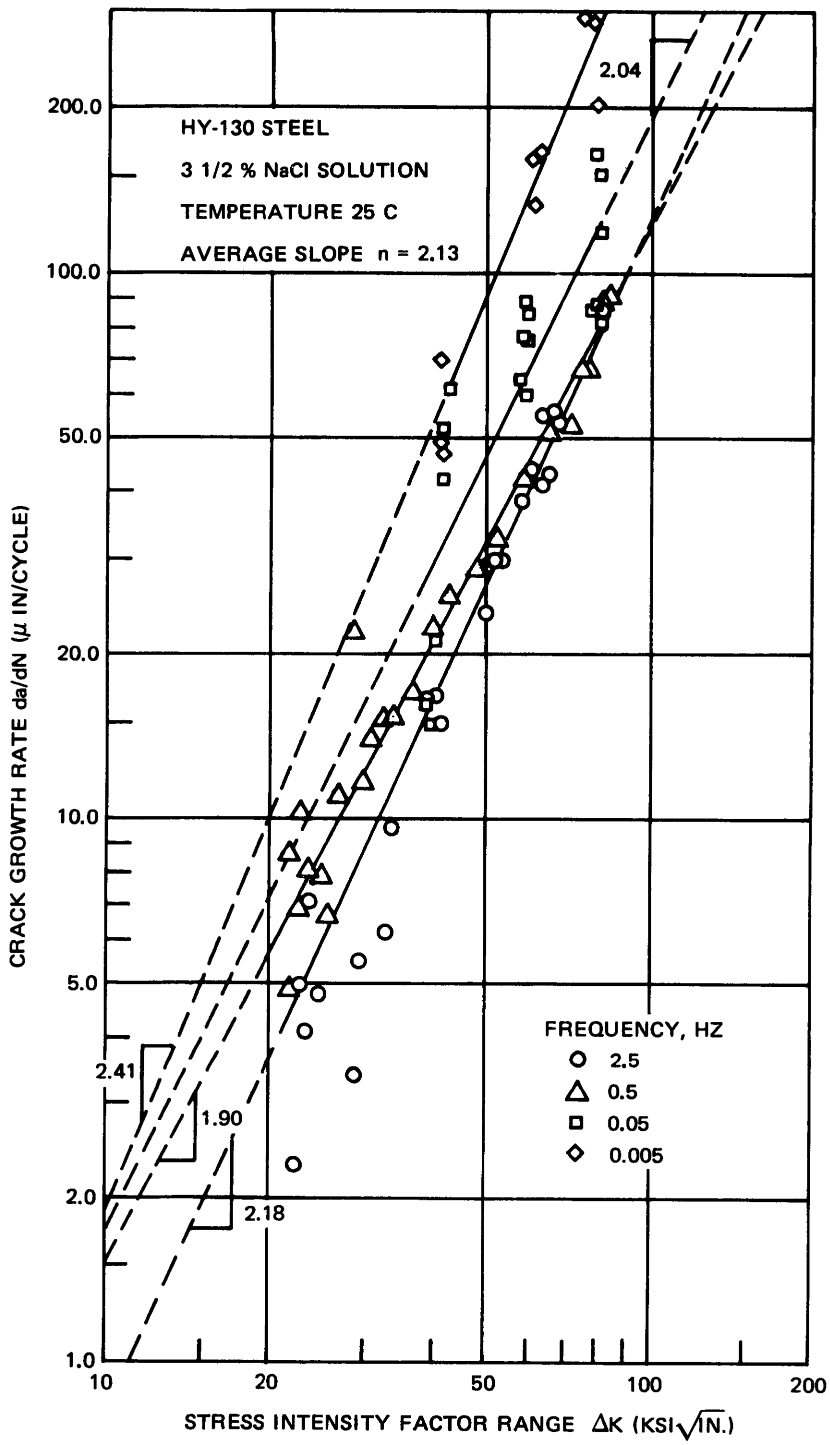


Figure 19 - Corrosion Fatigue Crack Growth Rate Behavior of HY-130 Steel at Temperature of 25 C

(From Ryder and Gallagher, 1972)

