Fatigue strength of weathered and deteriorated riveted members, October 1984. (DOT/OST/P-34/85/016) 138p

Johannes M. M. Out

John W. Fisher

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This report describes a study that has been performed on the fatigue and fracture resistance of corroded and deteriorated riveted members. A detailed literature study is included which examines available test data on the fatigue behavior of riveted members. The most important variables on the fatigue strength of such members have been determined as well as the way and to what extent they influence the fatigue life. The previous test programs provided no information on the applicability of the Category D fatigue limit and little on riveted connections other than simple splices. Well tightened rivets and normal bearing conditions provided a fatigue resistance equivalent to Category C at stress ranges above 12 ksi.

Fatigue tests were carried out on six 80 year old steel bridge stringers with a riveted built-up cross-section. The stringers were significantly corroded along the compression flange, and locally at the tension flange. They were subjected to stress ranges that were between the fatigue limits provided for Categories C and D. The corroded region of the tension flange proved to be the most severe detail, varying between Categories C and E. The Category D fatigue limit appears applicable to riveted details. The reduction of the compression flange had no effect on the performance of the member. A frictional bond between section components had a beneficial effect on the fatigue life. Significant numbers of cyclic stresses were also resisted after failure of one of the riveted components.

A series of reduced temperature tests on one cracked stringer did not induce fracture of the component. These tests and the behavior observed during the fatigue tests confirmed the redundancy of riveted built-up sections fabricated from mild steel. A second stringer was fractured after all the components had significant fatigue cracks.

**Keywords:** Bridge, Connections, Corrosion, Deterioration, Fatigue, Fatigue limit, Fracture, Rivet, Steel

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### METRIC CONVERSION FACTORS

#### Approximate Conversions to Metric Measures

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*1 m = 3.28 feet (approx.). For other exact conversions and more detailed tables, see HES Misc. Publ. 798, Units of Weight and Measures, Price 92.25, 50 Catalog No. C13.10.798.

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FATIGUE STRENGTH OF WEATHERED AND
DETERIORATED RIVETED MEMBERS

by

Johannes M. M. Out
John W. Fisher
Ben T. Yen

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EXECUTIVE SUMMARY

A. INTRODUCTION

Many of the older bridges in service today are riveted structures and potentially have accumulated extensive fatigue damage. Yet the criteria used for the control of fatigue and fracture is based upon studies of modern welded construction. Previous laboratory work on riveted components has only been carried out on simple butt splices and limited to stress ranges above 14 ksi. Both the American Association of State Highway and Transportation Officials (AASHTO) and American Railway Engineering Association (AREA) specifications use a lower bound estimate, based on this limited data, to classify the fatigue strength of riveted built-up members. Research was needed to establish better estimates of fatigue resistance of riveted built-up sections.

B. PROBLEM STUDIED

Initially, a detailed literature survey was conducted to collect and summarize available data on riveted details. The data were used to test the validity of Category D as the fatigue strength above the fatigue limit. Major factors influencing fatigue strength were identified.

The objective of the research was to establish data on the high cycle fatigue behavior and fracture resistance of riveted built-up members in their weathered and deteriorated state. Tests were conducted on six stringers taken from a railroad bridge whose cross-sections were significantly affected by corrosion.

An analytical study on the behavior of a cracked rivet detail was also carried out. The test program yielded crack growth rates that were less than expected. This was believed to be a result of a frictional bond between the web plate and angles. The analysis made use of a computer program incorporating finite elements. The shape and size of the unbonded area was investigated.

C. RESULTS ACHIEVED

Approximately 1100 test results were collected and evaluated. The major variables observed to affect the fatigue resistance of riveted joints are the rivet clamping force and the rivet bearing ratio. Steel connections with good clamping force and normal bearing ratios have a lower bound fatigue strength defined by Category C. Plates with open holes provided greater fatigue resistance than riveted joints. The effects of different methods of hole preparation on fatigue strength were insignificant based on the available data. The lower bound fatigue resistance of riveted steel connections
including those with low clamping force and high bearing ratio is reasonably well represented by the Category D curve. Specimens subjected to stress reversal provided a fatigue resistance significantly greater than other specimens.

From tests on weathered and deteriorated members, the extreme life fatigue resistance of the web-flange riveted connection appears to be close to the Category D fatigue limit. The fatigue resistance of the corroded section was observed to vary between Category E and C depending on the severity of the corrosion of the section. Significant bonding of the angles and web plates as a result of their corroded condition extended the fatigue life. Fatigue cracks that formed in the corroded legs of the compression flange arrested in the heel and therefore had little effect on fatigue resistance of the member.

As a result of the finite element analysis, it was demonstrated that the frictional bond between the flange angles and the web plate was responsible for significant load transfer to the uncracked components. The shape of the unbonded area found to be more probable was an ellipse with its center at the middle of the crack. The presence of this bond reduced the growth rate of the crack in the outstanding leg. The increase in crack growth rate was small when the crack was less than two-thirds of the angle leg.

D. UTILIZATION OF RESULTS

The ultimate objective for implementation of research results is the incorporation of the findings into the AREA Manual for Railway Engineering and AASHTO Standard Specification for Highway Bridges. These findings suggest, that, 1) steel connections with good clamping force and normal bearing ratios can be considered equivalent to Category C, 2) wrought iron riveted connections are equivalent to Category E, 3) steel members whose outstanding flange is reduced by 50% or more due to corrosion loss correspond to Category E. Comments on the following would be incorporated into the text of these manuals: 1) plates with open holes tend to provide greater fatigue resistance than riveted joints, 2) method of hole preparation is not a major factor influencing fatigue strength, 3) members subjected to stress reversal provide fatigue resistance significantly greater than for other riveted members. An effective stress range defined by:

\[ \Delta \delta_{\text{eff}} = \delta_{\text{max}} - 0.6 \delta_{\text{min}} \]

provides comparable fatigue resistance when part of the stress cycle is compression.
E. CONCLUSION

Research performed under this project provided a means for consolidation and evaluation of available test data on riveted specimens. Also it pioneered the extreme life testing of six members in a weathered and deteriorated state. Analytical work provided insight into the existence, role, and shape of the bonded and unbonded regions between the flange angles and web plate of riveted built-up members.
1. INTRODUCTION

Major concerns of bridge engineers today are the safety of old riveted structures and the potential fatigue damage that has accumulated. Many of these structures were fabricated and placed into service at the beginning of the century. The question of safety is of major importance as increasing traffic, deteriorating components and the accumulation of large numbers of cycles are a reality for highway, railroad and mass transit bridges.

The criteria adopted for control of fatigue and fracture in new bridge structures are based upon studies of modern welded construction and ongoing laboratory research on welded members. Most older bridges are constructed of riveted built-up members. Research was needed to establish better estimates of the fatigue resistance of riveted built-up sections.

