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A STUDY OF THE INFLUENCE OF GEOMETRY ON THE STRENGTH OF PATIOUE CRACKED PANELS

B. K. Walker



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#### FOREWORD

This report was prepared by Northrop Norair, a Division of Northrop Corporation, Häwthorne, California, under Air Force Contract AF 33(615)-2522. The effort reported herein is a part of an advanced development effort under Project 1407, "Structural Analysis Methods," Task 146704, "Structural Fatigue Analysis." The work was administered under the direction of the Air Force Flight Dynamics Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio, by Mr. V. E. Kearney, FDTR, Project Engineer.

The research reported herein was conducted between June 1965 and Hay 1965. The report was submitted by the author for review by the AFFDL on 1 June 1966. This report has been assigned NOR 65-131 for internal control at Northrop. Norair.

The author expresses appreciation for technical support provided throughout the program by Mr. D. P. Wilhen, the valuable contributions of Mr. John Spratt, Test Engineer, and Mr. Mark Welever, Laboratory Technician, and to the many other Norair personnel who contributed to the program. The aforementioned program was under the technical direction of Mr. R. D. Hayes.

Fublication of this report does not constitute Air Force approval of the reports findings or conclusions. It is published only for the exchange and stimulation of ideas.

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FRANCIS J. MANIK, JR. Chief, Theoretical Mechanics Branch Structures Division

#### ABSTRACT

The objectives of the study program were to define and verify a synthe is of strength-limiting paremeters for fatigue cracked panels which would be applicable to the wide range of conditions of interest in the engineering problem of strength analysis and to present this synthesis in a form that would lead to a better conceptual understanding of the interaction between parameters.

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The program consisted of an analytical study and a supporting experimental study. The analytical study, governed by the above objectives, considered fracture in the elastic range with buckling restraint provided, fracture combined with net fortion and gross section yielding, and fracture in the elastic range for unrest rained panels. The design problem involving appreciable amounts of slow hear was also considered. The experimental program provided supporting information on the behavior of fatigue cracks for bare 2024-T3 aluminum. Limited test data were elso obtained for dupler annealed titanium 8A1-1Mo-1V. The aluminum alloy crack lengths ranged from .5 inch to over 10 inches. Panel widths were thirty, twenty, twelve and nine inches; and nominal panel thicknesses were .080 inch, .063 inch, and .032 inch. The titanium alloy panel widths were twelve and nine inches, and thicknesses were .045 inch and .020 inch. Buckling restraints were used for approximately half of the panels tested.

Test information from other sources was used to illustrate specific points in theory and to show the generality of conclusions.

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## LIST OF SYMBOLS

A	area	inches <sup>2</sup>
С	boundary influence coefficient	·
c	spring constant for elestic restraint of column	psi
E	Young's modulus	ksi .
e <sub>B</sub>	critical column strain for buckling	inches/inch
Esec	secant modulus	ksi
epy	component of plastic strain normal to a crack	inches/inch
eu	ultimate crack tip strain	inches/inch
e <sub>x</sub>	component of elastic strain parallel - to a crack	inches/inch
ey	component of elastic strain normal to a crack	s inches/inch
I	moment of inertia	fiches
k	crack tip stress intensity parameter	ksi Vinch
k2	crack tip stress intensity parameter corresponding to the beginning of unstable tear	ksi Vinch
L	crack length	inches
$l_1$	initial crack length	inches
Π	interaction exponent	
2 <sub>B</sub>	critical column load for buckling	kpr of z
r	radius of plastic zone	inchés
5	$\sqrt{1+\frac{4}{2}}$	
t	panel thickness	inches
W	panel width	nches
ß	4 c/421	inches

LIST OF SYMBOLS (Cont.)

inches

ksi .

A limped multiplying parameter for comparison between crack buckling and an Euler column

buckling deflection measured at crack

foisson's ratio

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Poisson's ratio for plastic strain

effective crack tip radius	inches
width adjusted stress	ksi
critical column stress for buckling	ksi
gross uniaxial stress normal to and - away from a crack	ksi
gross panel stress away from and parallel to a crack (biaxial stress)	ksi
gross panel stress away from and normal to a crack (biaxial stress)	ksi
net cross section stress	ksi
ultimate gross panel stress corresponding to e <sub>u</sub>	ksi
	-

## yield stress

#### I INTRODUCTION

During the past several years, there has been considerable advancement in the concepts of fracture mechanics and in the application of these concepts to the problems of material evaluation1. In those design cases where relatively small flaws are present at the onset of fracture; a fracture mechanics approach has also proven valuable<sup>2</sup>. However, for design and strength svaluations for those relatively ductile materials of most interest for algoraft structure. larger flaws or fatigue cracks are more likely to ba of interest. For these larger flaws, parameters not normally considered is part of the materials evaluation can have a significant influence on the resulting strength. Thus while materials evaluation studies have for the most part epiloyed the fractore mechanics concepts, many of the studies more directly concerned with atrautural evaluation have chosen elternate approaches which permit the introduction of additional variables3,4,5,6. One of these alternate methods, the notchstrength analysis method<sup>5,6</sup> has found favor for its ability to evaluate the strength reduction resulting from fatigue cracks for those cases where general yielding accompanies fracture and also for those cases where buckling occurs due to the presence of a fatigue crack. The notch analysis method makes use of an effective radius concept, and, thus, the information usually gathered during material evaluation studies based on fracture mechanics concepts is not useable. Data from which the influence of general yielding and panel buckling can be determined are seldom available.

In order that the bulk of information now being complied on fracture strength be more applicable to design oriented problems, further understanding of the influence of geometric variables must be attained and design methods using this understanding in conjunction with fracture mechanics concepts should be explored. The program reported herein has been undertaken with this objective in mird.

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The influences of gross section yielding and panel buckling on the stress Extensity for the end of stable tear in wide panels is presented in the form of a diagram (Figure 29) having three non-dimensional area representing ultiate strength in lure, elastic fracture and the influences of panel buckling. Three sones of behavior are designated on the diagram as follows:

Zone I Sport Cracks - The beginning of unstable tear occurs due to a combination of fracture and gross section yielding. The suggested equation for predicting the stress intensity at the beginning of unstable tear is

$$\left\langle \frac{\sigma_{c} - 0.8 \sigma_{y}}{\sigma_{u} - 0.8 \sigma_{y}} \right\rangle^{m} + \frac{\overline{\sigma} \ell^{\frac{1}{2}}}{k_{2}} = 1$$

Zone II Intermedizte Cracks - The beginning of unstable tear occurs with gross panel stress in the elastic range. The influence of panel buckling in 2024-T3 aluminum can be assumed constant, with the stress intensity k, at the onset of unstable tear correspondingly less than in guided panels. The quantity,  $\sigma_0 - \cdot 8 \sigma_y^{-m}$ , is

as zero so that the equation for 
$$p$$

negative and, thus, assumed as zero so that the equation for predicting unstable tear becomes

$$\frac{fl^{\frac{1}{2}}}{k_{2}} = 1$$

Zone III Long Gracks - Gracks whose length to panel width ratio exceeds 1/3 can be expected to "how further reduction in the stress intensity, k<sub>2</sub>, resulting from the influence of panel width on buckling.

The use of the interaction diagram is illustrated by data from 20 and 30 inch wide panels of 2024-T3 aluminum. Trends and behavior of fatigue cracks in 9 inch wide and 12 inch wide 2024-T3 aluminum and titanium SAL-IMo-IV are explained in terms of components of the interaction diagram and by curves showing strength reduction in narrow panels beyond that predicted by elastic analysis methods.

#### 111 PREFACE

The discussion and theory are presented in the following sections. Section IV deals with the problem of panels to which sufficient lateral support at the panel remains essentially flat at failure (guided panels) 's provided uss section remains elastic. These limitations in behavior curand the n rently i ... ne the problem area in which linear elastic fracture mechanics have proven relatively successfull. In approaching the presentation of theory for this range of behavior, the need to incorporate problems involving stable crack growth led to the choice of static considerations of ultimate strain at the crack tip as a failure criterion rather than the more standard energy approach. The first section of theory thus represents an attempt to restare basic concepts of fracture mechanics in terms of static considerations insofar as prace tical. An attempt has also been made to define limitations of current theory and thus define the limits of panel geometries to which the extensions of theory explored in subsequent sections are applicable.

The sections that follow consider extensions of theory for problems of general yielding accompanying fracture, failure of unrestrained panels that distort from a flat panel prior to failure (panel buckling) and finally, the synthesis of the strength reducing influences of fracture, yielding, and panel buckling into a single failure diagram.

An additional section discusses the problem of predicting the amount of slow tear preceding final rupture and includes suggestions of how this additional variable can be introduced into failure considerations.

Because of the complex nature of the fracture problem, many of the formulations suggested are empirical in nature. In each case, however, an attempt has been made to ratain at least a qualitative theoretical base and to provide for growth potential within the basic formulation as understanding is increased. It is hoped that the resulting compilation will thus both add to the basic understanding of the interaction between strength influencing percenters and encourage additional studies to explore details which were of necessity left unresolved by the scope of the present program.

The experimental data for 2024-T3 aluminum and titanium 841-140-19 used in the development of curves and illustration of theory, unless specificatly noted, were obtained during the supporting test program. A tabulated summary of these data along with stress vs crack length curves are found in the Appendix.

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#### IV GUIDED PANELS WITH BLASTIC BEHAVIOR AWAY FROM CRACK

#### COMPARISON OF FAILURES IN MATERIALS WITH LOW AND HIGH DUCTILITY

The definition of failure in a brittle material is a relatively simple matter due to the lack of significant amounts of slow tear. Thus, the initial creck length and the stress corresponding to the seximum load are all that need be considered. Additionally, plastic deformation is not a significant consideration and an elastic formulation of stress concentration or energy is reasonably applicable. For a relatively ductile material, however, the probica bacomes more complex. Stable slow tear initiates at a load level co id-erably below the ultimate load. In this stable slow hear phase, the ter ng can be stopped by stopping the loading process. Eventually, a maximum 3d is reached. If this maximum load is approached through a process of 11 increments of loading, successively longer increments of tear an le observed as the maximum load is approached. At the maximum load, an additional increment in logd will result in a continued slow extension of the crack, indicating an unstable condition. Near the end of this unstable phase of crack extension, noticeable acceleration occurs ending in an explosive and almost instantaneous separation of the remainder of the uncracked section.

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From the above failure sequence for a relatively ductile material containing a crack, two different methods of measuring or defining failure criteria are currently used.

- 1. The initial crack length and stress at maximum load<sup>5</sup>.
- 2. The crack length and stress at maximum load 1.

Two suditional criteria could be of interest.

- 3. The crack length and load at the onset of crack acceleration.
- 4. The crack length and load at rupture.

Each of the above criteria properly have a place in the overall problem of strength evaluation and analysis. The typical sequence of these four possible criteria are shown diagramatically in Figure 1. From Figure 1, it can be seen that with the exception of the first criterion, each criterion could be represented by some instantaneous condition of stress, strain, or energy within the panel during the failure sequence. The first criterion of initial crack length and maximum load is not subject to rigorous stress, strain or energy interpretation. It is a combination of two quantities occurring at distinctly different times during the failure sequence. It can also be seen that only the first criterion permits the determination of the maximum load associated with a known initial crack length. A criterion relating initial crack length to maximum load is definitely needed. A possible method for developing this criterion, through parameters of stress or strain, is through the definition of the amount of stable crack extension<sup>9</sup>. This is also shown on Figure 1.

For the purposes of this report, the second criteriun, crack length and



FIGURE 1 T

TYPICAL STAGES OF TEAR FOR A PATIGUE CRACK IN DUCTILE HATERIAL stress at maximum load, will be used as a definition of crack instability. Whenever reference is made to one of the four points shown on the Figure 1, the appropriate subscript will be used.

### CRACK TIP STRESS INTENSITY PARAMETER

Because of the need to consider stable tear as well as the critical crack length - maximum load relationship, a crack tip stress or strain approach is most applicable. This approach can be presented in the form of a stress intensity parameter for wide panels

$$\mathbf{k} = \sigma_0 L^{\frac{1}{2}}.$$
 (1)

where:

 $\mathbf{k} = \mathbf{a}$  measure of crack tip stress intensity

or = gross panel stress

 $\lambda$  = the total crack length

In applying the scress /ntensity approach to the critical crack length maximum load point, the upp//r limit of the stable crack lengths can be considered to be the same as the lower limit of unstable crack lengths defined by a critical energy release rate. This resolves to the fact that either a critical crack tip stress or strain, of a critical energy release rate is sufficient criteril for the definition of instability <sup>9</sup>, <sup>10</sup>. It is thus possible to use a stread to naity approach and still be compatible with fracture mechanics concept instability and energy release rates.

#### STRAIN INTERPRETATION OF THE STRESS INTENSITY PARAMETER

For the purposes of explanation of slow tear phenomena and the consideration-of failure under combined conditions of fracture and yielding, it is desirable to appraise at least qualitatively the components of the stress intensity parameter k. This can be accomplished by considering the equation for elastic stress or strain at the tip of a crack in an infinitely wide panel:

$$e_{\rm u} = \frac{\sigma_{\rm u}}{E} = \frac{\sigma_{\rm o}}{E} \left( 1 + \sqrt{\frac{2L}{\rho'}} \right)$$
(2)

where:

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eu = critical or ultimate crack tip strain (actually, this is a physically undefinable quantity as neither the gage length nor stress condition is known to the extent that it can be derived from present methods of measuring strain on unnotched tensile coupons)

 $\sigma_{\rm u}$  = Ultimate gross panel stress corresponding to  $e_{\rm u}$ 

L = Young's modulus

- $\mathcal{L} = \operatorname{crack} \operatorname{length}$
- $\rho = \text{Effective crack tip radius similar to that defined by Neuber'$

Equation (2) involves two unknowns,  $e_u$  and  $\rho'$ . In order to use equation (2) without solving independently for  $e_u$  and  $\rho'$ , it is necessary to assume that  $\rho'$  will be small so that  $\sqrt{2L} \gg 1$ . With this assumption, equation (2) becomes

$$\sigma_0 l^{\frac{1}{2}} = e_u E \sqrt{\frac{p'}{2}} = k$$
 (3)

Equation (3) is most applicable to problems involving elastic behavior. For those cases where the observed critical crack lengths occur at a near constant value of  $k_2$  with local plastic deformation adjacent to the notch tip, equation (3) can be used provided the quantity p' is assumed as a lumped parameter used to account for the influences of local plasticity.

The stress intensity parameter can thus be considered a parameter having two unneasurable components  $e_{ij}$  and  $\rho'$ . Of these two,  $e_{ij}$  must be at some critical or limiting value whenever tear initiates. Instability may or may not follow as instability depends on incremental changes in crack tip conditions as well as on the instantaneous condition of critical crack tip strain. These incremental changes can be qualitatively explained by variance of the quantity  $\rho'$ .

#### RELATIONSHIP BETWEEN THE STRESS INTENSITY PARAMETER AND CRACK TIP STRAIN

During the slow tear phase, an interesting relationship between the stress intensity parameter, k, and true crack tip strain can be observed (see Figures 44 and 45). The onset of slow tear indicates that a maximum or critical crack tip condition has been reached. After the first increment of tear at constant load, the crack remains stationary until additional load is applied. With sufficient additional load, additional tear occurs which will again halt if the load is held constant. Thus, it can be observed that the critical strain level at the crack tip can be reached many times between onset of tear and instability; each time at an increased value of k. Referring to equation (3), for a given value of k, the maximum crack tip strain is dependent upon the value of the effective radius  $\rho'$  which is assumed to account for the influences of local plasticity. While this interpretation of equation (3) is not rigorous, some useful qualitative evaluations can be made.