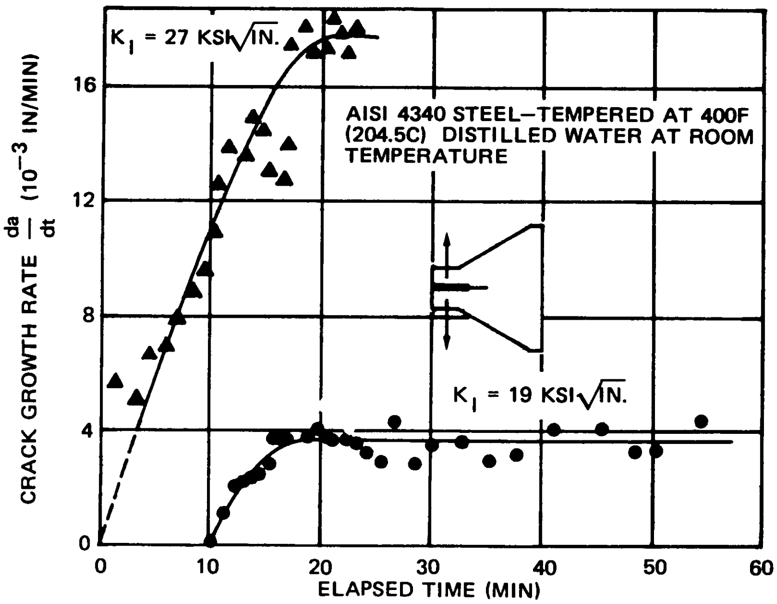


Figure 20 - Sustained-Load Crack Growth under Constant K_I Showing Incubation, Crack Acceleration and Steady-State Stages of Crack Growth

(From Hahn and Rosenfield, 1968)

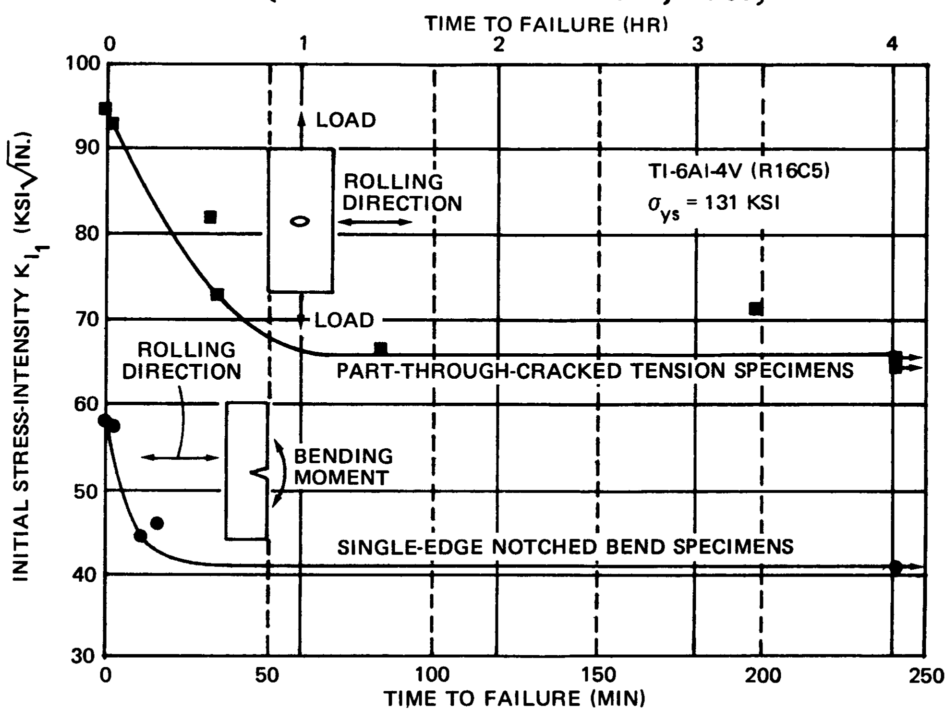


Figure 21 - Initial Stress-Intensity K_{I_1} versus Time-to-Failure for a 133-KSI Yield Strength Ti-6Al-4V Plate Material

(From Crooker and Griffis, 1972. The upper curve refers to data obtained from part-through-cracked (PTC) tension specimens, and the lower curve shows data from single-edge notched (SEN) bend specimens. Schematic illustrations of the orientation of the PTC and SEN specimens are shown with respect to the original rolled plate.)