Most of the previous laboratory work on riveted components has been carried out on simple butt splices. A further limitation is that none of the previous testing has been performed with stress ranges below 14 ksi (97 MPa). Both the American Association of State Highway and Transportation Officials (AASHTO) and the American Railroad Engineering Association (AREA) specifications utilize a lower bound estimate, based on these limited data, to classify the fatigue strength of riveted built-up members [1, 2]. This lower bound corresponds to Category D in the joint classification system. A description and summary of the database is given in the commentary to the AREA specifications. [2]

This report provides a detailed literature survey which confirms the validity of Category D as a lower bound estimate for the fatigue strength of rivet details above the fatigue limit. The survey identifies the major factors of influence on the fatigue strength and their relative significance. The fact that the data originated from several independent sources makes it difficult to establish the significance of some of the test results. The majority of test results that fall short of Category C exhibit low clamping and high bearing ratio.

A pilot test program on the high cycle fatigue behavior and fracture resistance of riveted built-up members in their weathered and deteriorated state was carried out. The need for this investigation stems from the desirability to ascertain whether or not a difference exists at splices, along the built-up section, at cover-plate terminations and other related regions of riveted built-up members. Category D fatigue restrictions impose a penalty on the structural assessment. It is of particular interest to investigate the applicability of this category near the fatigue or endurance limit.

Six stringers taken from a railroad bridge were tested under constant amplitude load cycles. The stringers had a built up cross-section consisting
of a web plate and four angles, attached to the web plate with two rows of rivets. The test program provided data on the fatigue behavior of the rivet details and the cross-sections that were significantly affected by corrosion.

An analytical study on the behavior of a cracked rivet detail was also carried out. The object was to find the relationship between crack length and stress intensity factor $K_I$, and thus indirectly the crack growth rate. The test program yielded crack growth measurements which showed a crack growth rate that was less than expected. This was thought to be caused by a frictional bond between web plate and angles. This bond was absent adjacent to and ahead of the crack. The shape and size of the unbonded area was investigated. The analysis made use of a computer program incorporating finite elements. The feature of the program is the crack tip element which embodies the stress singularity existing at a crack tip.
2. REVIEW OF EXISTING TEST DATA ON RIVETED STEEL COMPONENTS

2.1 Introduction

A detailed review of the available data on the fatigue behavior of riveted steel members or components is provided in this chapter. Data are included from studies performed in the United States and Europe between 1934 and 1983. Each test result provides data on the stress cycle versus number of cycles until failure (or observed cracking). Primary focus is given to the cyclic stress range in this investigation as the main parameter influencing the fatigue life. However, other related stress variables such as the stress ratio and the bearing ratio are also examined.

The test data indicate that several variables have an influence on the cyclic stress - life relationship in addition to the stress range. The most important variables are: 1. Stress ratio R; 2. Yield stress; 3. Clamping force; 4. Bearing ratio; 5. Method of hole preparation; 6. Specimen state: manufactured from virgin material or cut out of existing structures; 7. Specimen type: e.g. simple shear splice, coverplate end or built-up girder in bending.

Unfortunately, not all of these parameters are always clearly defined in the available literature.

In most of the studies the stress variables have been defined on the net section, and "failure" defined the fatigue life. Very few crack size measurements have been reported.

All of the fatigue test data have been stored in a computer to form a data base, and a number of programs have been written to sort the data and help evaluate the major test variables. The primary means of assessing the significance of the variables was to construct S-N curves. Approximately 1100 test results are included in the data base.

In the following sections a number of S-N diagrams have been constructed for review. The solid lines are the AASHTO and AREA fatigue design lines C, D, E and E', developed from tests on welded details, which serve as reference conditions.

Since most of the riveted structural component test data are not distributed over a wide range of cyclic stresses, their regression line was not included in the diagrams.
2.2 Factors Influencing the Fatigue Resistance

2.2.1 General Remarks

Figure 1 summarizes all data points concerning riveted steel specimens, with no indentification of the control variables. Most test results exceed design Category D, although a small number of data points fall below Category D and E. Note that no tests have been conducted at stress ranges below 14 ksi (97 MPa). Very few specimens were subjected to more than 2 million cycles.

The test data mainly concern shear splices.

The following sections examine the influence of the previously mentioned variables known to affect the fatigue strength of riveted structures.

2.2.2 Influence of the R-Ratio

In most of the fatigue tests, the R-ratio was used as a controlled variable. The R-ratio is defined as the algebraic ratio of minimum and maximum stress in a stress cycle, \( R = S_{\text{min}}/S_{\text{max}} \). The published tests were divided into three categories: 

- \(-1 < R < 0, \) 
- \(0 \leq R \leq 0.3, \) 
- \(R > 0.3.\)

Figure 2 summarizes the test data for alternating loading, with \( R < 0 \). A large number of specimens did not exhibit failure in the section and are identified by the symbol ' o '. The data indicate that the fatigue strength exceeds the Category C resistance line.

Figure 3 shows the test data with low R-ratios \( (0 \leq R < 0.3) \). It is apparent that most fatigue tests were conducted under this stress condition. A number of test results are seen to fall below the Category D resistance line. Many of these specimens were tested with reduced clamping force and high bearing ratios. Section 2.2.4 provides additional discussion on these factors.

Figure 4 summarizes the test data with high minimum stress levels \( (R > 0.3) \). A number of tests fall below Category D.

High minimum stress results in net section yielding when the stress range is higher than 20 ksi (138 MPa). It seems likely that this is the primary reason for the reduction in fatigue resistance of these specimens. An examination of Figures 2, 3 and 4 indicates that the alternating stress condition is not as critical as a positive R-ratio. This was recognized in early European Convention for Constructual Steelwork (ECCS) Specification drafts by permitting a reduction in the stress range for connections without significant residual stresses [10]. The effective stress range is defined as:
\[ \Delta \sigma_{\text{eff}} = \sigma_{\text{max}} - 0.6 \sigma_{\text{min}} \]

where \( \sigma_{\text{max}} \) is the tension component of the stress cycle and \( \sigma_{\text{min}} \) is the compression component. The adjusted stress cycle values for the reversal loaded test specimens are given in Figure 5. The test data can be seen to be more compatible with the Category D resistance curve. A significant number of tests can still be seen to exceed the Category C resistance line, although not by the large margins apparent in Figure 2.

### 2.2.3 Influence of Yield Stress

Figures 6, 7 and 8 summarize the fatigue resistance according to the material yield point. Little difference can be seen between Figures 6 and 7. The scatter in the test data is apparent by the number of data points below the Category D resistance curve. It is probable that yielding developed at the net section in the case of materials with a low yield strength, most likely in combination with a low clamping force and high bearing condition.

The test data of higher yield strength material are seen to lie generally above the Category C resistance curve as shown in Figure 8. Only the highest stress range tests can be seen to lie below Category C, again, due to net section yielding, which promotes low cycle fatigue.

### 2.2.4 Influence of Clamping Force and Bearing Ratio

The effects of clamping force and bearing ratio are illustrated in Figures 9-12. Test specimens with normal clamping force do not seem to be greatly affected by wide variations in the bearing ratio according to Figures 9 and 10. Category D can be seen to provide a lower bound resistance for both low and high bearing ratios with normal clamping force. Several tests can be seen to fall below Category D, when the bearing ratio exceeds 1.5. However, the decrease in fatigue resistance is not a major one.