In terms of equation (3), the range of stable tearing that takes place prior to instability of a crack can be interpreted to mean that once the crack tip strain reaches some critical value, additional stable tear is possible only with an increase in  $\rho'$ . Instability is thus considered to occur whenever the crack tip strain has reached a critical value for tear and  $\rho'$  can no longer increase sufficiently to compensate for additional increases in k. For changes in k with the load held constant, equation (3) could be written for an incremental increase in the length  $\lambda$  up to the critical crack length at which instability occurs.

$$\frac{dk}{d\lambda} = \frac{e_{\rm u}}{\sqrt{2}} \frac{E}{d\lambda} \frac{d\sqrt{\rho'}}{d\lambda}$$
(4)

For the first unstable increment of crack extension, equation (4) becomes

$$\frac{dk}{d\ell} > \frac{e_u E}{\sqrt{2}} \quad \frac{d \sqrt{\rho'}}{d\ell}$$
(5)

It has been suggested that the increase in  $\rho'$  can be attributed to the development of the shear mode of fracture<sup>13</sup>; however, observations on 2024-T3<sup>13</sup> which were substantiated during this program showed the development of the tear resistance to occur with fully developed shear suffaces throughout. Thus, a more general dependence of tear resistance on plastic deformation is indicated.

#### TAS INFLUENCE OF PANEL WIDTH

The influence of free panel boundaries near a stress concentration such as a fatigue crack causes stress in the vicinity of the crack tip to be higher than would be the case if the boundaries were remote. To account for this influence, a stress correction is usually employed. The stress correction used throughout this report is that proposed by Dixon <sup>11</sup>.

$$\overline{\sigma} = \sigma_0 \left[ \frac{1}{1 - \left( \frac{l}{w} \right)^2} \right]^{\frac{1}{2}}$$
(6)

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 $\overline{\sigma}$  = width adjusted stress

panel width

The Dimon correction has found favor in engineering studies  $^{6,12}$  and is within 3 percent of the Westergard width correction used in the current fracture toughness formulation 12

$$\frac{1}{1-\left(\frac{\ell}{W}\right)^2} = \sqrt{\frac{w}{\pi \frac{\ell}{2}}} = \sqrt{\frac{\pi \frac{\ell}{2}}{\frac{\pi}{2}}}$$
(7)

In addition to the elastic width correction (equation 6), an additional width influence has been illustrated 1,13 which, when significant, would cause the stress intensity at the beginning of unstable tear  $(k_2)$  to be a variable with width. An easy way to explain qualitatively this width influence can be obtained by rewriting equation (4) for a panel of finite width using equations (1) and (6)



Equation (8) shows that the rate of change of k with respect to l increases with the l/\* ratio time agreeing with the observations of Reference 1. Since the rate of change of  $\sqrt{p'}$  with respect to l seems to diminish near the instability point, the last possible equilibrium solution of equation (8) tends to be at lesser values of k for increasing values of l/\*. For values of l/\*less than 0.5 in 2024-T3 aluminum, the change in instability from that of an infinitely wide panel is relatively small as shown by the tangency of effective stress e ' tear curves, Figure 2a, and in the  $k^2$  vs l plot, Figure 2b. Figure 2b can easily be compared to the energy release rate form of presentation. Figure 2a is however considerably easier to construct.

The two width corrections discussed above, equations (6) and (8), are both based on elastic theory and are thus increasingly inaccurate as local plastic deformation near the notch increases. However, as long as the local plastic deformation reaches approximately the same extent at the beginning of unstable tear over the range of geometries of interest, predictions of tear instability based on these elastic equations can be relatively successful. In this respect, there is an addicional width influence that must be considered. This is the possibility that local plastic deformation at the crack tip can be significantly influenced by the proximity of the panel boundaries. In actuality, the plastic deformation should be influenced by boundary conditions whenever the boundaries are close enough to influence the elastic stresses. For a given crack length, this influence should generally increase as ductility increases and as width decreases. The panel widths for which this influence causes significant error in unstable tear predictions based on elastic equations can usually be avoided by following recommended fracture mechanics practice. Particular problems arise, however, when elevated temperature testing is involved.

To illustrate the nature of the influence of panel width on guided panels of varied materials. Figure 3 shows the fraction of wide panel fracture strength  $\left(\frac{k_2}{k_2}\right)$  strained in successively smaller widths for a veriety of materials. Width corrections were made using equation (6). Width corrections of the type illustrated by equation (8) were considered to be small as the *l*/w ratics of the test panels were generally 0.4 or less. The yield/ultimate ratio of the several materials is also shown to indicate the general influence of ductility. Figures 4 and 5 show similar behavior as a function of temperature in test panels data selected from the same heats of materials tested at ambient and elevated temperatures.

#### DEFINITION OF WIDE AND NATBOW PANELS

From Figure 3, it can be seen that for each material, there is a width of panels above which further increase in width will cause little if any change in the stress intensity at instability. Panels having widths equal to or above this limiting value will be referred to as wide panels in this report. Panels having widths less than this limiting value will be referred to as



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36 NCH NCH NCH NCH FIGURE 3 RELATIONSHIP BETWEEN YIELD/HUTIMATE RATIO, STRESS INTENSITY, AND WIDTH FOR GUIDED PANELS .06.0 I 020 060 060 ALL CANSTANT Lo, "DATA FROM REF. 14 32 1 1 1 1 ר רו ה רו a 10/m A AH 355 BASED ON JONSTANT I V 7075T6 BASED ON CONSTANT I 2024TB1 BASED ON CONSTANT I O 2024TB BASED ON CONSTANT I 2024TB BASED ON CONSTANT I 2024TB BASED ON CONSTANT I .25/15 58 24 ۰. PANEL VIDTH (W) IN MUCHES ۲. ۲. <u>ا</u>ه ūo 9 8 -95 ĩ لوح 6 Aa 5 5 1 1 1 5/8 30 ٦.6 • 9 4, 4 <u>k</u>5∞ <u>k</u>5 STARSS INTENSITY AT UNSTABLE TEAR IN SIDE FANELS 11

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#### narrow panels.

For the present, strength prediction of narrow panels can best be handled by use of curves such as Figures 3, 4, and 5. While this catagory of panels is generally known to exist, it is significant that much of the available data falls within this range. It is possible that correlations such as shown will lead to a better understanding of this phenomena and to methods of interpreting wide panel strength from data obtained from narrow panels. Before this can be done, however, a considerably more complex means of ranking materials must be devised to account for ultimate strein differences and strain hardening characteristic.

Because of the limitations in using the stress intensity parameter in con-<u>junction with marrow panels</u>, the discussion of stress intensity applications in this report is limited to wide panels for which elastic considerations of width correction are sufficient.

#### PLASTIC ZONE CORRECTIONS TO STRESS INTENSITY

At this point in discussion, wide panels have been defined as those panels whose tear behavior can be correlated in terms of parameters based on elastic considerations (equations 1, 5, 8). Normally, fracture mechanics includes an additional correction based on the size of the plastic zone adjacent to the crack tip. The plastic zone correction is not used in this report. However, the wide use of the plastic zone correction, makes it desirable to discuss the reasons for not including it in the computations of stress intensity.

The plastic zone correction to the stress intensity parameter requires that the radius of the plastic zone be added to each end of the crack tip and that the resulting increased length be used in stress intensity calculations is an "effective crack length."

The Irwin model for computation of the plastic zone size can be expressed

 $r_{p} = \left|\frac{1}{2}\left(\frac{k}{\sigma}\right)^{2}\right|$ 

where 
$$k = \sigma_0 \sqrt{\pi - \frac{1}{2}}$$

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 $r_p = radius$  of the plastic some

An improved form<sup>14</sup> based on the Dugdale model for a crack<sup>15</sup> shows the size of the plastic zone to be dependent on the crack length in the form

$$r_{\rm p} = \frac{\hat{j}}{2} \left[ \sec \left( \frac{\pi}{2} \frac{\sigma_0}{\sigma_y} \right) - 1 \right]$$
(11)

(10)

The dependence of  $r_p$  on crack length, as proposed in Equation (11) can be seen in its series expansion13.

$$\mathbf{r}_{\mathbf{p}} = \frac{\mathbf{Q}^{2}}{4} \left[ 1 + \frac{5}{12} \left( \frac{\mathbf{Q}^{2}}{\mathbf{L}} \right) + \frac{61}{360} \left( \frac{\mathbf{Q}^{2}}{\mathbf{L}} \right)^{2} + \frac{277}{4032} \left( \frac{\mathbf{Q}^{2}}{\mathbf{L}} \right)^{3} + \cdots \right] (12)$$

where

$$\dot{q} = \frac{\pi}{2} \frac{k}{\sigma y}$$

It would appear that use of a correction to crack length based on a plastic zone predicted by equations (10) or (12) would considerably improve the lower limit to the range of widths for which strength could be predicted by use of stress intensity parameter k. Hence width influences shown in Figures 3, 4, and 5 might be greatly reduced.

An attempt to apply this correction to data obtained during the test program for 2024-T3 sluminum showed an interesting fact. With reduced width for panels of 20 inches, 12 inches, and 9 inches, unstable tear  $(k_2)$  occurred at reduced stress levels. Gross stress at unstable tear plotted against crack length to panel width ratio at instability, showed all three widths to have nearly equal failure stresses at the same l/w ratio (Figure 6). To illustrate the influence of this relationship between l/w and gross stress on the computed plastic zone sizes, equation 10 may be used to write the ratio of plastic zone sizes for a 9-inch and 12-inch panel of 2024-T3 aluminum.



From Figure 6, a crack of l/w ratio of .3 will fail at the same gross stress  $\sigma_0$  in panels of 9-inch and 12-inch widths. Since the relationship between gross stress and width corrected stress,  $\sigma_i$  is dependent on the l/w ratio (equation 6), the values of  $\overline{c}$  will also be the same at failure. For this example, equation (13) can be written.

 $\frac{r_{p9}}{r_{p12}} = \begin{bmatrix} \overline{\sigma} (.3 \times 9)^{\frac{1}{2}} \\ \overline{\sigma} (.3 \times 12)^{\frac{1}{2}} \\ \overline{\sigma} (.3 \times 12)^{\frac{1}{2}} \end{bmatrix}^2 = \frac{9}{12} \text{ or } .75$ (14)

Equation (12), while giving slightly different results, still has the same trend as shown in equation (14). Computed plastic zone corrections are thus proportional to both panel width and crack lengths and revised values of the stress intensity parameter k2 showed the same velative influence of width. To verify that this phenomenon does occur in 2024-T3 aluminum, data from Reference 3 were also analyzed (Figure 7). No particular fundamental significance is, attached to this phenomenon as it does not occur for wider widths. The 20-inch wide and 30-inch wide panels of the test program showed no difference in strengths when compared on the basis of computed stress intensity at instability. Also, this / /w vs. stress relationship would not hold for panels of lesser ductility than 2024-T3 aluminum shown on Figure 3. Figures 6 and 7, and equation (14) do point out, however, that the practice of adding a plastic zone correction to crack length is less effective than the influence of width on stress intensity for the aluminum alloy 2024-T3. Due to the above reasoning, plastic zone corrections were not considered in the presentation of data of this report.





FIGURE 7 GROSS STRESS AT UNSTABLE TEAR VS. CRACK LENGTH TO PANEL WIDTH RATIO AT INSTABILITY FOR 2024-T3 ALUMINUM PANELS (DATA FROM REF. 3)

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#### INFLUENCE OF PANEL THICKNESS

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In general, the thickness of a panel can have significant influence on the stress intensity at which slow tear and crack instability will occur. However, the range of thickness for the aterials studied in this report caused both the beginning of slow tear and the beginning of unstable tear to occur in the shear mode (plane stress). While minor differences in tear behavior are bound to be present, they are considered subordinate to the more gross phenomens of geometric influences. For this reason, thickness differences have for the most part been ignored, and average values of stress intensity have been used.

### SUMMARY OF THEORY FOR GUILED PANELS WITH ELASTIC BEHAVIOR AWAY FROM CRACK

For wide panels, the range of crack behavior between the onset of stable tear and crack instability can be correlated and predicted in terms of stress intensity. This stress intensity parameter can be expressed in the form

$$\mathbf{k} = \overline{\sigma} \mathbf{j}^{\frac{1}{2}} \tag{15}$$

Tor wide panels, influence of width on the elastic stress intensity parameter can generally be adequately handled by use of a stress correction derived from elastic theory. Of these available, the Dixon correction has been selected

$$\overline{\sigma} = \sigma_0 \left[ \frac{1}{1 - \left(\frac{l}{v}\right)^2} \right]^2$$
(16)

Crack instability can be considered to be sensitive to the rate of change of stress intensity with length. This can be qualitatively illustrated by the relationship

$$\frac{d \left[\sigma_{0} l^{\frac{1}{2}} \left(\frac{1}{1-\left(\frac{1}{2}\right)^{2}}\right]}{dl} = \frac{\sigma_{criticel}}{\sqrt{2}} \frac{d\sqrt{\rho'}}{dl}$$
(17)

For values of //w less than 0.5, this width influence is small for 2024-T3 aluminum.

- 4. For panels having widths less than some minimum (Figure 3), the proximity of a free boundary can significantly influence the local plastic behavior adjacent to the crack tip and thus cause considerable reduction in strength from that predicted by elastic assumptions and wide panel behavior. In this report, panels in this category are referred to as narrow panels. The strength reduction in narrow panels generally increases as ductility increases and as panel width decreases (Figures 3, 4, and 5).
- 5. Plastic zone corrections to crack length are less effective as ductility increases. In 2024-T3 aluminum, a near constant relationship between *l/w* and gross stress at the beginning of unstable tear was found to exist. This relationship caused computed plastic zone corrections also to be proportional to width resulting in no improvement in the observed differences

in the stress intensity parameter for widths of 9, 12, and 20 inches. We difference in the stress intensity for unstable tear was found for 20 and 30 inch wide panels.

6. During the stable tear, the crack tip stress and strain can be considered to remain constant at a value critical for tear while compensating influences of local plasticity permit equilibrium to be sustained at increasing values of the elastic stress intensity parameter. This con be qualitatively explained in terms of an effective radius  $\rho'$  y the relationship:

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$$\frac{dk}{dl} = \frac{e_u E}{\sqrt{2}} \frac{d\sqrt{P'}}{dl}$$

7. The crack will continue to tear without further increase in load when

$$\frac{dk}{dl} > \frac{\mathbf{e}_{u} \mathbf{E}}{\sqrt{2}} \frac{d\sqrt{p}}{dl}$$

8. All observed failures in 2024-T3 and titanium CAL-IMO-IV were in the shear mode. Variation in critical stress intensities with thickness in guided panels is not a major consideration in 2024-T3 aluminum for thicknesses of .032, .033, and .030 inch. For the purpose of correlating large differences in the stress intensity at unstable tear resulting from geometric influences, average values of stress intensity can be used for the range of thicknesses in this report.
#### V GUIDED PANELS WITH INELASTIC BEHAVIOR AWAY FROM CRACK

#### APPLICATIONS

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For relatively ductile materials such as 2024-T3 aluminum at room temperature and titanium 8A1-1Mo-1V at 650 degrees (compare Figures 3 and 5), the behavior of fatigue cracks is such that the lower limit of the crack lengths that could reasonably be found in a structure are those that would only fail under stress conditions high enough to cause general yielding away from the crack. While this condition in itself implies a structure safe from catastrophic crack propagation at normal stress levels, it is desirable to be able to predict the ultimate strength of structure containing fatigue cracks in this range for the purpose of predicting probability of vehicle survival under severe conditions of environment. Additionally, for elevated temperatures, it wou'd be extremely desirable to be able to interpret correctly strength studies made using short cracks in small coupons<sup>16</sup>.

#### INTERACTION DIAGRAM

While there are many ways to approach the problem of fracture accompanied by yielding, the method selected herein uses the interaction diagram<sup>17</sup>. An interaction diagram can be constructed for any two (or more) failure mechanisms by the following steps:

- 1. The strength under each simple-loading condition (tension, bending, fracture, etc.) is first determined by analysis or test.
- 2. The combined-loading condition is represented by load (or stress) ratios R in which

$$R_{i} = \frac{\text{applied loading of type } i}{\text{critical loading of type } i}$$
(18)

the word "critical" can be interpreted generally to mean the loading at failure under conditions represented by the ratio  $R_1$  alone, whether it occurs by buckling, rupture, or any other form. For example, for the case of simple tension scress in an uncracked panel

$$R_1 = \frac{\sigma_0}{\sigma_u}$$
(19)

Thus, at failure under a simple tension loading

$$R_1 = \frac{\sigma_0}{\sigma_u} = 1 \tag{20}$$

3. The effect of one loading (represented by  $R_1$  in Figure 8) on the allowable or critical value of sucher simultaneous loading ( $R_2$ ) is represented by an equation or chart involving  $R_1$  and  $R_2$ . (More than two loadings can also be handled in this way).