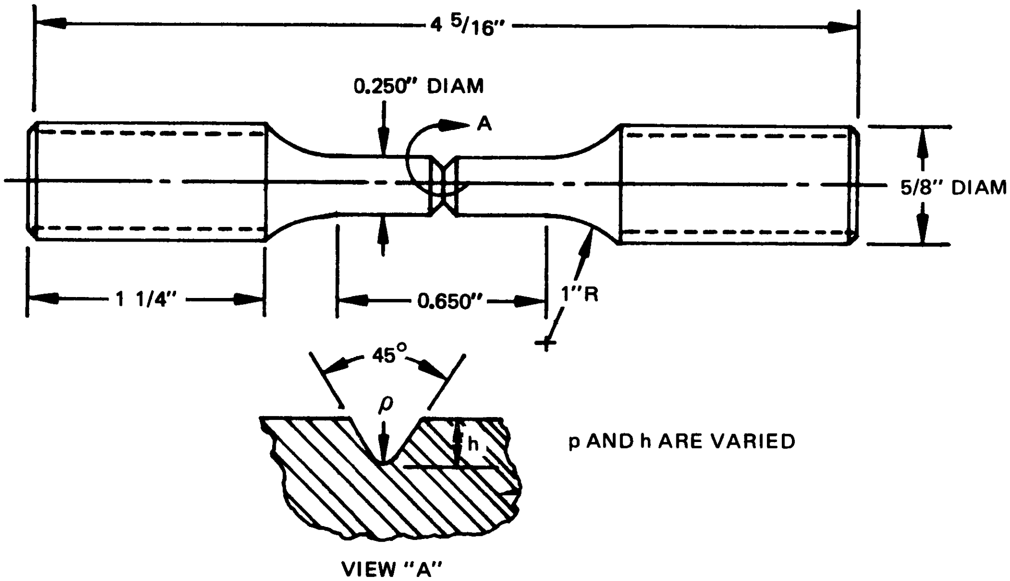


Figure 22a - Type 1

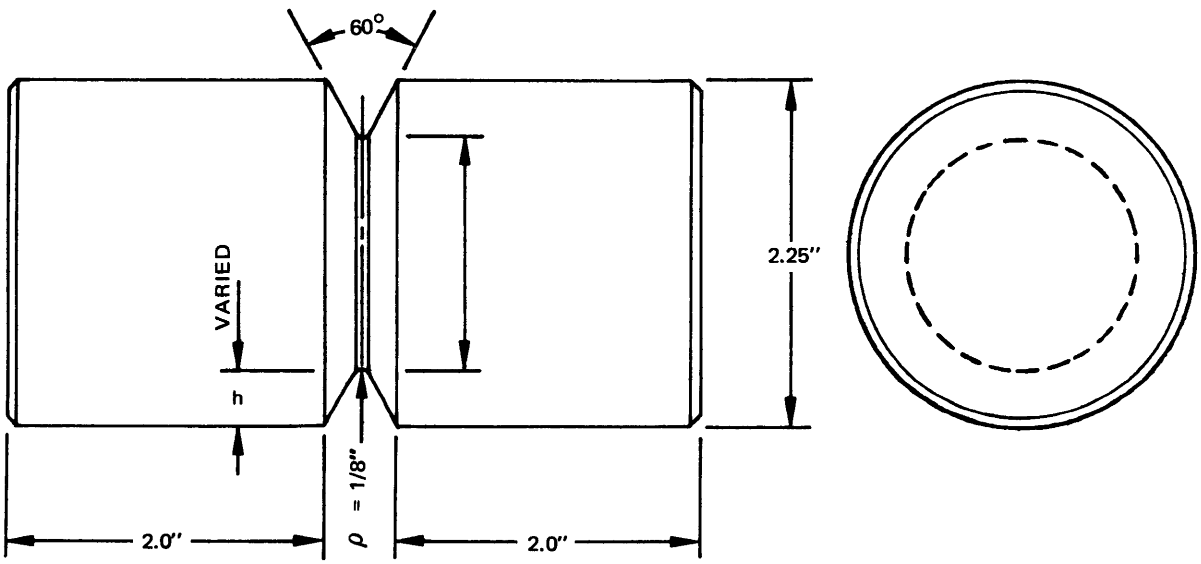


Figure 22b - Type 2

Figure 22 - Round Notched Bar Specimens