Figures 11 and 12 show the fatigue strength of specimens with reduced clamping force. This includes those specimens fabricated with cold driven rivets. It is clear that a high bearing ratio decreases the fatigue strength of members with reduced clamping.

A comparison of Figures 9 and 11 shows that the effect of a reduction in clamping force does not greatly affect the fatigue resistance, when the bearing ratio is smaller than 1.5. Only one point is seen to fall below the Category D resistance line.

When the bearing ratio is larger than 1.5, the reduction in clamping force has a significant effect, as seen when comparing Figures 10 and 12. The fatigue resistance is less than Category E in two instances. Significant
scatter in the test data is apparent in Figure 12.

The results summarized in Figures 9-12 suggest that Category D is a reasonable lower bound for riveted joints when the bearing ratio is compatible with the AASHTO and AREA Specifications, i.e. smaller than or equal to 1.5.

2.2.5 Influence of Method of Hole Preparation

The common methods of producing rivet holes were drilling, punching, subdrilling and reaming, and subpunching and reaming. The effect of the method of preparation on the fatigue life of riveted steel specimens is illustrated in Figures 13-16.

Although punched holes were most common in early steel structures, it can be seen that the majority of test data was acquired from specimens fabricated with drilled holes. A comparison of Figures 13 and 14 shows that the results for riveted joints with punched holes are well within the scatterband for the specimens with drilled holes. The size of the sample of punched hole specimens makes the reliability of any conclusion questionable. All respective data were developed from specimens fabricated for laboratory tests (with low bearing ratios) so that an unrealistically high quality of the punched holes might account for the small difference. In all cases the plate thickness was 1/2 in (13mm).

Punch alignment and wear can result in minute cracks around the hole [19,25]. Obviously the orientation of such initial imperfections is critical. The reaming process seems to improve the fatigue strength, judging from the test data summarized in Figures 15 and 16. Both subdrilled and subpunched holes seem to be less susceptible to fatigue than the drilled holes. Nearly all the test data with subdrilled or subpunched holes can be seen to plot above the Category C resistance line.

On the whole it seems that the manner of hole preparation has minor influence on the fatigue resistance of riveted steel connections.

2.2.6 Influence of Specimen State

The specimens used in the previous studies can be divided into specimens specially fabricated for laboratory tests from as-rolled plate and specimens fabricated from members taken from existing structures. The former specimens have been fabricated and riveted under controlled conditions, whereas the latter contain the original rivets and have potential fatigue damage.

The test results associated with the newly fabricated specimens are summarized in Figure 17. Figure 18 shows the test results for the specimens taken from existing structures. It can be observed that the average fatigue
strength of the "existing" specimens is lower than that of the "new" specimens. The test data for the "existing" specimens, however, fall within the scatterband of the data shown in Figure 17.

Therefore it can be concluded that having been exposed to service conditions and difference in fabrication do not result in large differences in fatigue resistance. For both types of specimen states Category D appears to provide an appropriate lower bound.

2.3 The Fatigue Resistance of Steel Plate Specimens with Open Holes

2.3.1 General Remarks

A number of fatigue tests have been conducted on steel plate specimens with open holes. The results of these tests should provide a lower bound for the fatigue strength of similar riveted joints on account of the condition that the clamping force of a plate specimen with open holes being zero. On the other hand, the bearing ratio of a plate with open holes is also zero, which suggests that the average fatigue strength would be higher. These variables are constant for this type of specimen, eliminating the two main variables that influence the fatigue resistance of riveted connections.

The variables that influence the fatigue resistance of plate specimens with open holes, discussed here, are:

1. Method of hole preparation,

2. Specimen state: newly fabricated, used material with new holes and used material with original holes.

2.3.2 Influence of Method of Hole Preparation

As discussed earlier, the common ways to manufacture rivet holes in steel plates were drilling, punching, subdrilling and reaming, and subpunching and reaming. Figure 19 shows the test results for specimens with drilled and with punched holes, while Figures 20 and 21 show respectively the results for subpunched and reamed and subdrilled and reamed holes.

It is apparent that nearly all plate tests with open holes exceed the category C resistance curve. Both the subpunched and reamed, and the subdrilled and reamed holes yield a fatigue resistance higher than the resistance of the drilled and punched holes. However, from Figure 19 it is clear that the amount of test data with the latter condition is too small to compare these respective conditions.
A comparison of the fatigue strength of plates with holes to the fatigue strength of riveted specimens (Fig. 13-16) shows that the former is clearly higher than the latter. This indicates that bearing ratio as a detrimental effect dominates the beneficial effect of the clamping force on the fatigue resistance of riveted specimens.

2.3.3 Influence of Specimen State

The influence of the specimen state is illustrated in Figures 22 and 23. Figure 22 shows data points from specimens specially fabricated for laboratory tests from virgin material. Tests results on specimens manufactured from old material, with either newly drilled or original holes are displayed in Figure 23.

It can be observed from these figures that specimens made from "new" material exhibit better fatigue resistance than specimens made from "old" material. Furthermore, newly drilled holes appear to produce longer fatigue lives than existing holes as can be observed from Figure 23. It is likely that this difference can be explained by observing that the drilling of holes for laboratory tests would typically be done with more care than in outside practice, and by some accumulated fatigue damage from service in the case of existing holes. No existing cracks prior to testing were reported for any of these specimens.

Category C is applicable for specimens with newly produced open holes regardless of the age of the material, whereas Category D holds for old specimens with existing holes.
3. REVIEW OF EXISTING TEST DATA ON WROUGHT IRON COMPONENTS

Wrought iron was the predecessor of mild steel as the principal construction material for riveted railroad bridges. A number of these bridges survive and perform their function today. Little was known about the fatigue behavior of riveted wrought iron until in the recent past when national railroads started investigating this behavior [9,18,24].

Figures 24 and 25 summarize the available test data on riveted wrought iron specimens and wrought iron plate specimens with open holes. All of the specimens were fabricated from old material and the rivets were all original. Most of the specimens with open holes had original holes although a few contained newly drilled holes. Additionally, the vast majority of the specimens tested were oriented towards the rolling direction of the material.

A comparison of Figures 24 and 25 indicates that there is no major difference between the behavior of riveted specimens and of specimens with open holes. The fatigue resistance falls between Categories D and E. A few specimens provided resistances below Category E, but the corresponding stress ranges tended to be high so as to induce low cycle fatigue phenomena. Two of the riveted specimens exhibiting a fatigue strength below Category E and tested at a stress range of 13 ksi (90 MPa), had been tested before at lower stress ranges and conceivably contained cracks hidden by the rivet head that were not reported [18].

A comparison of Figures 1 and 24 indicates that riveted wrought iron connections have a fatigue strength lower than riveted steel connections: between Categories D and E.
4. FATIGUE TEST PROGRAM

4.1 Introduction

Fatigue tests were conducted on six riveted built up stringers taken from a railroad bridge. The purpose of the test program was:

1. to establish fatigue life data on rivet details with particular focus on the high cycle region,

2. to establish the fatigue behaviour of the deteriorated built up member.