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#### INTERACTION EQUATION FOR YIELDING SIMULTANROUS WITH FRACTIRE

Figure 8 shows an interaction diagram developed along lines illustrated above for the interaction between the fensile mode of failure and the fracture mode of reilure. Data obtained during the experimental program are shown and several interaction curves have been drawn bared in the equation

$$\left(\frac{\sigma_{0} - 0.8 \sigma_{y}}{\sigma_{u} - 0.8 \sigma_{y}}^{m} + \frac{\overline{\sigma} t^{\frac{1}{2}}}{k_{2}} = 1\right)$$
(21)

Equation (21) is an interaction equation for the simultaneous yielding and fracture of a panel containing a fatigue crack where

- $\sigma_{0}$  = gross stress away from the crack
- , = the yield stress of the material
- $.8\sigma_{\rm m}$  = an approximation of the proportional limit stress
  - $\sigma_{ii}$  = ultimate stress for uniaxial tension loading
  - $\overline{\sigma}$  = width adjusted atress for crack tip stress intensity
  - L = crack length
  - $k_2 =$  the value of stress intensity  $(\bar{\sigma}l^{\frac{1}{2}})$  for unstable tear without yielding
  - m = an interaction exponent to be determined experimentally

The bracket notation  $\langle \rangle$  is reasonably standard <sup>18</sup> and indicates that the negative values of the bracketed quantity are treated as zero, i.e.

$$\langle -\mathbf{x} \rangle^{\mathbf{m}} = 0$$
  
 $\langle \mathbf{x} \rangle^{\mathbf{m}} = \mathbf{x}^{\mathbf{m}}$ 

where x > 0

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In the form presented, equation (21) has a discontinuity at the proportional limit and reduces to a single parameter stress intensity equation for fracture when the gross cross section is elastic ( $\sigma_{c} < .8 \sigma_{c}$ ).

#### THE INTERACTION EXPONENT m

The interaction exponent, m, is a strain hardening sensitive exponent and can be qualitatively explained as two limits of material behavior are approached.

These limits are:

- 1. The elastic limit A material having the characteristic of a high degree of strain hardening will approach this limit as shown by curve 1 of Figure 9a.
- 2. The elasto-plastic limit A material having the characteristic of low strain hardening will approach this limit as shown by curve 2 of Figure 9a.

Interaction curves predicting characteristic failure trends for materials approaching the two above limits are shown on Figure 9b. From Figures 9a and 9b, it can be seen that the strain hardening characteristics of a material and the interaction exponent w are related. A typical stress strain curve for 2024-13 aiu inum is generally of the type illustrated by curve 2 of Figure 9a. Thus, agreement of experimental data for 2024-T3 eluminum shown on Figure 8 with a curve using equation (21) and an interaction exponent  $m = \frac{1}{2}$  can be seen to be qualitatively correct. In appraising the usefulness of equation (21) and the qualitative curves drawn on Figure 9, it must be remembered that the proportional limit is also a problem variable and shifts the region of the interaction diagram influenced by the exponent m. Thus, for a truly brittle material, the proportional limit approaches the ultimate strength and the region of diagram 9b influenced by the coefficient m is non-existent.

It is believed that further study of the relationship between strain hardening variables and the interaction coefficient m will result in a more quantitative definition. Until that time, some useful qualitative estimates of interaction exponents can be obtained directly from examination of the shape of uniaxial tension stress strain curves.

STRAIN INTERPRETATION OF THE INTERACTION EQUATION

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The quantity  $\frac{\sigma_0 - 0.8 \sigma_y}{\sigma_u - 0.8 \sigma_y}$  can be interpreted in terms of gross strain

away from the crack as shown on Figure 10. Figure 10 shows that the quantity

 $\left| \frac{\sigma_0 - 0.8 \sigma_y}{\sigma_u} \right|$  represents a straight line approximation of the fraction of  $\sigma_u = 0.8 \sigma_y$ 

critical strain in the gross cross section if elastic strains are considered to be small and ignored.

In a similar sense, the fraction  $\frac{\overline{\sigma} L^{\frac{1}{2}}}{k_2}$  can be considered to be an approx-

imation of the fraction of critical strain in the form of a concentration at the crack tip. This requires the assumption that the elastic stress intensity factor can still give approximations of crack tip strain concentration in the presence of general yielding. This of course, is not true. The error assumed in making this assumption is accounted for in the experimental determination. of the interaction exponent which implies a nonlinear interaction between an elastic crack tip strain concentration parameter and gress plastic strain. This approach, while arbitrary, does allow the elastic stress intensity factor to remain intact and, in turn, makes association with linear clastic fracture mechanics somewhat easier.



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FIGURE 9 RELATIONSHIP BETWEEN STRAIN HARDENING AND YIELD-FRACTURE INTERACTION



- YIRLD STRESS

- ULTIMATE STRESS

- CROSS STRESS IN PANEL

a CRACK TIP STRAIN

- GROSS STRAIM IN PANEL

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FIGURE 10. APPROXIMATION OF GROSS SECTION STRAIN IN TURNES OF STRASS VARIABLES

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Using the above strain interpretation of equation (21), the equation may be restated:

 $(Gross section strain)^m$  + elastic crack tip strain concentration = Critical crack tip strain.

# COMPARISON OF INTERACTION EQUATION AND NASA NOTCH ANALYSIS EQUATION

The NASA Notch Analysis equation (Reference 5) has a form similar to equation (21). The interpretation is, however, in terms of stress rather than strain. This equation can be written

$$\sigma_{\text{critical}} = \sigma_{n} + \sigma_{n} \sqrt{\frac{2l}{r'}} \frac{E_{\text{sec}}}{2}$$
(22)

where

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 $\sigma_{\text{critical}} = \text{critical crack tip stress (Figure 11)}$ 

 $E_{sec}$  = secant modulus at the critical stream  $\rho^{*}$  = effective notch radius

 $\sigma_n$  = net cross section stress

An approximate solution for the critical strain  $(e_u)$  should be obtainable by dividing both sides of equation (22) by  $E_{sec}$  (see Figure 11) so that

$$e_{u} = \frac{\sigma_{n}}{E_{sec}} + \frac{\sigma_{n}}{E} \sqrt{\frac{2L}{\rho}}$$
(23)

For a wide panel in which the differences between net and gross stresses are small, equation (23) can be stated as

critical strain = 
$$\frac{\sigma_0}{P_{sec}}$$
 + elastic crack tip strain concentra-  
tion.

The term  $\frac{q_0}{B_{sec}}$  cannot be directly interpreted in terms of strain. Further,

this term is continuous and significant for all values of  $\sigma_0$  at failure above and below the proportional limit. For this reason, equations (22) and (23) cannot be reduced to the fracture mechanics equation when the gross cross section stress is elastic. This lack of a discontinuity at the yield stress or proportional limit stress is regarded to be the most significant limitation of equation (22). The fact that equation (22) cannot be interpreted in terms of strain parameters is viewed as a related limitation.

Equation (21) does exhibit the required discontinuity in behavior at the proportional limit and does have a strain interpretation. Additionally, equation (21) incorporates the elastic stress in ensity parameter and reduces to linear elastic fracture machanics form in the elastic range. The interaction exponent m which is required in the inelastic range of behavior is related to



FIGURE 11 RELATIONSHIP BETWEEN STRAIN AND STRESS VARIABLES

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strain hardening characteristics. For these fasons, equation (21), while still empirical in nature, is believed to fave greater potential as a basis for future development. The emphasis of strain variables rether than stress should lead to further clarification and unification of theories.

SUMARY OF THEORY FOR THELASTIC BEHAVIOR AWAY FROM THE CRACK IN WIDE GUIDED

The influence of gross panel yielding can be correlated in terms of an interaction equation of the form

$$\left(\frac{\sigma_{0}-0.8\sigma_{y}}{\sigma_{u}-0.8\sigma_{y}}\right)^{m}+\frac{\overline{\sigma}_{v}^{\frac{1}{2}}}{k}=1$$

This equation can be restated

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 $(gross section strain)^m + elastic crack tip strain concentration$ 

= critical crack tip strain

- 2. The interaction equation is discontinuous at the yield point and reduces to the elastic stress intensity equation when  $\sigma_0 < 0.8 \sigma_v$ .
- 3. The exponent m varies with material strain hardening characteristics with high values of m corresponding to a high degree of strain hardening, and low values of m corresponding to low strain hardening.

#### VI THE INFLUENCE OF PANEL BUCKLING

#### IMPORTANCE

Considerations of fracture to this point have assumed that the test panel remains flat until failure. Normal fracture mechanics procedures used in material evaluation studies use restraining guides to hold the panel in this configuration. The natural tendency of the panel, however, is to buckle in the region of the crack (See Figures 12, 13, and 14). Typical dimensions of this buckled segment as obtained during the experimental portion of the program are shown in Figure 15. The strength reduction caused by buckling in 2024-T3 aluminum panels can be seen by comparing Figures 16 and 17. The problem of estimating the buckled strength of fatigue cracked panels cannot generally be resolved by testing of unguided simple tension panels. Unguided test panels with relatively large t/w ratios show reduction in strength due to buckling that may not occur. Additionally, engineering structures are often subject to biaxial stresses. This stress condition is not obtained in test panels except through complex loading procedures. Therefore, an attempt at indirectly estimating the buckling influence through biaxial strain considerations is warranted.

#### GENERAL CONSIDERATIONS

The phenomenon of panel buckling adjacent to a crack (Figure 15) can be easily explained in a qualitative sense. Quantitative definition of this buckling and its influence on fracture strength is extremely difficult. In order to obtain a qualitative understanding of these phenomena, consider a fatigue crack in a panel loaded as shown in Figure 18. The overall width of the panel can be considered to decrease by the relationship

$$\frac{\mu\sigma_{\text{oy}}}{z} = e_{\mathbf{x}} \mathbf{w}$$
(24)

where .

 $\mu = Poisson's ratio$ 

ex - strain normal to the load direction and parallel to the crack

Joy " gross panel stress away from and normal to the crack

if the panel is to remain flat, the portion of the width directly above the crack must decrease by the amount  $e_X^{\ell}$ . Since no load can be transmitted in the y direction across the crack, the transverse shortening due to the Poisson effect is not present. There are, however, compressive components of stress acting toward the center of the crack and parallel to the crack (Figure 18) which tend to force the panel segments above and below the crack to shorten by







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FIGURE 14 BUCKLING PATTERN SEQUENCE (NORMAL TO PANEL PACE) FOR 30 INCH WIDE 3 .08 'NCH THICK 2024-T3 ALUMINUM PANELS



FIGURE 15 TYPICAL DIMENSIONS OF PANEL BUCKLE NEAR A CRACK IN A TENSION PANEL and the statistic statistic of the second statistic statistic statistic statistics and the second statistics and the

FIGURE 16 STRESS INTENSITY VS. CRACK LENGTH FOR CONSTANT LOAD IN GUIDED PANELS



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FIGURE 15 ILLUSTRATION OF STRESS AND STRAIN IN A FATIGUE GRACKED PASEL

the mount  $e_{x}$ . The distribution of strain paraliel to the crack in these segments ill, however, not be uniform and, in general, not equal to the Poisson induced strain remote from the crack. The resulting streases and strains in the segment of the panel above and below the crack can be considered as these in a plate segment restrained on the boundaries except for one straight and free edge which corresponds to the crack. Seconse the load is being applied parallel to this free edge, the amount of compression that can be induced is limited by the stiffness of the panel segment: Thus, when the change in dimension away from the crack  $e_x/$  is equal to some limiting value which corresponds to the critical buckling displacement of the panel segment, the free edge of the crack will start to buckle from the first plane. For values of  $e_x/$  in excess of this critical value, the corresponding change in length measured along the edge of the crack should be equal to the critical displacement for bucking plus a component of displacement resulting from the buckling of the panel asyment.

The above relationship between buckling displacement adjacent to a crack and the corresponding displacement away from the crack should also be generally applicable to conditions of biaxial stress. For biaxial stress, the strain away from and parallel to the crack can be determined by considerations of plane stress and strain

$$\mathbf{e_x} = \frac{\sigma_{\mathbf{0x}}}{\mathbf{E}} - \mu \frac{\sigma_{\mathbf{0y}}}{\mathbf{E}}$$

For the case of uniaxial tension discussed above,  $\sigma_{ox} = 0$ .

#### COLUMN ANALOGY FOR CHACK BUCKLING

Correlations of the observed beginning of buckling in 2024-T3 aluminum were made based on the assumption that the critical buckling strain adjacent and parallel to the crack will be equal to the corresponding strain away from the crack. An expression for the critical buckling strain was derived from the equation of a column on an elastic foundation<sup>19</sup>.

$$P_{B} = c \left(\frac{I}{\pi}\right)^{2} + EI\left(\frac{\pi}{I}\right)^{2}$$
(25)

where

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PR = critical column load

#### a = spring constant for electic restraint

When c = 0, equation (25) reduces to the familia. Euler backling equation as suggested by Reference 20. Equation (25) can be presented in terms of critical buckling strain eg by dividing both sides of the equation by the product of Young's modulus (F) and the area (A)

$$\mathbf{P}_{\mathbf{B}} = \frac{\mathbf{c}}{A\mathbb{Z}} \left(\frac{\mathbf{k}}{\pi}\right)^2 + \frac{\mathbf{BI}}{A\mathbb{E}} \left(\frac{\pi}{\mathbf{k}}\right)^2 \qquad (26)$$

For the case of unfazial fersion where  $e_B$  is equal to the corresponding strain away from the crack, equation (26) can be written

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$$\int_{0}^{\infty} \frac{c}{\Lambda \mu} \left(\frac{I}{\pi}\right)^{2} + \frac{EI}{\Lambda \mu} \left(\frac{\pi}{I}\right)^{2}$$
(21)

#### CONTARISON PETREES FEST DATA AND A STMPLE EULER COLUMN

Considering the elastic support parameter (c) to be negligible, equation (27) or be expressed for a unit width of a wide column as

 $\sigma_{\rm c} = \frac{E_1}{A\mu} \left( \frac{\pi}{L} \right)^2 = \gamma \frac{g_{\rm E}}{L^2}$ (28)

where

# Y(gamma) a lumped multiplying parameter to be determined experimentally

Using equation (28), values of gamma can be selected to correspond to the observed buckling instability at longer crack lengths in .032, .063, and .080 inch thick 2024-T3 aluminum. The results are shown on Figure 19. The agreement between equation (28) and the observed buckling in .032 inch thick aluminum can be seen. The lack of agreement for .063 and .080 inch thick material can also be seen. Since it is possible to shift the divergence to long crack lengths rather than short crack lengths by changing the value of gamma selected, no particular significance is attached to the crack lengths at which the divergence occurs on Figure 19. Further attempts to modify the single parameter approach of equation (28) by modifying the exponent of L will not significantly improve the overall correlation.

If it is assumed that the reasons for divergence from equation (28) result from the fact that the elastic restraint provided the assumed column segment is not negligible, then a limit can be established for the use of equation (28) provided the nature of the elastic restraint can be defined. Because of the complex nature of the stress distributions, the extent of the buckled region, and boundary restraints, a direct assessment of c is difficult. It can be expected that c will, in fact, not be a constant as suggested in equation (27), but it will vary directly as EI and inversely at some function of  $\lambda$ . Examination of the data trends as shown in Figure 19 would seem to confirm this conclusion. It would appear that an empirical criterion limiting the use of equation (28) to values of  $\frac{Et^2}{t^2} < 11$  ksi is justified until more can be learned about the problem. The curve  $\frac{Et^2}{t^2} = 11$  ksi is also shown on Figure 19.