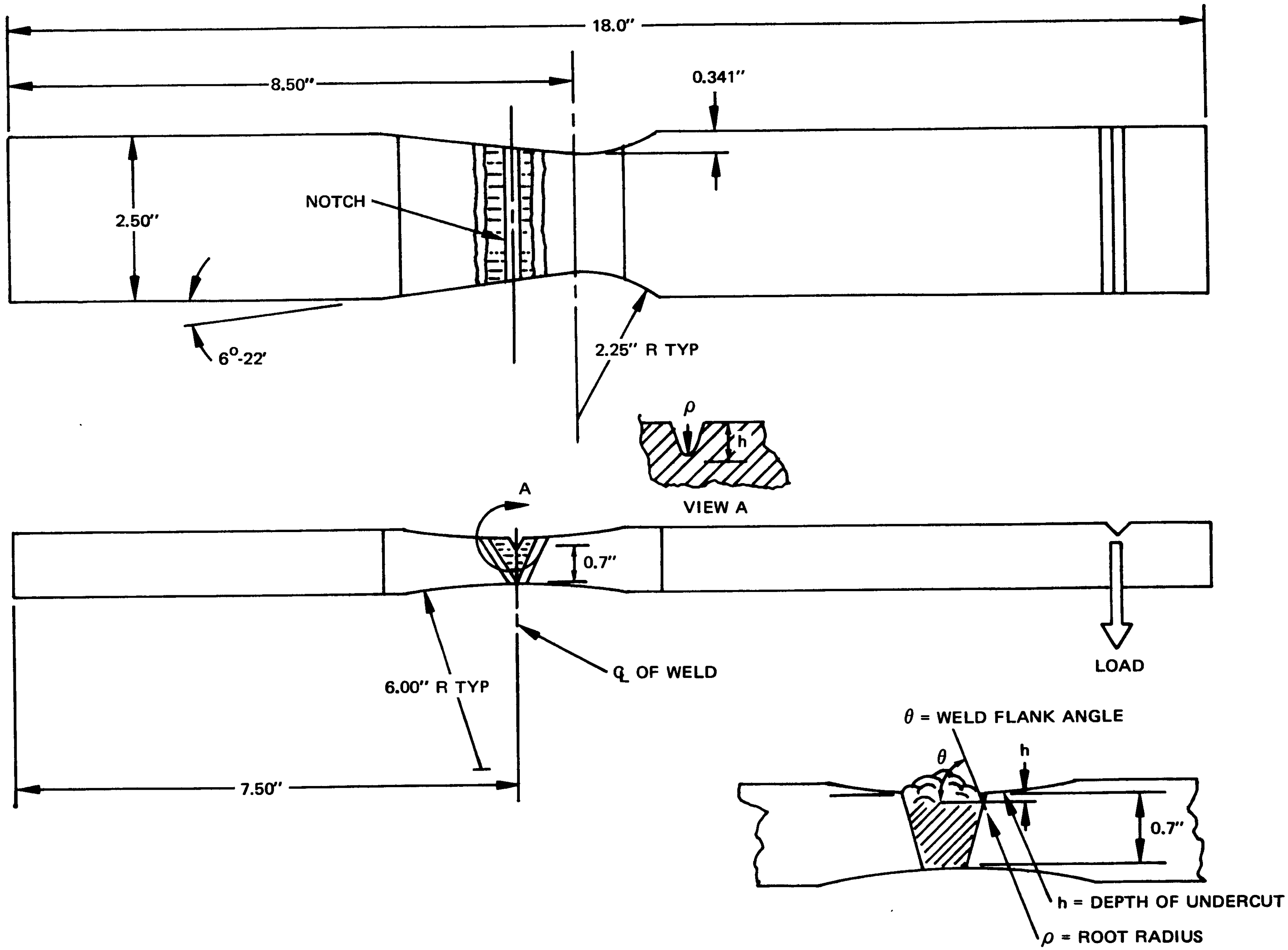


Figure 23 - Notched Welded Cantilever Plate Specimens

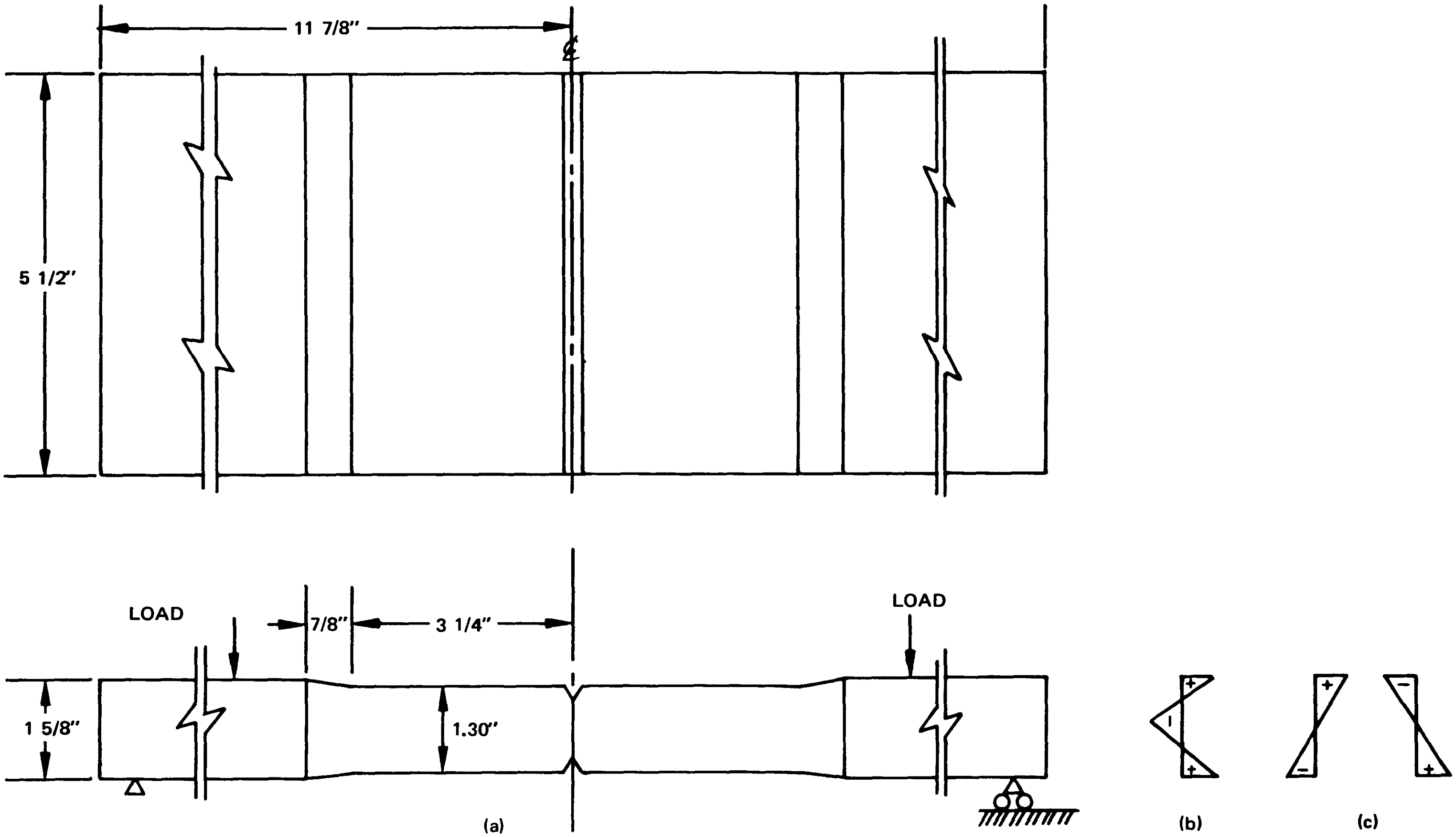


Figure 24 - Prestressed Notched Beam Specimen
(a) indicates specimen geometry, (b) is an example of the initial residual stress pattern, and (c) shows load-induced stress distributions)