A second objective deals with the effect of force redistribution to the other section components as a result of crack extension at a rivet detail or corroded flange angle. This redistribution raises stresses and produces progressive crack initiation and propagation in those uncracked components. It should be kept in mind that riveted built up members possess a degree of redundancy, allowing for an important increment of life after cracking develops in one component. The factor of redundancy did not appear in the majority of the previous experiments, having been conducted on simple splices.

The project concentrated on the high cycle fatigue behaviour, that is: near the constant stress range fatigue limit of AASHTO/AREA Categories C and D, respectively 10 and 7 ksi (69 and 48 MPa). This generally meant continuation of cycling beyond $10^7$ cycles.

4.2 Test Specimens

The fatigue tests were conducted on members which had been removed from a railroad bridge. It was a three span riveted truss bridge, which supported a single railroad track. The bridge was owned by the Southern Railroad Co. and was located near Marshall, North Carolina, spanning the French Broad Ivy River. It was built in 1903 and demolished in 1982. Figure 26 shows the plan and elevation of the structure.

Strain measurements made while in service indicate that about 1% of the stress cycles exceeded the Category D fatigue limit so that the cumulative fatigue damage from service was negligible [12]. The bridge was constructed by the Phoenix Steel Company, also the producer of the construction material which was 'medium steel', an early alloy steel. In 1903 alloy steels had just replaced wrought iron as the principal material for metal structures.

Fritz Laboratory acquired six of the stringers. They were built up I-shapes, 39in (1m) deep and consisted of a web plate and four angles, connected to the web by two rows of rivets as illustrated in Figure 27. Their original
length was 24 ft. (7.3m). As cut from the bridge, they were about 20 ft. (6.1m).

The condition of the stringers appeared to be good. Their surface had been protected by a heavy tar coating and was eventually cleaned by sand blasting. Inspection indicated that the tension flange was relatively undamaged except at sections where the cross frame had been connected to the web (Figs. 28 and 29). At those locations, the bottom inside flange angle was severely corroded, so that a reduced thickness resulted. Corrosion also eliminated part of the rivet head at that section. The regions of reduced thickness contained a set of notches and associated stress concentrations, which proved to be rather severe.

Significant deterioration was generally present along the compression flanges, as illustrated in Figure 28. The thickness reduction of the flange developed where the cross ties had rested upon the stringers. Several long cracks were found in the compression flange at the location of the lateral bracing connection plates, as illustrated in Figure 31. It appears that the bracing connection had provided restraint to the top flange adjacent to a tie bearing point.

4.3 Test Set-up

The stringers were tested in a four point bending set-up. The repeated loads were applied by two Amsler 110 kip (245 kN) hydraulic jacks and one pulsator, as illustrated in Figure 32. The distance between the jacks was 5 ft. (1.53 m). The loading signal had a constant amplitude and the frequency of the cycle was 520 [cyc/min].

Lateral braces were attached adjacent to each jack to prevent lateral movement due to the slight distortion and lack of symmetry of the deteriorated section. The high frequency of the cyclic loads required special care in order to prevent vibration of the set up and the jacks.

4.4 Results of the Fatigue Tests

4.4.1 General Remarks

Six stringers were tested. The attention focused on the following details:

1. the corroded region of the flange angles,

2. the riveted connection between web and angles.

Table 1 summarizes the test results for the fatigue strength of the corroded
region. For each test beam, the gross section stress range (at the full section) and the net section stress range (at the section reduced by corrosion) are tabulated. The table also includes the number of cycles until first detected cracking, the cycles corresponding to failure of the corroded angle, as well as the number of cycles until failure of the section, where applicable.

The test results on the rivet details are summarized in Table 2. Only the test data for those fatigue cracks that were not affected by cracking of the corroded section or other adjacent sections are listed. It was observed that progressive cracking of a section caused force redistribution from the cracked section components to the other cross-sectional elements. This redistribution often generated rapid cracking in those elements. This effect is illustrated in Figures 33 and 34. Soon after severing of the corroded angle, the opposite flange angle developed several cracks within a short time period.

4.4.2 Fatigue Resistance of the Corroded Region

The six test stringers all had a region of reduced thickness due to corrosion. The degrees of reduction, however, were quite different and varied from 5 to 40% of the angle leg area. The angle leg thickness reduction was the principal influence on the fatigue strength of the detail. In three cases there was also a reduced width. These effects resulted in significant stress concentration at the corroded section. The stress concentration resulted from the notches on the rough irregular surface. No convenient measure of quantifying this was found.

Figure 33 shows the cracked reduced section of beam 1. The crack surface at this section is shown in Figure 35. Cracking was observed to initiate at multiple sites in the region near the edge of the angle, where the thickness was minimal.

The corroded section of beam 2 after fracture is shown in Figure 36. Before the test, a small pre-existing crack had been detected in the corroded section. This was removed by grinding so that the initiation of the crack under known cyclic load conditions could be studied. The pre-existing crack is shown in Figure 37. It was possible after fracture of this section, to continue testing by splicing the cracked section. The splice was made by clamping steel plates to the top and bottom of the cracked tension flange with C-clamps. Continued testing provided test data on fatigue cracking of the rivet details which are reported in the following section.

The degree of corrosion of the third stringer is shown in Figure 38. No cracking was observed at this section throughout the test. The maximal thickness reduction was less than half the original thickness.

Figure 39 shows the crack in the reduced section of beam 4. This crack was
arrested twice by drilling holes of increasing diameter that were centered on the crack tip. The second hole was drilled after the crack had grown to a length of about 2.5 in. (64mm). The crack finally reinitiated after 2.2 million additional stress cycles and the section was spliced to permit continued testing of the stringer.

Beam 5 had the corroded condition shown in Figure 40. The first attempt to arrest the crack which developed at the corroded section failed after 700,000 cycles. After crack reinitiation the section was spliced so that continued testing was possible.

The sixth beam had one of the most severely corroded angles as shown in Figure 41. The angle leg was about 40% corroded away. After cracking developed at the corroded section, this detail was retrofitted by drilling a hole at the crack tip and splicing the section. The crack had propagated to near the mid-width of the outstanding angle leg at the time of retrofit. (See Fig. 41)

The fatigue test data of the corroded flange angles are plotted in Figure 42. The stress range is defined on the net section of the corroded member. Additional conditions that developed following the first observed cracking for each detail are defined in Table 1. Beam 6 was tested under a higher stress range and higher relative minimum stress level than the other five beams.

The corroded areas of stringers 2, 4 and 6 (Figs. 36, 39 and 41) had a fatigue life, at first observed cracking, that was lower than Category E. The fifth stringer (Fig. 40) had a corroded section which provided a fatigue strength slightly greater than Category D. The corroded section of stringer 1 (see Fig. 32) had a fatigue resistance just below Category C. Stringer 3 (see Fig. 38) did not develop a crack at the corroded section. It should be noted that a considerable amount of life was consumed between first observed cracking and failure of an angle as well as fracture of the cross-section. Three of the stringers (4, 5 and 6) were retrofitted by drilling a hole at the crack tip and splicing the cracked angle before it failed. The first two beams tested quickly demonstrated that the corroded section was more severe than the riveted details. Retrofitting permitted continued testing of those riveted sections. All cracked sections were subjected to a large number of cycles between first observed cracking and the retrofit. Figure 42 shows the number of cycles at failure of an angle indicated by "angle failure" and the additional cycles corresponding to "section failure".