#### PARAMETRIC STUDY OF BUCKLING BEHAVIOR

Because of the above difficulties associated with definition of c and also in associated difficulties with defining variable behavior in the second "Euler" term, an attempt at a direct solution of equation (25) or a more complex plate model does not appear justified provided a parametric means of data reduction can be found. Applicable parameters can be found by reducing Equation (25) to dimensionless form<sup>19</sup>.

$$\frac{P_{\rm B}}{\sqrt{cEI}} = \left(\frac{\sqrt{2\beta l}}{\pi}\right)^2 + \left(\frac{\pi}{\sqrt{2\beta l}}\right)^2 \tag{29}$$

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where

C 4EI



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From equation (27), '> dimensionless parameters are available: P<sub>1</sub>/ $\sqrt{cEI}$ , and  $\frac{2}{\pi}\beta l$ . If constants that are not significant dimensionally are ignored in equation (27), a similar set of parameters could be defined as



Ασ<sub>o</sub>

In equation (30), neither c no can be adequately defined. By multiplying the two quantities of (30) by  $-\frac{\sqrt{A}}{\sqrt{C}}$  and  $\frac{\sqrt{C}}{\sqrt{A}}$  respectively, and assuming that - the ratio  $\frac{A}{\sqrt{A}} \approx 1$ , the parameters of (30) are reduced to

$$\frac{\sigma_{o}}{\sqrt{2I/A}} \cdot \sqrt{\frac{A}{c}} \approx \frac{\sigma_{o}}{\sqrt{Et^{2}}}$$
(31)  
$$\frac{l}{\sqrt{EI/K}} \cdot \sqrt{\frac{A}{K}} \approx \frac{l}{\sqrt{Et^{2}}}$$

(30)

Figure 20 shows the collapse of data from Figure 19 along with data obtained during the study of titanium panels. Good cortelation can be seen. The two empirical parameters of equation (31) eliminate the need to define separate oultiplying parameters for each material as was seen necessary in the use of squation (28) (Figure 19). Since the data correlated represent 5 thicknesses and two values of Young's modulus, general applicability of the correlating parameters can be makerial for values of Et<sup>2</sup> bategen 7.2 ksi (in.<sup>2</sup>) and 53.9 ksi (in.<sup>2</sup>). Figure 21 shows the correlation of the data of Figure 19 with curves obtained by use of the average buckling curve of Figure 20. Some divergence in behavior can be seen in the .080 inch thick sluminum. Until further evaluation of possible relationships for the massic support of the crack can be studied, the curve shown on Figure 26 can provide a means of estimating the onset of bushing for variables of the range represended.

# THE RELATIONSFER METHER DEOSS STRAIN AND RUCKLING D'SPLACEMENT

Panel buckling can be assured to soon when the strain away from and petallel to a fatigue crack enceded the critical buckling strain of the panel regments above and below the exact. This critical strain level ten be computed using the strain levels obtained from Figure 30 if the kinck length ful panel geometry are known. After panel buckling accurs, the total required shortening of the panel segments above and below the crack is made up of two parts: the critical buckling displacement and a component of displacement resulting from the deflection of the powel segment from a flat plane.

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TOTAL CRACE LENGTH (1) IN INCHES

FIGURE 21 CONPARISON OF THE REGINNING OF BUCKLING IN 20 INCH WIDE 2024-TO ALUMINUM PANELS WITH CURVES DEFINED BY FIGURE 19

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Results obtained during the experimental portion of the program (Table 19 and Figures 12, 13, and 14) showed that the characteristics of the buckle measured in the plane of the unloaded panel did not appreciably change from that shown on Figure 15 as the load was increased. Thus, it can be reasonably assumed that the characteristics of the buckled crack will show parallel trends to some easily measured quantity such as the center line displacement of the crack from a flam plane. In this manner, strain parallel to and away from the crack, the critical buckling strain, centerline deflection of the crack, and atrength reduction can be interrelated.

$$\frac{\mu}{E} (\sigma_0 - \sigma_B) l = \delta B_1 = (\sigma_2) B_2$$
(32)

where

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 $\sigma_{\rm B}$  = Gross panel stress corresponding to the critical buckling strain

- $\sigma_n = Gross panel stress$ 
  - $\delta =$  Deflection from a flat plane measured at the center of the crack
- $\sigma_2 =$  Stress at the beginning of unstable tear
- $B_1$  and  $B_2$  = Constants to be determined experimentally

From equation (32) dimensionless parameters for data correlation can be defined:

$$\frac{\mu}{E} (\sigma_{\rm c} - \sigma_{\rm B}) \quad \text{and} \quad \frac{S}{I} \tag{33}$$

Figure 22 shows a correlation of measured centerline displacements for cracked panels in terms of the above parameters. Seatter in data at the lower range of values of  $\mu/E$  ( $\sigma_0 - \sigma_B$ ) can be contributed in part to the increased influence of error in computed values  $\sigma f \sigma_B$ . From Figure 22, qualitative agreement between the correlating parameters(33) and equation (32) indicate that it should be possible to correlate strength reduction trends observed to occur as a result of buckling with the parameter  $\mu/E$  ( $\sigma_0 - \sigma_B$ ). This correlating parameter can also be interpreted for conditions of blaxial stress for structural applications.

# THE INFLUENCE OF PANEL WIDTH ON BUCKLING DISPLACEMENTS

Before proceeding to the correlation of strength reduction resulting from buckling, a qualitative understanding of the influence of panel width on buckling of a crack must be obtained. Referring to equation (26), and Figure 15, buckling of panel segments above and below the crack risult in a corresponding damped buckling pattern beyond the ends of the crack. This buckling pattern is analogous to the damped displacements of a continuous column (or beam) on an elestic foundation as implied by equation (27). If this damped buckling pattern is terminated at i free edge before the pattern has progressed far enough sway from the crack, a significant reduction in the buckling restraint of the segment of panel above and below the crack could result. DEFLECTION PARAMETER  $\begin{pmatrix} \mu \\ E & \langle \sigma_0 - \sigma_B \rangle \end{pmatrix}$ 

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FIGURE 22 BUCKLING DEFLECTION CORRELATION FOR FATIGUE CRACEED PANELS OF 2024-T3 AUGMINUM

In Figure 23, the relationship between the beginning of buckling and the stress away from the crack for 12-inch wide 2024-T3 aluminum is compared to curves representing behavior of 20-inch wide panels taken from Figure 21. The beginning of buckling can be seen to occur at lower stress levels in the .050 inch thick, 12-inch wide panels than would be expected from measurements made on the same crack lengths in 20-inch panels. The stress at which buckling occurs in .032 and .063 inch thick, 12-inch wide panels is the same as that obtained in the 20-inch wide panels. This would indicate that the length of the buckle pattern (wave length) can be expected to increase with increased Et<sup>2</sup>.

In order to demonstrate this interpretation of the buckling pattern in the inducatory, the buckle in 12-inch wide panels was forced from side to side. A visible corresponding Change in the displacement of the free edges of the panel was seen.

Since the manner in which the panel width influences buckling is different from the manner in which width influences the strength of guided panels, the two width influences should be considered separately. Thus, there may still be buckling width influences on strength in panels whose width is sufficient to allow elastic stress intensity parameter correlations when the panel is guided.

# THE INFLUENCE OF BUCKLING ON THE STRESS INTENSITY FOR UNSTABLE TEAR (2) IN WIDE PARELS

From Figure 17, the strength reduction in unguided panels from that in guided panels (Figure 16) can be seen. In wide panels the range of crack lengths between 3 and 5 inches show a strength reduction due to buckling from an average stress intensity of 80 ksi  $\sqrt{10}$  in guided panels to an average stress intensity of 74 ksi  $\sqrt{10}$ . In unguided panels. For longer crack lengths, the stress intensity at the beginning of unstable tear is further reduced to an average value of about 62 ksi  $\sqrt{10}$ . A trend of increasing stress intensity with increasing thickness is noticeable in unguided panels, Figure 17. This trend was not epparent in guided gamel data (Figure 16). Representative stress intensities for crack lengths between 3 and 5 inches (Figure 17) were found to be

t	<b>#.03</b> 2	inches	<b>k</b> =	68.5	ksi	1 in
٤	063	inches	k ==	73.5	kai	√ in
t		inches	k =	76.0	ksi	1/in

These trends could be the result of buckling and the differences of the quantity  $\frac{\mu}{E} (\sigma - \sigma_{B})$  where  $\sigma_{B}$  increases with the square of the thickness.

A study of the quantity  $\frac{\mu}{E}$  ( $\sigma_0 - \sigma_{\overline{B}}$ ) for the assumption that the beginning of unstable tear would occur at constant stress intensity in 2024-T3 aluminum







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shows that ( $\sigma_0 - \sigma_B$ ) would be a near constant for a given thickness over the entire range of crack lengths from 3 inches to 10 inches (the curves of critical buckling stress and the curves of constant stress intensity are very close to parallel in this range). From the observed critical stress intensities, a similar study shows a near constant ( $\sigma_0 - \sigma_B$ ) between crack lengths of 3 and 5 inches and lower values for crack lengths greater than 6 inches. These observations are in line with assumed constant relationship between  $\frac{\mu}{E}(\sigma_0 - \sigma_B)$ and the reduction of the stress intensity at the beginning of unstable tear.

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The reduced stress intensity for unstable tear at longer crack lengths can most probably be accounted for in terms of a width influence on buckling behavior. However, the possibility of a discontinuity in behavior from some other cause cannot be entirely ruled out.

Until such time as further investigations are made, it can be assumed that the additional strength reduction serm at long crack lengths in wide buckled penels is a width sensitive phenomenon. The portion of Figure 17, which has meaning in terms of application to reinforced structure is, therefore, the crack length range between 3 inches and 5 inches. A crack length of 6 inches roughly corresponds to a 1/w of 1/3 in 20-inch wide panels.

It is interesting to note that it the 20-inch wide panels, the buckling width influence seems to become effective over a narrow range of crack lengths for all thicknesses, Figure 17. This would indicate that the relatively large differences noted in the beginning of buckling (Figure 23) as a function of width and thickness is not carried over into the width influence on  $k_2$ . Physically, this probably means that the total shortening parallel to the crack at  $k_2$  is large and differences in the critical buckling displacement are thus not a major consideration in determining the buckling wave length. Sased on observations of 2024-T3 aluminum a limiting value of 1/w = 1/3 can be assumed for the buckling influence on strength for the thickness range considered. Not s corresponds roughly to one buckling wave on each side of the crack within the joundaries of the panel.

# THE INFLUENCE OF BUCKLING OF THE STRESS INTENSITY FOR UNSTABLE THAT IN KARROW PANELS

The influence of buckling on the stress intensity at the beginning of unstable tear in narrow panels can be assessed by assuming that the total width influence is separated into a two-dimensional stress and strain influence which should be close to that seen in guided panels (Figures 3, 4, and 5) and a buckling width influence similar to that seen in Figure 17.

In 12-inch wide panels (Figure 24) the buckling width influence on the strass intensity at the beginning of unstable tear starts near a crack length of 4 inches. This is approximately the same f/w ratio( $f/w\approx 1/3$ ) as that observed in 20-inch wide panels. A comparison of the stress intensity in guided and unguided 12-inch wide panels shows a change in average stress intensity from 67 ksi Vin to 57 ksi Vin for crack lengths unaffected by either gross section yielding or a byckling width influence.

Data from the 9-inch panel tests showed no distinct range of crack lengths for strength reduction due to buckling without a buckling width influence. This is due to the fact that the minimum crack lengths which result in fracture without general yielding is nearly 1/3 of the panel width.



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where 200,  $z^{-1}$  ould appear that the screas intensity at the beginping of unstable tear will show a finkling width influence whenever  $1/w \approx 1/3$ . Considerably more work must be done, however, before any general quantitative estimates can be made regarding the variance of panel strength as a function of buckling in either wide or nurses panels.

# THE INFLUENCE OF BUCKLING ON THE STRESS DITENSIFY FOR UNSTABLE TEAR (k2) WITH GROSS SECTION STRAIN ABOVE THE PROPORTIONAL LIZIT

It is difficult to see any influence of buckling on the strength of cracks less than 3 inches in length in 2024-T3 aluminum of the thickness range shown in Figures 16 and 17. It can be expected that the strains every from and parsilel to the crack will increase more rapidly with gross stress when the gross section is stressed shows the proportional limit. This is due to the fact that the strain perallel to and away from the crack will be:

$$x = \mu \frac{c_{\rm C}}{E} + \mu_{\rm F} e_{\rm py}$$
(34)

where

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e<sub>x</sub> = total strain in the x direction (parallel to the crack)

- 4 = Poisson's ratio (approximately 1/3)
- " = gross stress away from cruck
- 2 = Young's modulus
- epy = plastic strain in the direction normal to the crack

Assuming the strength reduction for a given crack length varies as  $e_{12}$ , reduction in strength due to buckling might be expected to exceed that of the elastic range. This influence is assumed in the construction of Figure 25 which shows an interaction diagram of the type shown in Figure 8. Figure 25 is identical to Figure 8 with the exception that for the purpose of developing the interaction curves, the stress intensity for the beginning of unstable tear with elastic behavior away from the crack has been assumed at an average value for all thicknesses as .93 times the stress intensity for the beginning of unstable tear in guided panels. Data whose crack length to panel width ratio is greater than 1/3 has not been shown in Figure 25.

#### SUMMARY OF THE INFLUENCES OF PANEL BUCKLING

- 1. The phenomena of buckling of panel segments above and below a crack which is normal to an applied uniaxial tension loading can be qualitatively explained by considering the Poisson affect and the resulting strains paraliel to and remote from the crack.
- The building of the panel segments above and below the crack can be predicted by a single curve for values of Et<sup>2</sup> between approximately 7 and 70.

WIDTH X THICKNESS TN INCHES

**A** m 20 x .032 **U** m 20 x .063 **U** m 20 x .063 **O** m 30 x .0b3 (All UNGUIDED)



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This curve is based on the empirical correlating parameters as fillows:

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- 3. Buckling definctions and reduction of the stress intensity at the beginning of unstable tear will vary as the difference between the strain away from and parallel to the crack and the critical buckling strain of the panel acgment adjacent to the crack.
- 4. The influence of panel buckling on the stress intensity at the beginning of unstable tear is nearly constant for the elastic range of behavior for values of L/w < 1/3 in 2024-73 aluminum. For values of L/w > 1/3 further reduction in stress intensity occurs.
- 5. The influence of bockling varies with penel width in narrow panels.
- 5. In 2024-73 aluminum, the reduction in stress intensity at the beginning of unstable terr resulting from buckling is not measurable in the range of crack lengths where unstable hear occurs with gross panel stresses above the proportional limit of the material. A small increase in buckling influence is probable, however, as the strain parallel to the crack should increase more than in elastic behavior.
- 7. Secause of the observed constant influence of buckling on the stress intensity for unstable tear in 2024-T3 aluminum, the interaction between gross section yielding, panel buckling and fracture may be handled in the same way as the interaction between gross section yielding and fracture in guided panels with the exception that a reduced value of the constant stress intensity for unstable tear must be used.

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#### VII STABLE TEAR

#### THPORTA LE

In relatively ductile materials such as 2024-13 sluminum and titenium EAL-IMO-IV, appreciable amounts of stable tear procede unstable tear. If the condition of first unstable team is used as a createrion for the ultimate strength of a fatigue cracked ponel, then an patimete of the amount of stable tear preceding the unstable crac. length is measured. Without an estimate of the amount of stable tear, it is not possible to determine the stress at which failure will occur for a given initial crack length.

#### CENERAL CONSIDERATIONS

Previous discussion of variance in stress intensity cannot be easily interpreted to yield changes in slow tear characteristics. A change in stress intensity can take place through either changes in stress or crack length, or a combination of the two. Thus, differences in the stress intensity at the beginning of unstable tear for guided and unguided panels does not indicate whether these changes are predominately the result of changes in stress or crack length. Figure 26 shows typical tear behavior of guided and unguided 2024-T3 panels. Similar slow tear behavior was found in titanium SAL-INO-IV. Tear behavior of this type was also shown to occur in 2024-T81 aluminum and AM 350 CPT and AM 355 CR7 steel<sup>15</sup>.