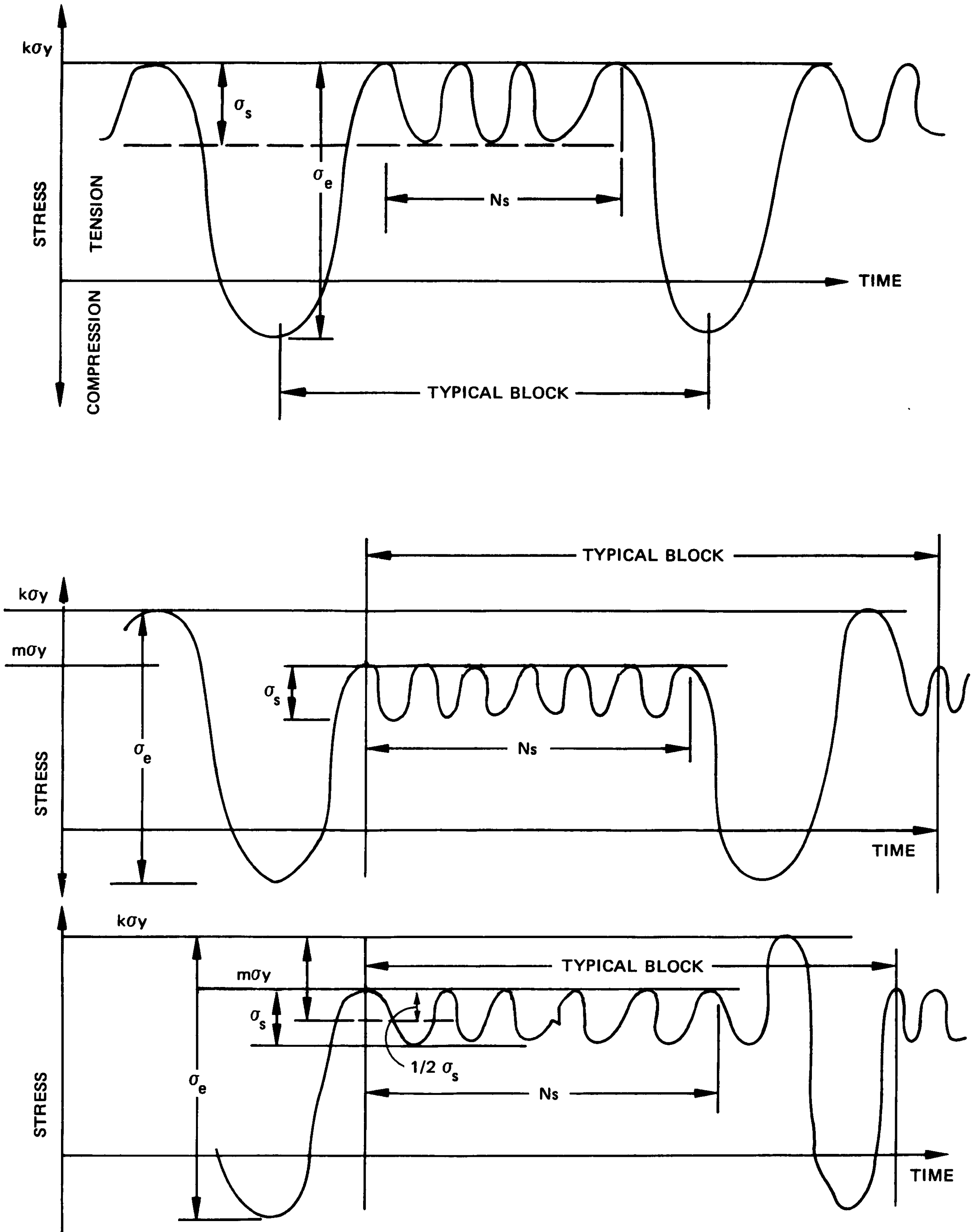


Figure 25 - Two Level Loading Profiles

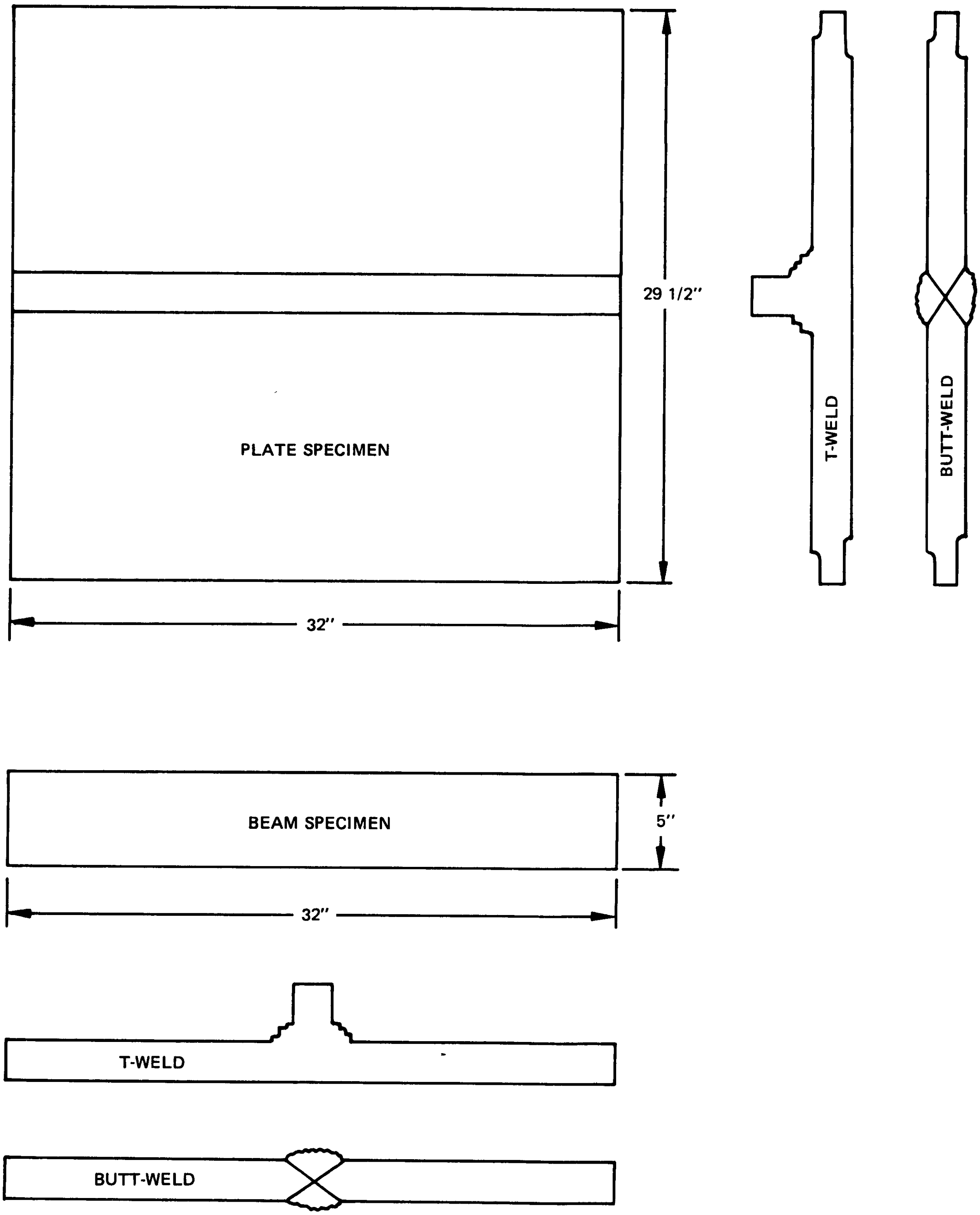


Figure 26 - Typical Plate and Beam Type Specimens