The deterioration of the flange angle of beam 3 was not severe enough to have a crack initiate. The severity of the corroded regions of the stringers 1, 2, 4, 5 and 6 was much greater than anticipated considering the loss of cross-sectional area alone. The test results plotted between categories E and C which was well below Category A. The irregularity and roughness of the corroded surface and the associated stress concentrations are the major factors reducing the fatigue resistance of the member.
The mechanism of crack formation in the corroded area proceeded as follows. First, several small cracks formed in the rough surface at the deeper notches close to the flange tip. These cracks coalesced and formed a long, shallow surface crack. This surface crack then propagated through the flange thickness at the tip and became an edge crack. Small cracks continued to form in the corroded surface and coalesced with the edge crack. The crack length measured at the bottom surface of the angle leg always lagged behind the length at the corroded top surface, as illustrated in the Figures 43 and 44.

A final note should be made regarding the initial crack length at discovery. To be able to evaluate the severity of the corroded detail and compare the five beams, it is necessary to consider the crack lengths and events given in Table 1 and Figure 42. The second event listed for beam 4 corresponds to a crack length smaller than the crack length at discovery for beam 1. The crack length at splicing for beam 5 was also smaller than the length at discovery for beam 1 and was just about equal to the length at the second event of beam 4, and to the crack length at splicing of beam 6. A possible ranking of the five cracked sections from best to worst: 2, 5, 4, 1 and 6.

4.4.3 The Fatigue Resistance of the Rivet Details

Fatigue cracks also formed at rivet holes, as illustrated in Figure 34. The crack surface of one of these details is shown in Figure 45. The fatigue strength of the riveted sections which developed cracking independently of each other are summarized in Table 2 and plotted in Figure 46 as a function of the net section stress range. Table 2 also provides a short chronology of the development of further cracking at the riveted sections, i.e. at the opposite edge of the same rivet hole or in one of the other components of the same cross-section. These data are not plotted in Figure 46.

In Figure 46, "cracking" denotes first observed cracking. Failure of the flange angle in the fatigue mode of crack extension only developed for stringer 3. In the case of stringer 6, the flange angle failed in a brittle fracture mode, at reduced temperature, as described in Chapter 5. The cracked angles of the remaining stringers were retrofitted before cross-section failure could occur.

Fatigue cracking was observed to occur below the fatigue limit for Category C [10 ksi (69 MPa)]. Two cracks developed below the fatigue limit of Category D (48.3 [MPa]). Both of these cracks were located in a shear span. The stress condition corresponding to bending and shear is slightly more severe than bending alone, if the rivets are in bearing.

The literature review demonstrated that clamping force and bearing ratio were the principal variables influencing the fatigue resistance of riveted joints. Most of the cracked rivet details in the test beams were located in a constant moment region. Hence, the rivets did not transmit a significant
bearing force. This was a favorable condition. In addition, the rivets appeared to be tight, which is favorable as well.

The shop drawings do not indicate the method of hole preparation. The apparent distortion of the holes may result from punching the holes or driving the rivets. It is most likely that the holes were punched, as that was a common practice.

There was no clear evidence of pre-existing cracks in the beams at rivet holes. In one or two instances, a dark oxide was found on the crack surface, but sometimes this oxide was removed from the hole. In at least one instance it appeared that a discoloring of the crack surface had occurred when the angles were flame cut from the section in order to expose the crack. None of these cracked rivet holes corresponded to an appreciably different fatigue life than other cracked sections without any indication of oxide.

The majority of the rivet details were observed to crack initially at the top of the hole (see Table 2), even though the nominal stress range is higher at the bottom. Most cracks initiated at the inner surface between web plate and angle, at the edge of the hole. It is possible that fretting aided crack initiation at the corner of the hole.

Observations during the test indicated that there was significant frictional bond between web plate and angles. This bond was due to paint and corrosion product between components. The significance of this bond lies in the effect it had on the propagation rate of the crack. The frictional resistance between web plate and angle, adjacent to the crack as well as ahead of the crack front, reduced the compliance of the cracked plate and the crack opening displacement. This decreased the crack growth rate and extended the fatigue life. Crack growth measurements indicated that the crack growth rate was fairly constant with increasing crack length, as long as the crack propagated in the vertical leg of the angle. This phenomenon is treated in more detail in Section 6.

The fatigue resistance of the riveted stringers is compared with the Category C and D resistance lines in Figure 47. Also plotted are the results of other tests on riveted members. Fatigue life is defined as first observed cracking in all cases. The truss joints tested by Reemsnyder [22] and the hanger members tested by Baker and Kulak [3] were subjected to much higher stress range levels than the stringers and therefore yielded much shorter fatigue lifes. All three sets of test data confirm that Category D is a lower bound for the fatigue life as defined by the development of a small crack.

The redundancy of the built-up section permitted significant additional stress cycles after first cracking was observed. This can be verified by inspection of Table 2. This behavior was comparable to that of the corroded area.
4.4.4 The Cracking of Deteriorated Compression Flanges

The significant loss of section of the compression flange apparent in Figure 30 was typical of every test beam. In two extreme cases, this loss was sufficient to result in the development of fatigue cracking in the outstanding legs of the angle. Figure 48 shows the crack surfaces of the crack that developed in beam 1.

The cracks always started at the section that had the largest thickness reduction. An explanation for this phenomenon is that the compression stress cycle results in yielding on the net ligaments of the reduced section as a result of the stress concentrations and reduced area. This creates a residual tension stress field and promotes crack initiation and growth. The cracks were observed to propagate towards the heel of the angle and arrest. Hence, the cracks in the compression flange did not adversely affect the load carrying capacity of any of the test beams.
5. REDUCED TEMPERATURE TESTS

5.1 Objective and Procedure

Reduced temperature tests were carried out on the third and sixth test stringers. The objective was to evaluate the behavior of the fatigue cracked section at low temperatures. It was desirable to establish whether or not brittle fracture would occur and how the fracture would affect the behaviour of the cross-section.

In the case of beam 3 the condition at the start of the test was a fatigue crack extending from the top of the hole to the edge of the angle and from the bottom of the hole to the angle fillet. No cracking was observed in the other flange angle or in the web plate at that cross-section.

The condition was different for beam 6 since both angles as well as the web plate were observed to have cracked. In one angle the crack extended from the top of the hole to the edge of the angle and from the bottom of the hole to the angle fillet; in the other angle the crack extended from the top of the hole to a point halfway between hole and edge; in the web plate from the top of the hole to a position slightly below the edge of the angle and from the bottom to the bottom edge of the plate.

The test procedure was in both cases as follows. The cyclic test was interrupted so that an insulating box of styrofoam could be built around the section. A grid of copper tubes with openings at regular distance was used to diffuse liquid nitrogen into the closed space, as illustrated in the Figure 49. The temperature of the enclosed section was decreased to approximately -40°F (-40°C) to -60°F [-51°C]. The temperature of the section was monitored by three temperature gages which were attached to the web plate at mid depth and to the top and bottom angles.