Stable tear was explained in-Section IV in terms of an effective notch radius  $\rho^3$  that increased as plastic deformation adjacent to the crack tip increased (equation (3)).

$$k = \overline{\sigma} k^{\frac{1}{2}} = \frac{e_{\overline{\alpha}}}{\sqrt{2}} \sqrt{\rho^{2}}$$

During stable terr, the crack tip strain was assumed to be at some Givimate value  $e_0$ . Additional increases in stress intensity accompanied by stable tear was considered possible only with corresponding increases in  $\rho^2$  (equation (4))

$$\frac{dx}{dt} = \frac{d(\overline{\sigma}t^{\frac{1}{2}})}{dt} = \frac{\sigma_{T}E}{T_{2}} \frac{d\sqrt{p}}{dt}$$

From a study of the stable tear behavior under incremental loading, the general nature of the dependence of P' on changes in stress and crack length can be deduced. If an additional increment of loading is spilled to a panel containing a stable crack whose crack wip strain is  $e_{\mu}$ , tear will start and continue with some increase in length to a new stable configuration. It can thus be seen that increase in P' is predominately dependent upon changes in length.

(35)

$$\frac{dt}{d\xi} = \frac{4u^2}{\sqrt{2}} - \frac{d\sqrt{f(\xi)}}{4\xi}$$



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FIGURE 26 TYPICAL TEAR DEHAVIOR IN 2024-TO ALGMINUM SHEET

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#### THE RELATIONSHIP BETWEEN THE ANO "NT OF STABLE TEAR AND THE INIT. L CRACK LENGTH IN WIDE PAYELS

In wide panels of 2024-T3 aluminum, there is a trend of increasing amounts of stable tear with increasing initial crack length (Figure 37). No corresponding increase in stress intensity ( $k_2$ ) occurs (Figures 16 and 17). Similar behavior was observed in titanium SAL-DO-IV (Figure 28). Figure 28 represents two was of titanium; thus, no significance can be attacked to differences occurring as a function of thickness. From the trends observed (Figures 27 and 28) it is suggested that the amount of stable tear in wide unreinforced panels be estimated as a fraction of the initial crack length ( $k_1$ )<sup>3</sup>. For example, the critical unstable stack length (L) could be written for guided panels of 2024-T3 aluminum (Figure 29) as

$$l = l_1 \div (\Delta l : l_1) l_1$$

$$l = l_1 \div 0.33 \quad l_1 = 1.33 \quad l_1$$

and the critical stress intensity could be waitten

intrial and

$$\dot{x}_{2} = \bar{\sigma} (1.33 \ \dot{L}_{1})^{\frac{1}{2}} = \bar{\sigma} (1.33 \ \dot{r}^{\frac{1}{2}} L_{1}^{\frac{1}{2}}$$

$$\dot{x}_{3} = (24 \ \dot{r}^{\frac{1}{2}} = \bar{\sigma} L^{\frac{1}{2}}$$

wiere

$$s = \sqrt{1 + \Delta g/g_1} = \text{constant for a given material and}$$
  
condition of lateral buckling restraint

(36)

Equation (36) can provide a direct means of estimating the ultimate strength of fatigue cracked papels from a given initial crack length  $L_1$  in a wide manely. This procedure appears equally applicable to guided and meguided papels  $\frac{1}{2}$ .

#### THE RELATIONSELP BETWEEP THE ANOUNT OF UNSTABLE TEAR AND INITIAL CRACK LENGTE IN MARRON PANELS

The stable tear of cracks in marrow panels was found to be significantly less than that of wide panels. This could be accounted for in part by the width dependence of the rate of change of stress int. Sity (equation 8). However, in an attempt to construct curves of this type shown in Figure 2s, it was apparent that the differences in unstable crack length could not be entirely accounted for by tangency considerations. Each width appeared to have its own set of tear versus crack length curves. Because of this observed decrease in stable tear with width, in both 2024-T3 simplifies and titanium SAI-BO-BV, it was concluded that tear studies applicable to reinforced panels could only be obtained from relations in considerations of delayed fracture in titanium, it is possible that delayed fracture studies in marrow panels could lead to false concluded that delayed fracture studies in marrow panels could lead to false concluded that delayed fracture studies in marrow panels could lead to false conclusions as to the severity of the problem as it pertains to wide and reinforced panels.




INITIAL CRACK LENGTH ( I) IN INCHES

VS. INITIAL CRACK LENGTH (E1) FOR 12 INCH VIEL PANELS OF

PIGURE 28 INCREMENT OF STABLE TEARA

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## VIII SYNTKESIS OF STRENGTH INFLUENCING PARAMETERS FOR WIDE PARELS

The influences of gross section yielding and panel buckling on the stress intensity for the beginning of stable tear in wide unreinforced panels can be collected and presented in a single disgram. This disgram can sid in the oversli understanding of the relationship between strangth influencing variables. The disgram is a three-dimensional representation with two of the axes representing an interaction diagram of the type shown in Figures 8 and 25. The third axes is the panel k/w ratio which denotes the limit of crack lengths for buckling width influence as k/w = 1/3. This diagram is shown in general form in Figure 29. For convenience of discussion, zones of behavior are designated on this diagram as follows:

Zone I Short Cracks - The Deginning of unscalle tear  $(\overline{\sigma L^2})$  occurring due to a combination of fracture and gross section yielding. The suggested equation for predicting the stress intensity at the beginning of unstable tear is

 $\frac{\sigma_0 - 0.8 \sigma_Y}{\sigma_0 - 0.8 \sigma_Y} + \frac{\overline{\sigma} f^2}{F_2} = 1$ 

Zone II. Intermediate Cracks - The beginning of unstable tear occurs with gross penel stress in the elestic range. The influence of penel buckling can be essented constant with the stress intensity k, at the caset of unstable tear correspondingly less than in guided

stable terr correspondingly less that in galace

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negative and, thos, assumed as sere so that the equation for predicting unstable tear is

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Zone 113, Long Gracks -

Cracks with length to pacel width ratio exceeding 1/5 can be expected to show further reduction in the stress intensity by resulting from the infleence of parel width on buckling. This fracture some is to be expected only in unreinforced papels and, thus, not of interest to the enjority of structural problems dealing with reinforced papels.

The test data for 2024-T3 sluminum from Figures 17 and 25 is shown in Figure 30. Figure 30 along with curves of the type shown on Figures 3. A, and 5 can provide the required understanding of the interaction between strength influencing variables. In plotting Figure 30, small variances in the streng intensity at the unstable crack length with thickness were included by using reparate k<sub>2</sub> values for each thickness. Also, the small variance in yield stress and ultimate stress were incorporated. These refinements were not considered in construction of provious figures.

#### VIII SYNTKESIS OF STRENGTH INFLUENCING PARAMETERS FOR WIDE PARELS

The influences of gross section yielding and panel buckling on the stress intensity for the beginning of stable tear in wids unreinforced ganels can be collected and presented in a single disgram. This disgram can sid in the oversll understanding of the relationship between strength influencing variables. The diagram is a three-dimensional representation with two of the axes representing an interaction diagram of the type shown in-Figures 8 and 25. The third axis is the panel #/w ratio which denotes the limit of crack lengths for buckling width influence as l/w = 1/3. This disgree is shown in general form in Figure 29. For convenience of discussion, somes of behavior are designated. on this disgram as follows:

Zone I

Short Cracks - The Deginning of unscable near (52) occurring due to a combination of fracture and groze section yielding. The suggested equation for predicting the stress intensity at the beginning of unstable Zear is

 $\frac{\sigma_0 - 0.8 \sigma_y}{\sigma_0 - 0.8 \sigma_y} + \frac{\overline{\sigma} t^2}{t_2}$ 

2000 II Intermediate Cracks - The beginning of unstable tear occurs with gross penel stress in the elastic range. The influence of peopl becking can be essened constant with the stress intensity h, at the onset of sa-stable tear correspondingly lass than in guided panels. The quantity / To-C.E.C.

> negative and, thos, assured as sore so that the equation for predicting unstable tear is

- Va .. 2.2 0v

Zone 113. Long Cracks - Cracks with length to parel width ratio exceeding 1/5 can be expected to show in that reduction is the stress intensity by resulting from the influence of press width on succling. This fracture some is to be expected only in wareinforced panels and, thus, not of interest to the enjority of structural problems dealing with reinforced penels.

The test date for 2024-73 sluminum from Figures 17 and 25 is shown in Figure 30. Figure 30 along with curves of the type shows on Figures 3, 4, and 5 can provide the required understanding of the interaction fetage strength influencing variables. In plotting Pigure 10, smill variances in the stress. intensity at the unstable crack length with thickness were included by using expersite by values for each thickness. Also, the small variance in yield stress and ultimate stress were incorporated. These refinements were not considered in construction of provious figures.



Figure 30 shows the sgreement between actual panel data and the division of the overall problem into zones are suggested by Figure 29. It is believed that Figures 29 and 30 can provide investigators with a data evaluation technique that will clarify many confusing geometric interrelationships influencing the strength of fatigue cracked panels. For application to design problems requiring the determination of the ultimate strength associated with an initial crack length  $f_1$ , it is suggested that the quantity  $sf_1^2$  (equation 36) be substituted for  $f_2^2$  in the interaction equation.

The data correlation shows in Figures 26 and 27 works equally well for narrow panels. The 12-inch wide panel data for 2024-T3 aluminum will plot in with the data for 20-inch wide panels shown if an appropriate value of  $k_2$  is assumed. Figures 29 and 30 thus represent nondimensional properties of the behavior of 2024-T3 aluminum over a reasonable range of geometries. Two specific additional parameters to adjust  $k_2$  are required, however, before a general solution to the problem is at hand.

1. A guided panel width correction (illustrated in curve form in Figures 3, 4, and 5).

2. An unguided panel width adjustment for the influence of buckling.

## IX CONCLUSIONS

Disid on the analysis of test date for 2024-T3 aluminum and supported in part by data from titanium SAI-lMo-IV and data from other investigations, it is concluded that in narrow pixels, width has a significant influence on crack extension that cannot be adequately accounted for by current fracture mechanics theory. Much of the available test data is from panels of this width range. Thus, use of the available test data is from panels of the strength of reinforced pixels is extremely difficult. Additional studies directed towards a more complete understanding of interaction between local yielding at the crack tip and the pixel boundaries are needed. Direct correlation of width influences with matorial properties should also prove fruitful. In this respect, a correlating parameter is needed which includes total elongation and strain hardening therecteristics as well as the yield and ultimate stresses used in Figure 3.

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The correlation and prediction of the beginning of unstable tear with gross stress above the yield stress can be accomplished by an interaction equation (equation 21). While actual data correlations were limited to 2024-73 aluminum, it is believed that the equation is sufficiently general for application to other relatively doctile materials including materials at elevated temperatures. It is therefore recommended that additional studies be undertaker using materials at room temperature and elevated temperatures. These studies should provide more information on the variation of the interaction exponent "m" with strain hardening characteristics and prove the general usefailments above the proportional limit.

The results obtained during this program showed the influence of panel width on the reduction in strength due to buckling. For 2024-T3 aluminum, it wis shown that the buckling influence was nearly constant when gross section yielding or buckling width influences were not involved. Studies should be undertaken to determine whether a similar range of constant buckling influence exists in other materials so long as the quantity  $(\sigma_0 - \sigma_2)$  remains nearly constant. In these studies, thicknesses and fracture characteristics should be selected to test the influence of buckling under conditions where  $(\sigma_0 - \sigma_2)$ varies appreciably within the elastic range with  $\int_{-\infty} \frac{1}{2}$ . Studies of the in-

fluence of buckling under conditions of biaxial stress should also be undertaken.

The problem of stable tear requires considerably more investigation. This important aspect of the engineering problem of strength prediction has not had adequate study. From the results of this study, prediction of stable tear in wide panels can be accomplished by considering stable tear as a constant fraction of the initial crack length. This is undcubtedly sn over simplification of the problem, but one that may prove useful.

Further studies of stable zear in wide panels should be undertaken. These studies should include delayed tear and fracture such as has been observed in titanima 641-1Mo-1V. The results of this study could prove that the phenomenon of delayed unstable tear will not be as significant in wide panels.

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#### APPENDIX

## test frozak

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The test program consisted of an in-depth study of the tear and failure characteristics of bare 2024-T3 aluminum and a limited supporting study of duplex somesled titaning SAI-1Mo-1V. The test program was conducted for the purpose of providing a consistent set of data which extends beyond the limits of normal fracture mechanics mersurements to include the influence of panel buckling and yielding on the strength of fatigue cracked penels. Fanel widths tested were 30 inch, 20 inch, 12 inch and 9 inch for the bare 2024-33 aluminum. Nomical thicknesses were .080 inch. .063 inch and .032 inch. For the duplex annealed titanium SAI-1Mo-1V the widths were 12 inch and 9 inch. Nomical thicknesses were .045 inch and .030 inch.

## MATERIALS

The bare 2024-T3 aluminum was selected from available stuck of the three thicknesses, .032, .063, and .060 inch. At least one tensile coupon was taken from each cheet. In some instances where failure stresses were relative by low, coupons were obtained directly from the test panels after failure. Strain rates were varied from .002 in/is/min. to .004 in/is/min. which approximately coincided with the strain nuter of the 12 incl and 20 inch wide, .062 inch thick panels. No significant trends were moted. A summery of the average engineering properties of the aluminum panels is given in Table 1. Coupon data and panel and sheet designations are given in Table 3.

### Isble 1-

Average Properties of Bare 2025-T3 Almine

Norinal	Held	Bleisete	Eleogration
Thickness	Strength	Strengtä	( 2º Cage
(Inches)	T <sub>T</sub> (ksi)	G (isi).	Langth )
9,032	52,0	71.1-	19.7
9,032	51.9	68.2	19.2
- 9,080	53,3	71.1	16.3

# 2 = 16.3 x 10<sup>3</sup> ksi

The depicer annealed titamine Sal-186-17 was obtained from the Titamine Metals Corporation of America. The two thicknesses were of one different bests. Their yield and mitimate strongths were nearly identical. However, the elongations were less for the .000 inch thick material. Significently the resistance to tear and fracture was subsequently found to be less in the .020 inch thick material. Two concous mere taken from each best. The engineering properties are given in Table 2 as follows:

Heat No.	Noninal Thickness (Inches)	Yield Strength Gy(ksi)	Ultinate Strength Su(ksi)	Elongation (2" Gage Length)
B-9226	.045	133.5	145.0	14.0
D-9226	.045	31.4	142,9	14.5
G-699	.020	135.9	146,6	13.0
G-699	o <b>920</b>	135.0	145.0	11.6

Properties of Duplex Annealed Titanium &th-140-14

Table 2

z = .045i  $E = 15.0 \times 10^3$  ksi  $\dot{z} = .020i$   $E = 16.0 \times 10^3$  ksi

## EST PROCEDURES

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The tisk panels were unreinforced initially flat panels containing centrally located new slots perpendicular to the load axis. All panels were but with the slot perpendicular to the rolling direction. The length of all perels measured between the grips was 2.5 times the panel width.

The initial are slots were entended by jewelers are cuts from which fatigue cracks were grown for a distance necessary to obtain a crack extension at least three times the thickness of the panel and parallel to the axis of the saw slot. All cracks in the 2024-T3 sluminna panels were grown at a single value of stress intensity of  $\overline{\sigma I}^2 = 30$  ksi V in, where  $\overline{\sigma}$  is the width adjusted stress and I is the crack length. This value was approximatel 75 percent of the lower limit if stress intensity at which slow tear was observed to start. A value of  $\overline{\sigma I}^2 = 40$  ksi was believed for fatigue cracking in the titusion panels. All fatigue cracks quickly developed into a shear mode of cracking once out of the influence of the motch. Thus all specimens were fatigued and failed in the through-the-thickness 45 degree shear mode.

After the fitigue cracks were developed so as 50 simulate fatigue.cracks of the sequired length, initial crack longths were observed through a transit. The loss was then slowly increased until slow tear was observed to start. In an attempt to gain consistency in the recording of slow tear the vertical cross bair of the transit was placed at the end of the visible crack and slow tear was recorded when the crack was visible beyond the cross hair,

After the start of slow tear was observed, the panels were loaded at a rate of 30,000 pounds per minute and the remainder of the panel behavior was recorded on film. The film record was reduced to give the following information:

- i. The crack leigh vs. load.
- 2. The beginning of maximum load.
- 3. A grack velocity of one inch per second.
- 4. The last recorded crack length prior to rupture.