(From Macco 1972)

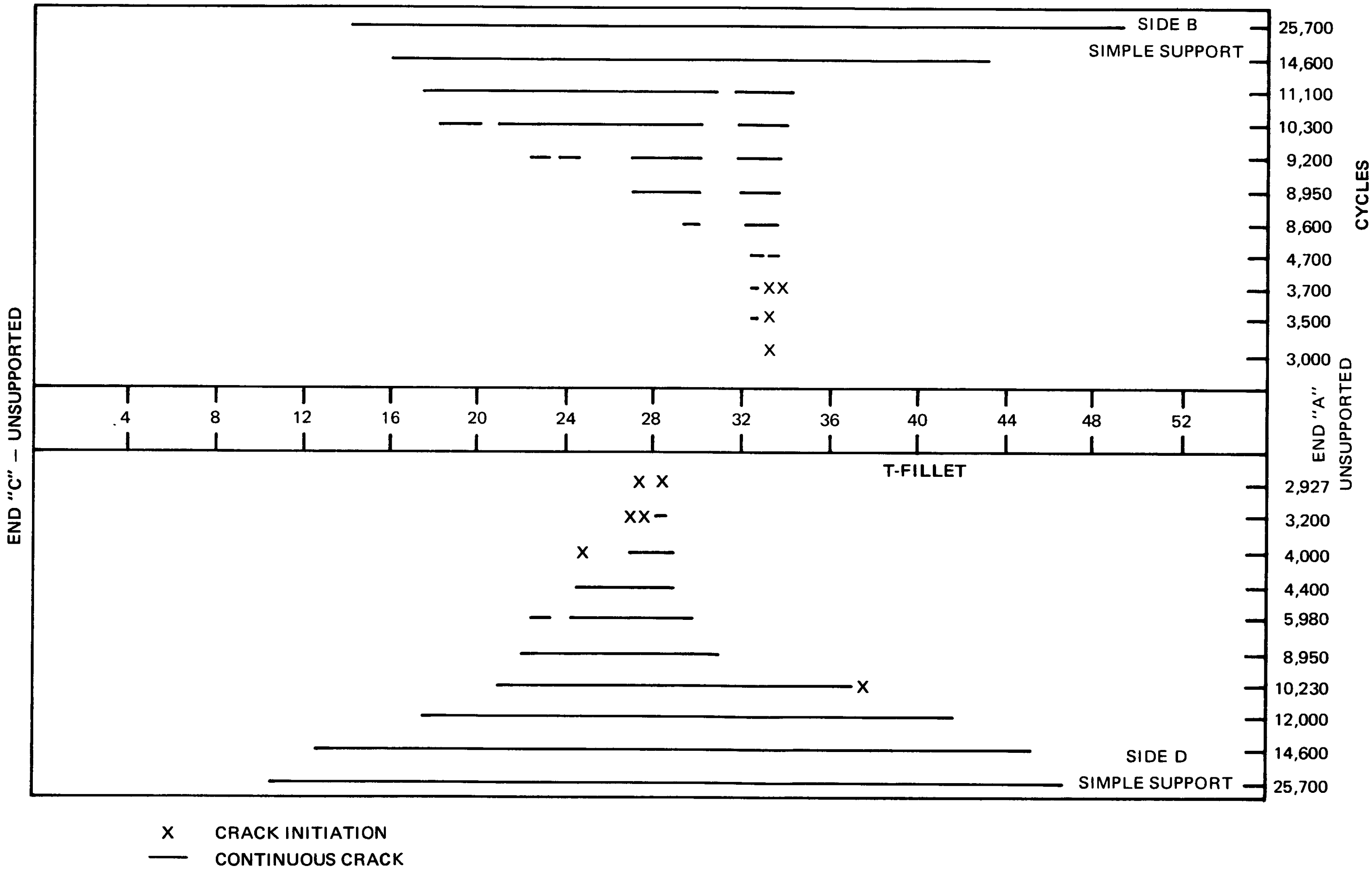


Figure 27 - Crack Initiation and Crack Growth Data for Plate Specimen
(From Rosen and Cordiano, 1966)