When the cracked section reached the desired test temperature, a static load corresponding to the maximum load of the repeated load cycle was applied. The cyclic loading was then resumed at a frequency of 260 cycles per minute or 4.33 Hz. The crack front advanced in a stable, fatigue mode. The cyclic loading was continued for a period of half an hour to one hour at the reduced temperature. Then the crack would be propagated at room temperature for an additional 1/2 in. (12mm) to 1 in. (25mm). This procedure would be repeated.

It was not possible to have a uniform temperature distribution over the stringer depth or to regulate the nitrogen flow such that fluctuations of 10°C could be avoided. For test beam 6 the temperatures measured at fracture were, from top to bottom: +39, -38 and -57°F (+4, -39 and -49°C).
5.2 Material Fracture Characteristics

An indication of the fracture characteristics of the material was obtained by performing a series of Charpy V-notch impact tests on eighteen specimens, taken from a tension flange angle of one of the stringers. Temperatures varied from 0°F (-18°C) to 150°F (66°C). Results are summarized in Figure 50.

A large variation in absorbed impact energy can be seen at test temperatures between 70°F (21°C) and 110°F (43°C). The estimated 15 ft-lbs (20 Joule) transition temperature was about 70°F (21°C). Hence, the material would satisfy the impact energy requirement for Zone 2 of the AASHTO and AREA Specifications.

Correlations between Charpy V-notch data and $K_T$ values have provided an empirical relationship between the two measures of toughness. This permits an estimate of the fracture toughness of the material as a function of the temperature using the Charpy V-Notch impact tests [23]. The estimated dynamic fracture toughness curve given in Figure 51 and the test points were developed from the Charpy V-Notch test data. This curve estimates the fracture toughness $K_{1D}$ under impact loading. For intermediate loading rates, corresponding to 1 sec loading, a temperature shift of 120°F results from using the strain rate shift:

$$T_s (1 \text{ sec}) = (3/4) (215 - 3\sigma y/2)$$

The resulting intermediate strain rate fracture toughness relationship is shown as the dashed curve in Figure 51.

5.3 Results of the Reduced Temperature Test

Reduced temperature tests were performed for a number of different crack lengths. The crack lengths and the number of stress cycles applied at reduced temperature are recorded in Table 3 for the two test beams.

No unstable crack extension occurred in the cracked angle of beam 3. During the process of crack extension, the gross section stress increased by about 30%. It is apparent from Table 3 that significant numbers of stress cycles were applied at each crack length increment.

Reduced temperature tests were also carried out on test beam 6. The pattern of fatigue cracking that developed at the critical section was substantially different than observed in beam 3. Table 2 described the crack condition observed in the angles and web. Figure 52 is a schematic diagram that identifies the crack front in each of the components at the start of the three major fracture tests. A brief description of the test conditions is given in Table 3. The crack fronts shown in Fig. 52 were marked by cycling the beam at half its normal stress range. This resulted in beach front markings on the
crack surface as can be seen in Fig. 53 which shows part of the fracture surface.

No crack instability developed in beam 6 during the first two low temperature fatigue crack extensions. The crack tips at the end of the second test are defined by the beach marks of mark 3. After marking the crack fronts, the cooled section was cycled an additional 25,900 cycles during which time the crack tip extended up the remaining leg of the south angle and down into its fillet. The vertical leg in the north angle was already cracked and the crack front in the outstanding leg extended about 1.2 in. to a point 3.5 in. (89mm) from the heel of the angle.

Figure 54 shows the fractured cross-section of beam 6. It can be seen that the crack extended through both angles and up the web until it encountered one of the lower rivet holes of the top flange angles. The crack opening can be seen in Fig. 55. Cleavage crack extension occurred in each of the beam elements at failure.
6. ANALYTICAL FATIGUE CRACK GROWTH PREDICTION USING FINITE ELEMENTS

6.1 Introduction

During the tests on the riveted stringers it was observed that the cracks which formed at the top of the rivet hole and propagated upward in the leg of the angle attached to the web plate, exhibited only a small opening displacement. This was one of the reasons why these cracks were only discovered after they were 3/4 in. to 1 in. (20-25mm) long. The geometry of the cracked detail is shown in Figure 56. Furthermore, it was noted that the rate of crack propagation was low for a crack of such length and was fairly constant with increasing length.

The reduced temperature test on test beam 3 discussed in chapter 5 indicates that the built up section had a great degree of redundancy. Even when the angle was nearly cracked in two, no crack instability was observed at a maximum stress of 10ksi (69 MPa) on the gross section. Hence, the cross section was able to redistribute the load from the cracked angle to the other section components without significant distress. The degree of restraint of the opening displacement was too large to be explained by the nearest rivets providing the transfer of load in bearing, since they were top rivets instead of bottom rivets and were positioned 3 in. (76mm) away from the crack. Also, it should be noted that no cracking developed at those rivets. The geometry of the cracked detail for beam 3 with the crack tip in the outstanding angle leg is shown in Figure 57.

It was apparent that a frictional bond existed between the faying surfaces of angles and web plate. This bond was due to the corrosion and lead paint between these components and was confined in this limited space. It is probable that the bond was brittle and progressively broke in the immediate vicinity of the crack. A strain differential between cracked and uncracked components resulted in high frictional forces which were transferred by the bond product. When the differential was too high, the product broke. This occurred in the area around the crack tip.

The load transfer from the cracked angle to the other section components occurred away from the crack by means of the frictional bond. Compatibility required that the extension of the cracked region under reduced load was the same as the extension of the adjacent region of the uncracked section components which were obviously subjected to an increased stress level. A region in the immediate vicinity of the crack was unbonded. The shape of this unbonded region could not be visually defined as a function of crack propagation.

The objective of the analysis presented in this chapter is to predict and characterize the stress intensity factor applicable to this complex condition as a function of crack length. As long as the stress intensity factor $K_I$ remains below the fracture toughness $K_{IC}$ of the cracked component, the mode of
crack extension is stable fatigue crack growth. Once the fracture toughness is exceeded, crack instability will occur in the cracked component.

Measurements of crack propagation during the test on the third stringer provided experimental data that could be used to compare with the predicted results.

6.2 Analytical approach

The analysis of the detail makes use of concepts from linear elastic fracture mechanics. The detail provides a very complicated joint and crack condition for which the stress intensity factor is not available in the literature [27]. A means of solving such a problem is provided by the numerical technique of the finite element method.

6.2.1 Finite Element Program QIFEVCEM; Possibilities and Limitations

The analysis makes use of a finite element program, developed by C. K. Seong, called QIFEVCEM, which is an acronym for 'Quarter-point Isoparametric Finite Elements and Virtual Crack Extension Method' [25]. The program is capable of analyzing plane structures under plane strain or plane stress conditions. The main elements incorporated in the program are QUAD-8 isoparametric elements with 8 nodes and quadratic interpolation for the coordinates and the displacements. Thus, they are capable of following parabolic boundaries and of reproducing a linear variation of stress and strain.