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S-2	-	.062	483.	50.6	65.7	21.3		
S-3	-	.062	.074	53.2	68.8	21.5	week" Hear	
S-4	-	.052	.0005	52.7	64.7	18.5		-
-5	-	.0625	.0033	\$9.2	i 68.3	17.0		5 - <b>1</b>
\$_€	-	.0£2	.0923	53.4	\$ \$5.4	15.5	ion a bisie	
5-7	-	.0625	.0923	51.4	i i \$8.3	20.0		; ;
S3	-	.062	.0025	51.6	£6.7	15.6		
5-9	-	.061	.0075	<u>3</u> 3.5	<b>69,3</b>	15,0		within a s
S-10	-	-06Z	.9025	52.4	69.5	2.0		:
S-11	-	.061	.604	53.2	€9.2	17:5		21 Q
S-12	-	-062	.094	52.4	<b>62.</b> 2	17.5		apar and
5-13	~	.063	.0035	<b>5</b> 3.5	68.9	19.0		(Helphine)
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5-14	-	.961	.9630	i ( 30.3	63.7	-16.0		ي محمل المجد ال
S-15	-	.062	-9025	51.0	56.4	19:0		
5-16	-	-042	.2025	A.F	67.2	<b>3</b> 1-0		hour -
S-17 ·	-	.679	.0035	47.6	67.x	27.5		
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5-26	21	.632	.323	52-5	70.4			NAMANA
5-21	^ <b>_ </b>	.02		52.5	77.4	10 A 1		T-LIL M
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TASIE 3 HATEFIAL PLOPERTIES OF BASE 2024-13 AUGUSTAN FROM 1 INCH WIDE TENSILE CONTROLS

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#### ST EQUIPHENT

The terring was accomplished using a load frame and a 300,000 pound hydraulic load cylinder (Figures 31 and 32). Load control was attained by the use of an electro-dedraulic servo channel and a feedback signal provided by a strain gauge bridge with the strain gauge attached to a load link in series with the test panel and the hydraulic load cylinder. For development of fatigue cracks prior to loading the panels to failure, a combination of mean plus simusoidal signal was used as isput to the servo valve. For final loading to failure, a motor driven potentioneter calibrated to provide a nominal load rate of 30,800 pounds per minute was used. Incremental loading was applied by manufally operating the mean load potentiometer. Load monitoring was obtained through two additional strain gauges on the load link. One strain sauge was used for visual monitoring on an oscilloscope using a BA-12 bridge mit. The second gauge provided a signal operating a voltmeter which was photographed simultaneously with the crack length by a 35 millimeter camera operating at 16 frames-per-second. The signal from this second strain gauge was also recorded directly as load on an x-y plotter. All load recording elements usually agreed within 3 percent.

## GURVES AND TABULAR DATA

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In order to provide information and discussion on the tear characteristics of the materials, it was necessary to record the entire failure sequence on film. Actus: tear behavior determined from film records showed the tear to be comprised of a series of bursts of tear rather than a smooth contimuous process. These bursts were sporadie in time and tended to differ slightly for the two ends of the crack. In general, however, the total tear accumulated at either end of the crack was very nearly the same, the crack thus remaining symmetrical about the panel center line until final rupture. Rupture often occurred simultaneously on both sides of the crack (particularly for higher stress levels and shorter cracks). In other instances (usually at longer crack lengths) rupture would occur on one side only, these ruptures being about equally divided between the left and right side. Failure surfaces were of the shear type in all panels with no visual distinction noted between the slow tear and rupture surfaces. The results of the interpretation of film records are shown as average tear curves on Figures 33 through 43. The ordinate  $(\sigma)$  of these figures is a width corrected scress in the sense that it represents the nominal (gross) panel stress multiplied by the Dimon<sup>(1)</sup> finite panel width correction (Equation 6).

Direct visual comparison between all curves in terms of elastic stress theory is thus possible,

Four points repretenting significant changes in behavior are marked on the tear curve for each panel (Figures 33 through 43) unless two of the events occurred simultaneously as was occasionally the case. The crack lengths and loads corresponding to these points are given in Tables 4 through 12. The significance of these points along with remarks pertinent to their interpretation are summarised below in the sequence of their normal occurrence.

1. The beginning of slow tear: The beginning of slow tear proved difficult to record in a consistent manner. First, the slow tear did not always start simultaneously on each end of the crack. Second, the visibility and amount of initial slow tear varied with crack length and geometry.







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FIGURE 34 STRESS VS. CRACK LENGTH 2024-T3 ALUMINUM

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FIGURE AS STREBS VS. CRACK LENGTH 2024-T3 ALUMINUM





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FIGURE 41 STRESS VS. CRACK LEGGTE TE-SAL-ING. IV



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FIGURE 43 STRESS VS. CRACK LENGTH TI-BAL-IMO-IV.

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PANEL NUMBER	AUMUR NUMBER	L1 (INCHES)	12 (INCHES)	L <sub>3</sub> . (INCHES)	L4. (INCHES)	<sup>2</sup> 1 (1bs × 10 <sup>-3</sup> )	(lbs × 10 <sup>-3</sup>	1ba × 10 <sup>-3</sup>	(158 x 20	BUCKLING
19	\$1-S	0.65	0.79	1.37	1.37	30.3	30,5	30.3	30.3	No
20	s-20	1.23	1.55	16.1	1.91	24.6	29+2	29.0	29.0	
21	ũ-18	3.44	4.10	4.71	5.45	13.6	20.0	20+0	19.3	
53	5-18	5.30	6,37	6.37	7.89	15.7	16.4	16.4	16.2	
23	s-20	7.37	8.47	9.68	12.20	10.0	11.3	11.0	10.0	
24	8-19	0.64	0.87	1.20	1.45	30.5	31.0	30.0	30.7	Yus
25	S-20	1.12	1.43	2.06	7.59	27.6	30.1	30.0	30,0	
26	5-18	3.45	4.21	4.86	6.32	14.6	23.3	23.3	22.7	
27	S 19	5.26	6.27	7.07	10.77	12.8	17.7	17.7	17.0	
28	S-20	7.46	7.75	9.50	12.18	10.4	14.33	14.33	13.0	

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TABLE 5 2024-T3 ALUMINUM WINTH == 20 INCHES, THICKNESS == .063 INCH

S-,15 S-4 S-4		(INCHES)	(INCHES)	(INCHES)	(10-3)	$\left(1b_{8} \times 10^{-3}\right)$	(1bs × 10 <sup>-3</sup>	(10-3)	BUCKLING
S-4	0.74	06-0	1.42	1.96	56.0	56.5	56.5	56.5	No
	1.06	1.24	1.90	2.16	37.5	55.5	55.5	55 <b>.</b> 5	
S~14	1.28	1.55	2.10	2.65	50.0	55.0	54.0	54.0	
8-15	1.28	1.31	1.35	1.35	52.0	54.0	54.0	54.0	
80 - 1 संग	3.29	3.81	4.32	64.43	26.2	44.9	44.9	44.9	
8-8	3.34	3.91	4.32	4.81	36.0	45.4	45.4	<b>\$5.4</b>	
S=7	4.18	\$*03 \$	5.33	5,58	26.7	41.0	41.0	41.0	
. S. 6	4.93	5.74	90.9	8.19	19.0	36.4	36.4	36.4	
	7.39	7.78	8.63	11.80	16.7	25.6	25.6	24.3	
8-2	7.40	8.04	9+05	10.43	21.3	26.0	26.0	26.0	
8 I S	7.56	7.34		11.02	8.71 8	23,2	24.8	24.8	
S-7	0,78	k0.12	10.70	1.2.67	11.0	22+6	72.6.	22.6	
Stirs	0.87	<b>80.</b>	0 2.57	2,20	55.0	550	55.0	55.0	YœB
() ()	.0	1,36		2.60	5.94	25.0	53.0	35,0	
0	12.00	4.*2		8	24.2	<b>X</b>	47.5	47.5	
S. k	10.4	5	6.23	7.77	9	9 8 0	38,6	.38.€.	 r
	6.4	10.9	6.37	06.9	S S S S S S S S S S S S S S S S S S S	40.4	<b>6</b>	40.6	
	7.20	9	oritr	OE CI	<b>5</b> <b>5</b>	00	8	27.7	

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TABLE 5 2024-T3 ALUMINUM 20 INCHES, THICKNESS -.063 INCH

BUCKLING RESTRAINT Yea No  $\binom{P^2}{(16n \times^2 10^-3)(16n \times^2 10^-3)} \binom{P^4}{(16n \times^2 10^-3)}$ 56.5 55.5 54.0 54.0 41.0 44.9 422 36.4 26.0 24.8 22.6 55.0 24.3 55,0 47.5 38.6 40.6 27.7 A0.6 0 56.5 55.5 54.0 54.0 44.9 45.4 41.0 36.4 25.6 26.0 24.8 7.2.6 55.0 53.0 38,6 47.5 29, 2 56.5 55.5 55.0 54.0 44.9 45.4 41.0 36.4 25.6 26.0 23.2 22+6 55.0 55,0 47.5 38.6 \$10.6 29-2 (1 bo x 10-3 56.0 37.5 50.0 52.0 26.2 36.0 19.0 26.7 26.7 21.2 8.71 0-11 55.0 48.5 24+2 33.6 29+2 32 4.9 L4 (INCHES) 6,90 2.16 2.60 1.96 2.65 1.35 4.43 8.19 11.80 2,20 13.50 5, 38 5.03 7.73 4.81 10.43 11.02 12.87 (INCHES) 1.42 1.90 2.10 1.35 4.32 11.10 4.32 5.33 6.06 8.63 9,05 10.70 9.51 1.57 6.23 6.37 11.77 4.77 2 (suches) 4.42 9.42 0.90 1.24 1.55 5,03 5.74 1.31 3.81 3.91 7.78 9.04 7.34 10.12 3.03 6.07 1.38 5.51 (INCĤES) 0.74 1.06 1.28 1,28 4.18 7.20 3.29 3.34 7.40 4.93 7.39 7.56 0.78 4.93 loading to 0.87 96°0 3,27 4,31 SHEET NUMBER 51.15 S-14 2-15 SLIS \* Incremented 8-4 S=8 S-8 S..7 3-8 S..6 5 • 3 \$--8 S.. 7 3-4 9 T 5 Suk ي. ج S--8 PANEL NUMBER <sup>с</sup>. 87 ま Q 2 Ś

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	<u> </u>									
BUCKLING RESTRAINT	NO N				-	Yes				
(154, × 10-3	79.0	79.5	60.0	45.0	30.0	81.5	76.9	54.8	46.5	39.3
(ibs × 10-7	80.0	79.5	69.0	43.0	30.0	32.0	76.9	54.8	46.5	39.7
(1be * 10 <sup>-2</sup>	81,5	79.5	60.0	45.5	30.2	83.0	76.9	34.8	46.5	39.7
(155 × 10-3)	81.5	71.0	38.4	33.8	29.2	83.0	74.6	46.6	34.1	33.3
(INCHES)	2.34	2.45	4.25	8.23	9.16	2.39	2.79	5,08	64.89	9.73
(INCHES)	1.82	1.52	4.25	6.64	8.48	1.44	1.90	4,95	6.43	8.95
	0.69	1.50	4.00	6.25	8.18	0.70	1.78	4.42	6.19	8.60
(BAHONI)	0.69	1.21	3.81	5.17	7.14	0.70	1.27	3.31	5.09	7.35
SHEET NUMBER	8-1.7	S-17	0-28	G= 32	0-30	8-17	5-17	C-27	C-31	C 29A
ANA LANA Lana	67	30	10	32	υc	34	35	36	37	38
	PANEL SHEET $L_1$ (INCHES) $L_2$ $L_3$ (INCHES) (INCHES) (INCHES) (Ibs $\approx 10^{-3}$ (Ibs $\approx$	PANEL SHEET $I_1$ SHEET $I_1$ $I_2$ $I_3$ $I_4$ $I_4$ (INCHES) (I	PANEL SHEETSHEET $I_1$ $I_2$ $I_2$ $I_3$ $I_4$ $B_4$ $B_1$ $B_4$ $B_1$ NUMBER NUMBERNUMBER NUMBERNUMBER NUMBERNUMBER NUMBERNUMBER NUMBER $I_10^-3(Ibs \times 10^-3)(Ibs \times 10^-3)(I$	PANEL NUMBER SHEET Å Å Å Å Å Å Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø Ø <thø< th=""> Ø Ø</thø<>	PANEL SHEET Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å Å	PANEL NUMBER SHEET NUMBER I. NUMBER I. NUMER I. NUMER	PANEL SHEET I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I	PANEL SHEET I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I	PANEL SHRET I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I I	PANEL SHEET A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A A

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TABLE 7 2024-T3 ALUMINUM WIDTH --- 30 INCNES, THICKNESS --- .06.3 INCH

PANEL	SHRRT NUMHRR	(INCHES)	(INCRES)	(incitre)	(INCHES)	(c-01 × *1)	(12* × 10-3)	(-01 × *9)	(10* × 10 <sup>-3</sup>	BCKLING BCKLING
30	t t	0.33	1.12	1.20	L . J 7	105.0	158.0	108.0	106.0	°N N
0*	2	1.67	2.61	2.71	2.71	63.7	77.7	17.7	77.7	
41	Ł	75.6	6.63	4.65	4.65	46.4	62.0	62.0	62.0	
43	. 1	3.0	5.92	6.21	6.55	38.8	55.0	55.0	55.0	
43*	•	7.21	8.65	ŧ		27.3	42.5	Ę	3	
44	1	10.80	12.66	13.25	18.65	27.2	29.6	29.6	28.4	
45	:	3.67	4,80	5.55	6.71	52.0	75.0	75.0	75.0	Xe#
46	3	7.13	67*8	9.45	10.71	37.5	\$0.0	50.0	30.0	
47	ŧ	5.73	7.25	7.34	8.09	41.5	54.5	34.3	54.5	
89	ŧ	10.86	11.85.	13.10	14.40	33.2	34.5	34.0	34.0	
	÷	-						:	-	
	-				-	-				
* Inc.	rementa 11y	loaded.			-				-	
**************************************			שוויין ווייזיאועשיש איזאישעריין וישעי	A representation in the second second way at the	ייייע אוויינענענע איין פעעעעעעעעעעעעעעעעעעעעעעעעעעעעעעעעעעע	I THE REPORT DURING THE REPORT OF	A		and a man when the second to second back don't	

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		BUCKI, INC	UN .	-	-					·····	B vi X	-			
		(16. × 10-		-2.2	33.5	30.4	28.8	23.6	6.7	14.2	23.0	20.4			
		(1 × 10.	32.6	32.5	33.0	30.7	28.8	23.6	7.7	14.6	25.0	20.4			
		(16. n 10-3	32.8	32.5	33.5	30.7	28.8	23.4	7.7	15.0	25.1	20.9			
		P. 10-3	30.0	28,8	32.0	30.4	21.8	19.2	7.0	14.8	17.6	18.4			
	TANLE 8. 24-T3 ALUMI 24ES , THICK	(INCHRN)	1.61	1.72	2.11	2.10	2.31	4.81	7.30	7.45	3.96	6. L4			
	14 I 12 20	L <sub>3</sub> (INCHEG)	1.06	1.49	1.05	1.80	2.10	4.76	5.10	5.37	3.81	5.42			
Anthe	OTA TA	L2 (INCHEB)	0.69	1.18	1.60	1.52	2.23	4.40	4.75	5.05	3.58	4.99			
		(INCHRS)	96.0	0.92	0.97	1.33	1.68	06.6	4.44	4.79	3.08	4.72		1 ANORES	Determine C
		BHEET NUMDRR	S-32	8-13	s-s	8-4	8-13	f		S-2	S 13	s-13	······	[neos = .09]	
		PANGL. NUHKER	Ġţ	50	51	52	53	* 55.	55**	36	57	£8		* Thick	オイト さちょくし

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TANLY 9 2024-TJ ALIMINUM WIDTH --- 12 INCHES, THICKNESS --- 0.32 INCH