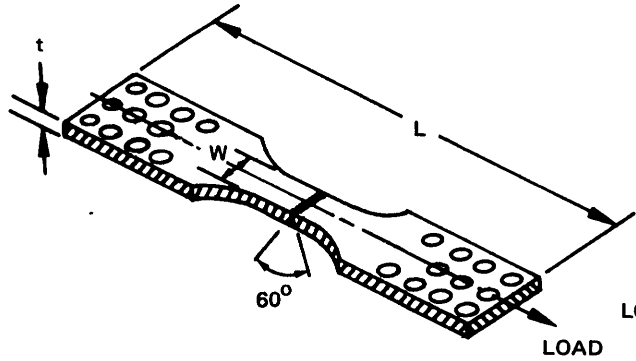


Figure 28a - Transverse Butt-Welded Specimen (Radziminski et al., 1970)

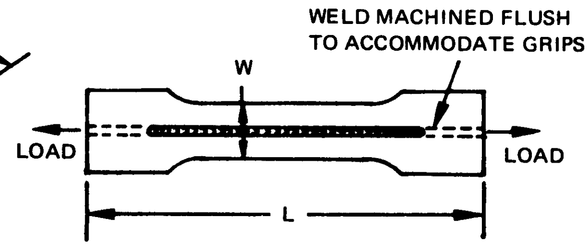


Figure 28b - Typical Longitudinal Butt-Weld Specimen (Gurney 1968)

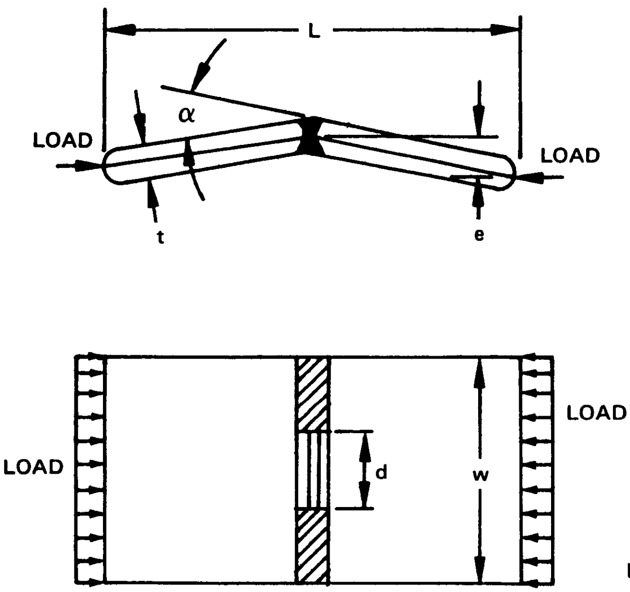


Figure 28c - "Knuckle" Specimen

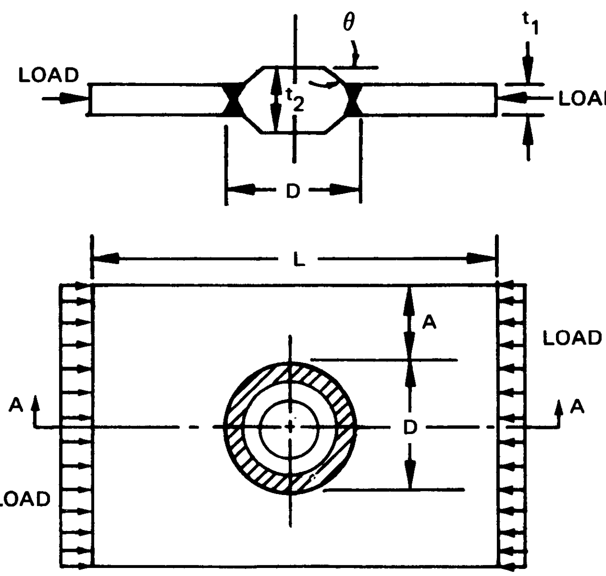


Figure 28d - Suggested Patch Welded Specimen

Figure 28 - Butt-Welded Axial Fatigue Specimens

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13 ABSTRACT

Low cycle fatigue may be one of the controlling considerations in the utilization of new high strength materials in submarine hulls. This report outlines a program of experimental studies aimed at providing information germane to various aspects of structural fatigue evaluation.

The specimens described range from simple materials characterization types to complex butt and T-weldment structural elements. Materials of interest are HY-130, Ti-100, and HY-180. The report includes a discussion of the relation between various facets of analytical modeling of structural fatigue and testing goals for specific specimens.

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