Essential to linear elastic fracture mechanics and in plane loading is a stress singularity of the order $r^{-1/2}$ at the tip of the crack. The program reproduces this singularity by utilizing singular elements around the crack tip. The singular elements implemented in this program are triangular 8-node elements which are degenerated from the QUAD-8 quadrilateral elements and have the midside nodes on the sides adjacent to the crack tip moved to the closest quarter point positions, which produces the required singularity within the element.

The stress intensity factor $K$ is calculated using a method known as the Virtual Crack Extension Method. The stress intensity factor is determined from the strain energy release rate in the elements surrounding the crack tip due to a virtual extension of the crack length.

A limitation of the program is that it only handles two dimensional problems. In addition to the QUAD-8 elements, the program does contain truss elements which were used to model the outstanding flanges, the plane of which is perpendicular to the plane of the web. This permitted the analysis to be carried out when the crack was confined to the angle leg attached to the web plate.
When the crack encounters the corner at the heel of the angle, the problem becomes a three-dimensional problem and cannot be directly analyzed with this program. The subsequent stages of crack propagation in the outstanding leg of the angle was approximated by simply rotating this leg into the plane of the web. The remaining, uncracked, outstanding angle leg was modeled by truss elements.

6.2.2 Preliminary Analysis

The crack growth rate was determined from measurements of the crack length as a function of the number of cycles during testing of the third stringer. They are summarized in Tables 4 and 5. The accuracy of the measurements was limited since dividers were used and the measurements were made during cyclic loading.

A graphical summary of the estimated crack propagation rates as a function of crack length is provided in the Figures 58 and 59, for the crack growing in the vertical leg and in the outstanding leg of the angle, respectively. The scatter in the test data stems not only from the accuracy of the measurements but also from the inherently discontinuous process of fatigue crack extension. It should be noted that an error in the crack growth rate results in a relative error one third as large in the stress intensity factor, when calculated using the Paris Power Law.

The dashed line in Figure 58 represents the regression line of the data points. The regression line is a flat sloping line and indicates that the crack growth rate is increasing slowly with increasing crack length.

The crack growth rate is directly related to the stress intensity factor, by the Paris Power Law:

\[
\frac{da}{dN} = C(\Delta K)^n
\]  \hspace{1cm} (6.1)

Rolfe and Barsom have suggested an upper bound estimate \( C = 3.6 \times 10^{10} \) for ferrite-pearlite steel, with \( n = 3 \) , \( a \) in inches and \( K \) in ksi\(\sqrt{\text{in}}\).

A detail having a constant crack propagation rate with increasing crack length is the infinitely long strip with a semi-infinite crack as illustrated in Figure 60 [27]. The stress intensity factor is a function of the stress and width of the strip. Under plane stress conditions the stress intensity factor is equal to:

\[
K = \sigma (h)^{1/2}
\]  \hspace{1cm} (6.2)

If the cracked rivet detail is assumed to have an unbonded area with a constant width, one can make an estimate of this width by dividing the stress
intensity factor $K_I$, calculated on the basis of the measured crack growth, by the stress $\sigma$ to which the section is subjected. The test results yield an estimated half width between 0.8 and 1.25 in. (20 to 32mm), for the crack tip at mid height respectively extended to the full height of the leg of the angle. This is significantly smaller than the 3 in. (76mm) distance between the crack and the adjacent rivets.

A more rational shape for the unbonded area is an ellipse, since the unrestrained crack opening displacement would have a comparable shape. The restraining forces transferred by friction vary along the crack length, which causes the bond between elements to be broken in an elliptical fashion. The estimates of the width provided by the strip model are helpful estimates of the short axis length.

Figure 59 shows the crack growth rates derived from measurements when the crack front was propagating in the outstanding leg of the bottom flange angle. The magnitude of the crack growth rates is an order of magnitude higher than those calculated for the crack advancing in the angle attached to the web. It is apparent that the restraint offered by the frictional bond between web plate and angle decreases significantly with increasing crack size.

The dashed line originating at the origin represents the crack propagation rate as a function of the crack length for a plate with a center through crack (see Figure 61) [27]. The finite width $b$ was taken as the flange width, equal to 6 in. (152mm), and the nominal stress range to which the plate is subjected was 9 ksi (62 MPa).

The similarity between the two cases is limited but the comparison is useful when interpreting the nature of the measured crack growth rate.

For small crack sizes (less than 2 in. (50mm) long) in the outstanding leg, the crack driving force is underestimated by the center cracked specimen. Apparently the completely severed vertical leg of the angle is of considerable influence driving the crack. For larger crack sizes, the center cracked specimen overestimates the crack propagation rate as a result of its inability to redistribute the load. The comparison between the two cases suggests that the restraint offered by the uncracked section components reduces the crack growth rate appreciably when the crack is smaller than one half to two thirds of the flange width.

6.3 The Formulation of the Finite Element Models

A typical finite element model representing a section of the vertical leg of angle adjacent to the cracked rivet detail is shown in Figure 62. The immediate area around the crack is shown enlarged in Figure 63. Use has been made of symmetry about a vertical plane which contains the plane of the crack.
In addition to the rivet hole from which the crack originated, the closest top rivet hole is included. No bearing pressure on the edge of the holes was considered. This is a reasonable assumption when no crack exists since the bending moment was constant and the rivets transmit no shear force. In the presence of a crack the adjacent rivets might be loaded in bearing, if the frictional bond is not capable of transferring the load to the adjacent sections. The preliminary analysis demonstrated that it was plausible for the width of the unbonded area to be smaller than the rivet spacing, so that these rivets needed not be in bearing. It was not considered necessary to include clamping pressure because the crack tip was well outside the rivet head. Smaller cracks might be affected by the clamping pressure and increased frictional restraint.

The load transfer by frictional bond was modelled assuming that the bond product was rigid so that shear transfer would take place without deformation. It was also assumed that, once broken, the bond was no longer capable of load transfer. Since the finite element program did not have any provisions for shear transfer between planes, the shape of the unbonded area had to be determined by trial and error.

The unbonded area around the crack consisted of two independent layers, one cracked and one continuous. The two layers became common where the bond was complete. Since shear transfer occurred without deformation and plane sections remained plane, the bonded areas of the cracked angle and the uncracked components were strained equally and could be modelled as one plane of elements.

The finite element mesh arrangement was flexible as shown in Figures 62 to 66 providing an element configuration which permitted the crack to propagate up step by step in the angle leg attached to the web. A relatively simple readjustment provided the appropriate mesh for different crack lengths and unbonded lengths alongside and ahead of the crack. It was possible by means of supporting programs to readjust the nodal point configuration and obtain different shapes of the unbonded area.

Figure 67 shows a finite element mesh for the condition that the crack tip resided in the outstanding angle leg. The unbonded area between web plate and vertical leg of the angle extended over the depth of the angle.

There are a number of variables which characterize the unbonded area. These include its shape, size, unbonded length ahead of the crack and whether the edge of the rivet hole is unbonded.