PANE1. NIMBKR	SHERT NUMBER	(INCHRS)	(INCHES)	( SARONI)	L (INCHES)	(-01 × w1)	(1he <sup>P2</sup> 10-)	tba x 10-3	(16a × 10-3	INCKLING RESTRAINT
A-1	1	4.10	4.5Å	5.20	7.20	¢.8	9.0	0.9	8°8	ů N
A 2	ŧ	3.14	3.66	3.85	6+34	4.2	9.8	6 8	9.5	
A-3	3	1.68	2.18	2.20	3.97	8.2	14.4	14.8	14.7	
¥-4	ę	0, 83	2.20	2.26	2.68	16.0	17.5	17.5	17.3	~
L	A very results a summer of			ע מרדיים, ורפועם ומרטיומודוי בשרמי כן או ארשי	han 1942 - Trainhyamau X, 1942 - T	ויינער איז אולאינגעין איזירי, אווער אוון אין א	-	VIII	I MONG NUM DURANNA MALA SUN	withing participations and the

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		SUCKLING BUCKLING	No			*	# 0 X
		(60. × 10)	24.3	22.3	20.7	14.8	19.6
Î.		-01 × 49	24.3	22.3	20.7	84.8	18.8
	INCH	10- X 10- X	24.5	22.0	20.7	14.13	19.0
	Cityon and City	(16. × 10-3	24.0	21.2	17.6	12.8	9.01
Ĩ	tvalt 10 4-T3 AUMI	(INCHAS)	1.34	2.40	2.40	3.58	2.76
Concerned and the second se	202 - HUNA	(THCHES)	1.04	1.40	2.74	3.53	2.76
		Banort)	0.63	1.26	2.50	3.28	2.46
		(INCILRE)	60.0	1.03	1.57	2.95	2.26
		SHKET SHKET SHERE	61-8	5-13	8-13	S. 13	(T-1)
		PUMBER PUMBER	Ø.	¢0	÷1	¢2	63

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12 INCH WIDE TITANIUM BAI-IMO-IV

PANEL NUMBKR	THICKNR96 (JMCHKB)	(INCHKB')	1 (1401183)	L (TNCHES)	(INCHES)	(10-3)	(10- 210-3)	(-01 t x Huy)	(10 × 10 )	INICKLING RESTRAINT
F n L	.045	2, 15	3.23	64.6	3,68	24.0	36.0	36.0	36.0	°N No
T 2	.045	10.0	T	10	1.95	34.4	55.4	56.4	\$0-4	•
T	\$70.	0.64	1.00	1.30	1.50	42.0	55.0	53.0	35.0	
T-8	.045	4. LB	4.89		5.64	14.2	21.7	21.7	21.7	2 7
T4	• 020	7.02	2.25	2.36	2.48	10.0	11.7	11.7	11.7	Yen
3 + 2	. 020	0.95	1.24	1.24	1.24	16.0	20.4	20.4	20.4	
7-6	.020	0.58	0.63	0.70	0.75	22.8	36.5	26.5	26.7	
£ = 7	.020	2.12	2.80	2.80	3.00	10.2	13.4	13.4	1.3.4	4 <del>4</del> 7
	forthal were we printing and	y h bishinnan dala jula mwala wang	And semister with but at running to	A HERE TRUCK IN AND AND AND A	a un sensi nontre primeter del	Asses, we municute the summer	a queste survey, at sa queste parte b	AND IN FARMA LUBBLANCE CANNER.	i ki ki minanaran na mananan ku ki ki ki	too was a stal strated strassing (house a b d

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PANRI. NUMARK	THICKNESS NUMBER	(Incluss)	(INCHES)	(TNCIJKS)	(SHCHES)	(c01 *	(10+ × × × × 0-3)	(1. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2.	2 -01 × -94	MUCKLING REGTRAINT
T. 9	.045	2.20	2.48	2.60	2.85	17.0	25.0	25.0	25.0	84
T-10	. 043	0.50	1.31	1 . 40.	1.35	. 26.0	37.7		37.7	
1-11	.045	0.60	0.08	1.14	1.15	33.2	40.0	40.0	40.0	-
T-16	. 045	2.10	2.88	2.97	3.21	18.6	26.8	26.8	27.0	Kea
T-12	.020	2.26	2.48	2.64	2.64	7.0		7.7	1.5	¢ N
r-13	.020	10.01	1.05	1.19	1.36	34.0	14.1	14.1	13.7	
T-14	.020	0.62	0.87	0.87	0.87	16.4	17.0	U*41	17.0	<b></b>
T-15	. 020	2.11	2.39	2.63	3.20	11.2	11.2	13.2	13.0	Yeu
Third, the initial slow tearing was small and was accompanied by relatively large changes in load. As a result, considerable scatter in the recorded values of the onset of that was observed.

"h. P. Sherry Herry

- 2. The beginning of maximum load: The stable slow crack extension was abtained during a continuous loading process of approximately 30,000 pounds-per-minute after varifying the approximate equivalence of incremental slow tear and slow tear at a load rate of 30,000 pounds-per-minute (Figures 44 and 45). At a yoint corresponding to the maximum load obtained by incremental loading, the load, which was initially increasing at 30,000 pounds-per-minute, was observed to hold constant even though the signal to the serve value was continually increasing. (This can be attributed to the relatively large volume of all required to displace the 300,000 pound load cylinder and to the combined characteristics of the MIL supply system and pressure sensitive serve value.) Because of this characteristic of the test machine and the convenience afforded in loading and in recording subsequent unstable crack behavior, the majority of maximum load points were determined during the continuous loading process.
- 3. A crack velocity of one inch per second: Initially, attempts were made to separate tear at constant velocity from the latter stage of acceleration as suggested by Lorens<sup>2</sup>. Curves of film frames versus crack length were plotted. As it was not possible to definitely distinguish a tear of constant velocity from tear accompanied by acceleration, an elternate definition of a slope of one luch per second was chosen. This slope occurred in all instances just at or shortly before the very rapid crack growth immediately preceding rugture.
- 4. The crack length at rupture: The last frame of film record at 16 framesper-second was taken for this point. Since the crack velocity near failore is high, the scatter in crack length obtained as a result of the random relationship between exposure at 1/123 record and supture is considerable.

Figures 46 through 55 show someries of the first the point for all widths of 2024-T3 aluminum. Because of differences in behavior, the 78 and 30 inch wide panels are shown separately from the 9 and 12 feeth with markets.

## SUPPLEMENTAL STUDIES

During the course of the main test program, questions arose regarding procedures and possible influences that required clarifications. These occurred, supplemental studies were undertaken.

A study of the dependence of maximum load and critical brack length on the rate of loading was conducted at the beginning of the Reat program. This for adopting the procedure of continuous loading at a problem if the difference before per minute through the close tear phase; an evaluation of the difference before this procedure and an incremental loading procedure was made (Figures 44 and 45). Panels 5 and 9 were loaded incrementally. The load was first trained until slow near could be seen. After the crack length and load were recorded, the load was increased until additional tearing was seen. This process was continued until at the last small increment of load, the crack continued to extend with the load held constant. At this point, the camera was turned an







IN UNGULDED PANELS 2024-T3 ALIMINUM

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FIGURE 47 STRZSS V3. CRACK LENCTH FOR START. OF SLOW TE IN GUIDED PANELS 2024-T3 ALUMINEM

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PICURE 50 STRESS VS. CRACK LENGTH FOR CONSTANT LOAD IN UNCUTUED PANKLS 2024-T3 ALUMINIM



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TOTAL CRACK LENGTH (  $L_2$ ) IN INCHES

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and the second sec K THIRDRANESS (ALL GUITED) C = 20 × .003 INCHES TCURE 31 BTRESS VS. CHACK LENGTH FOR CONSTANT LOAD IN GUIDRE TANKLE 2024-TU ALIMINUM 08 -LOUDIN L 0.24 2 Q TOTAL ORACK LANGTH ( 12) IN INCHAS 2 2 q ٥Þ 9 0 . 1% **\$** Ű G > ¢ 20 ġ 30 Š 20 ALLER VOLUMENTS ( 2) IN FILL

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FIGULE SJ STRESS VS. CRUCK LENGTE FOR CONSTANT LOAD IN CUIDED PARELS 2024-TJ ALIMINEN





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and the unstable crack extension at constant load was recorded. A comparison of the results of this procedure with the results of the continuous loading procedure showed little difference (Figures 44 and 45). Because of the convenience afforded in loading and in recording subsequent unstable crack behavior, the majority of panels were loaded at 30,000 pounds-per-minute. The panels which were incrementally loaded are indicated in the data summary contained within this report.

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The fact that the load reached a maximum value and held nearly constant after an unstable crack length had been attained must be attributed to the response characteristics of the load system. The fact that the recorded behavior was not sensitive to the above differences in procedure was encouraging and should indicate the general usefulness of the data obtained.

During the testing of panels with gross and net sections near the yield stress, the question of whether the point of constant load could still be associated with crack extension needed further resolution. Since the constant load point on the tear curve is actually dependent upon the response of the load system to the rate of travel of the test grips, it was reasoned that in the range of behavior where gross and net section yielding accompanied fracture, the maximum load point could possibly be reached without an accompanying change in crack extension. Figures 56 through 60 show the load-crack length-elongation wersus film frames at 16/sec. for 12 inch wide panels near failure. It can be seen that tear velocity decreases with increasing crack length and in the longer clack lengths the point of peak load has only moderate significance. In the shorter cracks, good correlation between peak load and significant increase in tear rate were obtained.

Buckling studies were conducted on 12 inch, 20 inch and 30 inch wide panels of each thickness. These studies were conducted for the purpose of decommining whether the beginning of significant buckling displacements could be correlated with the observed drop off in strength at longer crack lengths for unguided panels. The results of this study showed that this was not the case. Definition of the panels started at shorter crack lengths than the observed drop in strongth. A summary of buckling deflections is given in Table 19. These measurements were taken using a tool makers microscope from photographs taken parallel to the load direction and as close to the panel as possible. The results of other buckling studies are shown on Figures 19 through 23.

Figure () was taken an instant before the failure of panel 43 to show the extent of plastic deformation near the crack tip. The grid on the panel was applied using a silk screen process. The lack of a large visible plastic zone is of interest when a calcering the possible use of a plastic zone correction.

(A ELONGATION) IN INCHES 02 CHANCE IN ELONGATION RDTH CHES THICKNESS L1 INCH **₊06** = 12 INCHES .01 5 .5 CHANGE IN CRACK LENGTH (AL)IN INCHES .4 -.3 .2 .1 (A LOAD) IN KIPS CHANGE IN LOAD EISG TOPP 71P7 **A**T 1625 2 FRACTURE 100 120 119 90 80 70 60 50 40 30 20 10 0 FRAMES FROM POINT OF FRACTURE (16/sec) FIGURE 56 LOAD - CRACK LENGTH-ELONGATION VS. FRAMES FROM FRACTURE FOR TEST PANSL 49, UNGUIDED 2024-TS ALUMINUM 193

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( A ELONGATION) IN INCHES STLADIO IN IL AUNCH THICKNESS 47 M <u> MAE</u> = .066 2KC = 1.48 INC •5 (AL) IN INCHES .3 2 .2 , <u>1</u> 3 A LOWD IN KSPT FRACTURE 100 0 50 70 60 50 40 30 FRAMES FROM FOINT OF FRACTURE (16/SEC) 10 Ó 120 四 90 20

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PRANCE FROM FORMET OF FRACTURE (16/SEC)

FIGURE 60 LOAD - CEACK LENGTH-ZLONGATION VS. TRAKES FROM VEACTURE FOR TEST PANEL 57, GUIDED 2024-73 AUGUNDH

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TABLE 13 CALCULATED DATA SUMMARY VIEDD - 20 LOCHES, THIZCKNESS - 032 INCH

Pickel. Filmarr	5.	<b>4</b> 2 11	S. 3	د تر زر	001 (ka1)	62 (k#2)	с. (к#1)	0.4 (k#1)	71 (k#1)	<del>6</del> 2 (kat)	₩3 (k#4)	744 (Kal)	67.1 (k31)	0.2 (kal)	0n3 (kai)	(kai) (kai)
61	.032	620.	. 069	• 069	47.4	47.6	47.4	47.4	47.5	47.8	47.6	47.6	40.9	49.64	51.0	51.0
20	.062	.077	.095	.095	38.5	45.6	45.4	43.4	38.7	45.8	45.7	45.7	41.1	49.5	50.4	50.4
21	.172	.205	. 236	.272	21.4	01.3	31.3	30.2	21.7	31.9	32.2	31.4	25.8	39.4	6.04	41.7
2:	.262	.319	.318	. 393	24.6	25.6	23.6	25.3	25.4	27.0	27.0	27.4	33.2	37.8	33.8	6.14
23	.405	.423	. 483	.610	1.5.1	17.7	17.2	13.7	17.1	19.4	19.7	20.0	26.4	30.8	23.4	40.3
24	.032	640.	0\$0.	.072	47.7	48.)	48.0	48.0	47.8	48.7	48.2	48.2	48.0	30.5	51.4	51.6
25	, 056	.071	.103	.378	43.2	47.0	46.9	46.9	43,3	47.2	45.4	30.5	15.2	\$0.5	52.1	75.0
42	.172	.210	.243	.316	22.8	36.4	36.4	35.5	20.1	37.2	37.6	37.4	27.6	46.6	40.8	52.0
27	. 263	116-	.333	.539	20.0	27.7	27.7	26.6	20.8	29.2	29.6	31.3	27.3	40.6	0.64	56.6
28	.373	.367	.47.5	.610	16.3	22.4	22.4	30.3	17.6	24.3	29.4	25.8	26.1	36.8	43.0	52.1
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CALCULATED DATA SUMMARY \*\* 20 INCHES, TRICENESS \*\* . 063 INCH TABLE 14

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45.4 49.4 67.5 49.95 0.9.60 49.64 46.2 45.8 47.4 50.6 49.2 43.5 49.64 40.9 47.5 50.2 1.00 46.1 (K#4) 24 24 4.8.4 45.7 44.5 47.5 48.0 46.2 41.4 35.6 37.6 37.5 47.5 48.0 4.69 0.4.0 47.9 45.4 36.5 0.13 (hail) (k#1) 42.4 32.5 42.4 40.5 47.2 40.5 47.5 6.64 4.3.9 44.7 6.Cv 60.3 01.0 34.5 46.0 47.0 6.8.2 21.0 36.4 46.2 31.2 42.4 44.5 23.0 34.2 20.9 20.0 26.8 22.9 13.0 40.6 23.0 34.0 13.9 (Kat) 24.1 55 24.2 44.0 11.0 45.4 64.5 43.3 43.1 34.1 91. IC 23.6 23.2 24.0 39.0 34.4 36.7 37.1 44.1 1.00 (Fat) ¢, (km1) 27.8 36.5 36.9 93.9 30.4 43.9 45.3 44.4 43.2 1.64 22.3 23.2 22.0 0.04 30.4 32.2 21.2 34.1 5 (KHA) 44.3 43.0 36.7 9.00 21.9 22.6 6. Co 6.11 9.1.6 26.2 43.1 6.CA 30.3 21.3 20.7 36.2 43.4 36.8 ÷۳ 41.4 24.11 (kaa) 44.5 29.8 21.0 28.8 21.7 15.6 15.0 27.4 26.6 39.7 15.2 63.8 19.4 14.1 18.1 38.6 Ъ (kai) 0.4 0 4 44.0 42.8 42.8 36.0 28.9 19.3 20.7 17.6 43.7 1.2.1 22,0 44.9 33.6 32.5 19.7 37.7 30.) 32.3 (kn1) 44.9 64.0 42.8 42.8 35.0 36.0 32.5 28.92 20.3 17.9 43.7 23.2 20.7 19.7 1.64 30.7 32.3 ۍ د د 1.10 (K#1) 32.5 (1.4.4) 44.1) 4**3.6** 42.8 33.6 36.0 28.9 30.7 20.3 20.7 17.9 23.2 19.7 43.7 7.70 32.3 £0 1.03 (k#1) 44.4 C. 1 29.7 39.6 41.2 20.8 28.5 23.2 13.2 16.8 13.5 38.5 26.7 23.2 15.1 63.7 19.2 23.7 14.1 . 5.55 .110 .6,5 .098 .068 .279 . 590 . 524 .130 . 190 .345 .108 .133 .222 .409 643. .233 .241 1020. . 555 .453 . . . . . 319 .095 ,105 .216 .216 .267 . 304 .432 .312 .068 477 .080 .239 <u>دا</u> » .071 .472 .062 .078 .066 .190 .156 .389 402 .069 . 24.5 .251 .287 . 507 .051 .277 , 304 .392 .221 - 13 · 004 .360 .053 .064 .165 .209 .370 .379 870 .216 1.42. 1 .037 . 347 .170 .440 043 .164 .167 KIIH HUN FANEL. 10 4 1 27 2 ŝ 91 2 33 110

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WIDTH - 20 INCHES, THICKNESS - , OUO INCH CALCULATED DATA SUMMARY

TARLE VILLE

47.6 42.3 59.4 \$6.0 5.14 47.5 36.0 30.00 34.6 34.4 9.4 (Fal) 0.00 52.0 43.0 (1).) 44.6 32.4 4.04 42.1 32.6 67.5 43.5 42.4 41.4 21.5 43.5 52.0 \$3.4 4444 54.1 32.1 (ka1) (ka1) 20.6 32.9 20.5 33.0 32.0 42.6 29.4 29.45 \$0°0 54.1 (kei) 77 (kat) 0.55 25,0 32.5 30.6 21.0 42.4 32.5 30.0 38.4 50.1 (K#F) (K#F) 24 24 30.4 51.0 30,0 38.4 8,95 20.6 52.7 47.3 3.5.4 (k # 1 ) (k # 1 ) 30.3 30.0 29.9 1.2 38.3 20.6 5.2 - 2 67.3 دي به در 5. 40 14.2 22211 52.42 45.5 24.4 21.8 46.9 01 (km1) 51.2 14.5 29.1.1 51.0 2.1.6 49.64 37.5 28.1 19.2 40.8 54.3 5.05 (kat) (kat) 32.0 30.5 49.64 34.21 241.8 37.5 28.1 1.8.7 46.8 29.1 13.4 51.0 52.0 97 6 <del>1</del> 31.5 28.4 44,64 34.3 26.1 24.45 (K#1) 1:0 2: 51.0 20.6 چې د دو د 24.0 46.7 44.5 18.2 シャッシ 21.3 21.5 .410 5.4 H V .344 .139 . 1.86 - 2.6.7 .1.2.2 .212 4.50 . 7.5.6 \*15 , 426 h 9.44.6 0%0 (60" .331 82D. .003 .248 .23.2 322 ۲.) ۲.) .012 . 430 .073 , 200 ,409 ~035 .089 206. 1700" . 221 N 3 , 03*5*0, 254 .034 ,060 .150 . 253 336 83 .163 .367 a | 3 PANEL. NURDER 30 30 2 6 Y. 2 ž <u>.</u> 111



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0.44 38.0 38.7 37.6 9.90 51.2 30.8 34.6 34.6 (x#7) (x#7) 37.0 45.0 35.8 27.8 38.2 9. II. 38.7 4.8.4 38.7 3 (F. 3) 44.9 32.4 67.3 37.0 38.0 24.6 37.4 26.8 38.7 16.2 (fail) 27.4 36.9 35.4 27.6 19.1 31.2 27.0 27.1 24.8 22.7 (Jey) 41.5 30.00 20,02 30.0 20.6 35.9 33.2 1.9.4 40.04 4 (K) 41.5 30.0 20.0 8.42 33.2 17.3 40.4 27.8 29.8 ٤ (First) 41.5 19.6 \$. \$ 33.2 29.8 23.4 17.2 27.6 29.7 40.1 33.6 14.9 13.4 18.7 22.4 33.7 24.6 27.3 20.8 20.2 (Kait) 18.0 37.3 41.3 15.0 26.4 32.8 29.2 28.8 39.7 ÷ 18.0 57.3 41.3 13.6 26.4 32.8 29.2 39.7 28.8 ŧ (KA3.) 18.0 57.3 41,3 32.8 13.6 26.4 29.2 22.4 7.90 28.8 (kai) 17.5 33.8 34.5 24.5 14.4 27.5 19.8 22.0 20.6 \$5.7 1 1/2 ----.480 Incremental loading to tailure. .155 .218 .259 .046 . 224 160. .621 .321 ŧ 436. 040. .155 .244 144. .185 816. 160. .207 ~ ~ \$ .420 .395 .037 .087 .134 .197 .288 .160 .283 .241 ~~!> .055 .118 .240 .360 .017 .167 .122 .238 [9; , 191. RANEL. NUMBER \*(:') 30 40 44 ŝ 99 7 8¥ 41 42 43 112

TABLE 17 CALCULATED DATA SUMMARY WIDTH -- 12 INCHES, THICKNESS -- .063 INCH (UNLESS NOTED)

Chai) 75.0 49.2 4.44 53.0 47.9 40.6 4.8.9 54.0 48.5 48.2 45.6 48.4 48.4 48.6 48.9 47.6 47.4 7.04 2.45 35.3 (k#1) 47.5 46.4 45.9 52°0 46.4 38.4 32.8 32.5 47.5 46.1 (k#{) 19.7 44.9 28.5 32.2 30.0 41.2 43.8 31.4 41.6 33,3 (Kol) 35.0 0.0% 23.0 31.1 43.1 44.5 40.7 38.80 26.7 2.).8 (K#1) (K#1) 43.4 30.1 22.0 34.9 63.9 6.03 38.4 21.6 43.4 26.6 (ka1) (ka1) 43.4 40.9 30.6 20.3 21.7 21.6 30.2 23.9 24.8 4.3.6 6403 42.5 11.2 38.4 40.7 2.91 39.8 26.3 29.2 22.1 (%#£) 27.0 42.5 44.2 \$0.0 18.8 33.0 40.2 38.6 24.5 42.7 (Kan) 27.40 42.9 40.5 38.0 20.0 33.0 9.64 24.6 19.3 43.0 (Ka1) 43.0 20.0 33.62 43.4 44.2 40.3 38.0 24.45 4.9.4 87.4 (kal) 24.4 38.2 42.4 40.3 28.9 20.0 141.3 0.41 23,43 39.7 3 1.501 700° ÷53 .323 .140 .172 171. .205. **396** . 131 . 443 .455 .086 147 171. .390 .416 .311 .116 .122 **NUCHER** ~|× INCE m .032 .080 × 3 2791 404. 151. .124 066. . 392 .097 .1.82 .334 .056 011. .076 61E. .386 100. .137 .362 160, . 252 .049 Thickness ~|> Thinkna 5545 NUMBER ¥. . . PANKL. Ċ 49 30 2 2 8 5 Ř \*\* 3

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TABLE 18 CALCULATED DATA SCHMARY WIDTH == 9 INCHES, THICKNESS == 063 INCH

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<u><u>L</u><sub>1</sub> <u></u><u>L</u><sub>2</sub></u>	23		ć 3	<b>F</b> <sup>2</sup>	0,L	0.2 0.2	<b>3</b> 3	9.4	ы	. 16	١Ď	157	້ະ	<u>م</u> ,	с. , С. ,	0
V V V (ka1) (ka1)		V V (kst) (kst)	w (kst) (kst)	(ks1) (ks1)	(181)		(kst)	(ksi)	(ksi)	(Ks4)	(kö£)	(kst)	(kš£)	(ksi)	(kši)	(ksi)
.070 .092 .115 .149 42.5 43.2	• 092 • 115 • 149 42•5 43•2	.115 .149 42.5 43.2	.149 42.5 43.2	42.5 43.2	43.2		42.9	42.9	42°8	43.4	43.2	43.4	47.6	47.5	48.5	50. ¢
.113 .140 .156 .156 37.4 39.4	.140 .156 .156 37.4 39.4	.156 .156 37.4 39.4	.156 37.4 39.4	37.4 39.4	39.4		39.3	39.3	37.8	39.6	39.7	39.7	42.2	44.9	46.4	46.4
.174 .277 .304 .309 31.1 36.0	.277 .304 .300 31.1 36.0	.304 .300 31.1 36.0	.300 31.1 36.0	31.1 36.0	36.0		36.5	36.5	31.6	38.1	38.4	38.4	37.7	50.5	52.2	52.2
.328 .364 .395 .410 22.6 26.1	.364 .395 .410 22.6 26.1	.395 .410 22.6 26.1	.410 22.6 26.1	22.6 26.1	26.1		26.2	26.1	23,9	28.1	28.3	28.4	33.6	41.0	43.1	44.4
.251 .373 .307 .307 24.3 33.	.373 .307 .307 24.3 33.	.307 .307 24.3 33.	.307 24.3 33.	24.3 33.	33.	<del>ر</del> بر	33.2	33.2	25.1	36.2	32.2	35,2	32,1	53.5	48.5	48.5
.318 .351 .375 .408 28.6 31.	.351 .375 .408 28.6 31.	.375 .408 28.6 31.	.408 28.6 31.	28.6 31.	31.		30.9	30.5	30.2	33.2	33.4	33.2	42.1	47.9	49.5	51.5

, TABLE 18 CALCULATED DATA SLAMARY WIDTH == 9 INCHES, THICKNESS == .063 INCH

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Total	30.2 33.2 33.4 33.2 42.1 47.9 44.5 51.5
$\widetilde{\sigma}_{1}$ $\widetilde{\sigma}_{1}$ $\widetilde{\sigma}_{2}$ $\widetilde{\sigma}_{1}$ $\widetilde{\sigma}_{2}$	30.2 33.2 33.4 33.2 42.1 47.9 49.5
$\widetilde{\sigma}_{4}^{1}$ $\widetilde{\sigma}_{1}^{2}$ $\widetilde{\sigma}_{2}^{2}$ $\widetilde{\sigma}_{2}^{2}$ $\widetilde{\sigma}_{2}^{2}$ $\widetilde{\sigma}_{2}^{2}$ $\widetilde{\sigma}_{2}^{2}$ $\widetilde{\sigma}_{2}^{2}$ $2.9$ $42.68$ $43.4$ $k3.2$ $43.4$ $47.6$ $47.5$ $5.3$ $37.88$ $39.0$ $39.7$ $39.7$ $42.2$ $44.9$ $6.5$ $31.66$ $38.4$ $38.4$ $38.4$ $37.7$ $50.5$ $6.1$ $23.9$ $28.1$ $38.4$ $38.4$ $37.7$ $50.5$ $6.1$ $23.9$ $28.1$ $28.3$ $28.4$ $33.6$ $41.0$ $3.2$ $25.1$ $36.2$ $35.2$ $32.1$ $53.5$ $3.2$ $25.1$ $36.2$ $35.2$ $32.1$ $53.5$	30.2 33.2 33.4 33.2 42.1 47.9
Total     Total     Total     Total     Total     Total     Total     Total       2.9     42.08     43.4     6.3.2     43.4     43.2     43.4     47.6       2.9     42.08     43.4     6.3.2     43.4     47.6       6.5     31.6     39.1     39.7     39.7     42.2       6.5     31.6     38.1     38.4     38.4     37.7       6.5     31.6     38.1     38.4     38.4     37.7       6.1     23.9     28.1     28.3     28.4     33.6       3.2     25.1     36.2     33.3     28.4     33.6	30.2 33.2 33.4 33.2 42.1
$\overline{\sigma}_{4}^{4}$ $\overline{\sigma}_{1}^{2}$ $\overline{\sigma}_{2}^{2}$ $\overline{\sigma}_{3}^{2}$ $\overline{\sigma}_{3}^{4}$ $\overline{2}.9$ $(k_{B4})$ $(k_{B4})$ $(k_{B4})$ $(k_{B4})$ $\overline{2}.9$ $42.68$ $43.4$ $h3.2$ $43.4$ $6.3$ $37.8$ $39.6$ $39.7$ $39.7$ $6.5$ $31.6$ $39.1$ $38.4$ $38.4$ $6.1$ $23.9$ $28.1$ $28.3$ $28.4$ $6.1$ $23.9$ $28.1$ $28.3$ $28.4$ $3.2$ $25.1$ $36.2$ $35.2$ $35.2$	30.2 33.2 33.4 33.2
Total     Total     Total     Total       2.9     42.08     43.4     63.2       2.9     42.08     43.4     63.2       6.5     31.6     39.1     39.7       6.5     31.6     38.1     38.4       6.1     23.9     28.1     28.3       3.2     25.1     36.2     33.2	30.2 33.2 33.4
Total     Total     Total       2.9     42.8     43.4       2.9     42.8     43.4       5.3     37.8     39.8       6.5     31.6     38.1       6.1     23.9     28.1       3.2     25.1     36.2	30.2 33.2
37.8     42.8       2.9     42.8       5.3     37.8       6.5     31.6       3.2     25.1	30.2
66.5 66.5 3.2 3.2	
	30.5
633 (kai) (kai) 39.3 39.3 36.5 36.5 26.1 33.2 33.2	30.9
002 (kai) 39.4 39.4 36.6 26.1 33.5	31.0
(kst) (kst) 42.5 37.4 31.1 22.6 22.6 22.6	28.6
.149 .149 .300 .410 .307	. 408
<b>k</b> <b>.</b> 115 .115 .115 .115 .304 .307 .307	.375
2277 .092 .140 .277 .364 .373	.351
.174 .070 .113 .174 .328 .328	.318
PANEL NUMBER 59 60 61 62 63	64

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PANÉL WIDTH (INCRES)	PANZL THICONISS (INCHIZS)	CBACX LERGTH ((ISC)7.5)	euckle Load P (kips	SUCKLŻ STRESS O <sub>C</sub> .+1)	TOTAL LEEGTH OF STOLL PARALLEL YO CREAK (INCRES)	LESCINS NETWORK YOINTS OF THTLECTION (INCRES)	DISPLACEMENT AT & CF CFACK(INCHES)	¥0155
30 30 30 30 30 30 30 30 30 30 30 30 30 3	.032 .052 .032 .032 .032 .032 .032 .032 .032 .053 .063 .063 .063 .063 .063	3 4 5 5 5 3 - 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5	4.23 9.6 8.0 11.4 17.1 20.6 24.0 44.5 35.2 19.4 36.5 26.7 42.5	4.43 10.0 7,0 11.7 17.8 20.3 35.0 23.5 18.4 10.3 70.5 10.9 17.7	5.5 6.7 7.6 7.5 7.5 7.5 7.5 6.8 6.5 1.5 10.5 11.5 10.7 19.5	2.0 2.8 3.8 3.8 3.8 3.8 4.6 1.6 2.6 2.7 3.5 3.5	.10 .12 .15 .20 .25 .28 .36 .97 .12 .20 .23 .23 .07 .19	Start of tasr-3.16 inches c.wck = 1/2 grack extension Duckies s. ction acc-symmetri- cal Start of tear
30 30	.0%0 .0£0	5	50.3 62 S	21.9	13 5 12,7	3.5	,2ž ,28	Start : if ther
20 20 20 20 20 20	.032 .032 .032 .032 .032	2 3 4 5 6	10.0 4.3 2.3 1.6 1.2	73.7 7.5 4.4 2.5 1.88				=
20 20 20 20 20 20 20 20	.063 -953 .063 .063 .063 .063 .063	2.75 3 4 5 6 7 3	26.8 24.8 18.2 11.5 8.4 5.0 4.0	21.3 19.6 14.4 9.2 6.6 4.8 3.2				
20 20 20 20 20 20 20 20	80. 85. 80. 80. 80.	3 3.25 5 6 7	50.8 47.6 39.6 26.0 21.2 15.5 12.0	32.8 35.8 74.5 16.2 13.2 9.5	no janua basa fana kana kana kana kana	sensorum hannanssare - Judensonurver		
12 12 12	.032 .032 .G32	2 3 4	4 2 1	10.4 5.2 2.5			-	
12 12 12 12 12	.063 .063 .063 .063 .063	2 2.5 3 4 5	25 27.6 16.6 10.8 6.2	33.8 29,4 21.7 14.1 8.1				So becaling
12 12 12	-06 -05 -08	3.25 4 5	21.2 16 10.2	26.4 15.4 9.5		na-ana langan		

C.5LL 19 NEASUREMENTS OF RECIEN PASELS 2024-T3 ALIGHDAR 1110

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