6.3.1 Crack Tip Located in Vertical Leg of Angle

When the crack tip was located between the lower rivet hole and the top edge of the angle (see Fig. 56), the following assumptions were made.
The estimate of the width of the unbonded area was initially based on the semi-infinite crack specimen (see Fig. 60). It was found that the unbonded length ahead of the crack would have to be 20 to 30% of the crack length. The crack length was defined as the distance from the center of the rivet hole to the crack tip. The analysis indicated that it was necessary to include the edge of the rivet hole in the unbonded area. This is understandable since the hole is part of the crack and opens under tension.

Three different shapes of unbonded area were considered. First, an area with constant width as shown in Figure 63 was examined. This shape was modified to a region of conical shape (see Fig. 64). The estimates of the half width provided by the half infinite crack specimen on the basis of the crack growth measurements predicted a width that increased with increasing crack length. Hence, the conical shaped area had an increasing width with increasing crack length as measured perpendicular to the crack at the crack tip while it was also assumed that the advancing crack did not influence the width of the area behind the crack tip. A final model considered an elliptically shaped region as shown in Figures 56, 65 and 66. The shape was related to the elliptical opening displacement of the crack when unrestrained. The ellipse was centered midway between the center of the hole and the crack tip. The long axis $b_1$ was made equal to half the crack length plus twice the unbonded length ahead of the crack. The ellipse was truncated ahead of the crack and changed into a circle around the hole, as shown in the Figures 65 and 66.

The loading on the finite element segment was imposed at the edge where the segment was cut from the stringer, and was force controlled. The cut was made sufficiently far away from the cracked cross section so that the stress distribution on the loaded edge was the gross section bending stress distribution. Hence, the segment was taken big enough so that the increase of compliance due to the existence of the crack was negligible compared to the total compliance.

6.3.2 Crack Tip Located in Outstanding Angle Leg

When the crack tip was located in the outstanding leg of the angle, the unbonded area between web plate and vertical angle leg adjacent to the crack extended over the entire depth of the angle. The shape of the unbonded area was assumed to have a constant width $w_1$ from the top edge of the angle down to its half depth and then tapered out toward the heel of the angle, as shown in Figure 57. Width $w_1$ was taken as 1.8 in (46mm) and width $w_2$ as 3 in and 3.6 in. (76 to 91mm). A typical mesh is shown in Figure 67. The length of half the section was taken as four times the width of the angle leg.

The loading was displacement controlled since equilibrium could not be met with force controlled loading. The loading was divided into two stages. Initially, displacements were imposed at the edge of the finite element segment equal to the gross section strains integrated over the length of the segment. In the second stage, contributions corresponding to the opening
displacements along the crack as calculated in the first stage were added to
the imposed displacements. The maximum additional displacement along the edge
was approximately 10% of the initial displacement.

6.4 Results of the Analysis

6.4.1 Crack Tip Located in Vertical Angle Leg

The finite element analysis yielded the crack growth rates tabulated in
Table 6. These crack growth rates were calculated from the predicted stress
intensity factors $K_I$ by eq. (6.1).

An unbonded area with a constant width (Fig. 63) yielded results that
suggest that an increase of width is required in order to match the measured
values of crack growth rate as can be seen in Table 6. By linear
interpolation the widths are found to vary between 0.7 and 1.18 in. (18 and 30
mm). These results are in good agreement with the estimates made using the
infinite strip model of Figure 60.

The results for an increasing width with increasing crack length suggest
that the unbonded area grows in both the width and the length direction. This
is led to the assumption of the conically shaped unbonded area (Fig. 64). The
results shown in Table 6 indicate that if the width behind the advancing crack
tip does not increase as a result of the increased crack opening, the
predicted crack growth decreases. The crack opening displacement is maximum
near the midpoint of the crack. This suggests that the width of the unbonded
area should be maximum near that point as well.

An elliptical shape is a more probable alternative (Figs. 56, 65, 66). The
results of several elliptical shaped unbonded areas are given in Table 6. The
short axis length need to increase from 0.8in to 1.3in (20 to 33mm) in order
to maintain a constant growth rate. The short axis to crack length ratio
decreased from 0.56 to 0.41 with increasing crack length. The crack growth
rate values are close to the values obtained for the constant unbonded width.
The ellipse contains a total unbonded area which is smaller than that of a
constant width area which makes the elliptic shape more likely. The predicted
stress intensity range varied between 7.5 and 7.8 ksi in as the crack size
varied between 1.4 and 3.2 in.

6.4.2 Crack Tip Located in Outstanding Angle Leg

Figure 59 shows the results of the finite element analysis when the crack
tip resides in the outstanding leg of the angle. The crack growth rate was
calculated from the stress intensity factor $K_I$. The crack length is defined
as the distance between the angle corner and the crack tip, measured at the
bottom of the angle leg. The Paris Power Law (Eq. 6.1) was used to relate the
crack growth rate and stress intensity factor.
Figure 59 summarizes the results of the analysis for the following assumed debonded conditions (see Fig. 57).

1. assuming a width $w_2 = 3$ in. (76.2mm) and a first stage displacement induced loading;

2. assuming width $w_2 = 3.6$ in. (91.4mm) and a first stage loading; and

3. assuming width $w_2 = 3.6$ in. (91.4mm) and subjected to the second stage loading.

The agreement between the analysis and the measurements is good for all three assumed conditions. As was indicated by the measurements, the analytical predictions indicate that for intermediate crack lengths the restraint offered by the bond between angle and web plate reduced the crack growth rate significantly compared to the center through crack idealization. The analysis indicates that the increase of the stress intensity factor with increasing crack length was small compared to the increase predicted for the center through cracked model. The predicted stress intensity range varied from 21.5 ksi/\(\sqrt{\text{in}}\) (23.4 MPa/\(\sqrt{\text{m}}\)) for a 2 in. (51mm) crack up to 38 ksi ini (42 MPa/\(\sqrt{\text{m}}\)) for a 5 in. crack for the 8.9 ksi (61.4 MPa) stress range that the member was subjected to. When the crack length was larger than two thirds of the leg length, the crack length increased appreciably just as it was observed in the measurements.

Figure 59 shows that the finite element analysis slightly underestimated the crack growth rate when the crack size was less than 4 in. (102mm). It is possible that the sudden increase in the measured crack growth rate for larger crack sizes was caused by a sudden expansion of the unbonded area due to the brittleness of the bond product.

A comparison of the three predicted curves shows that an increased debonded width raised the crack growth rate. The variation between the three assumed conditions was small compared to that between the measured and predicted values.

The predicted stress intensity range and growth rate could be increased to the measured value but that would require a debonded width equal to or greater than the distance to the nearest rivet. Rivet bearing would likely assist in the transfer of load from the cracked to the uncracked section components under those conditions.

In general, the estimated stress intensity factor and the resulting predicted crack growth rates are in good agreement with the limited test data considering the complexity of the conditions and geometry.
6.4.3 Fracture Analysis

The maximum stress intensity factor during the reduced temperature tests was estimated assuming a simple center through crack as well as a finite element model estimate. For test beam 3, the maximum estimated stress intensity factor during the reduced temperature test assuming the crack model for a finite width center through crack (see Fig. 61) was 69 ksi/\text{in}. (76 MPa/\text{m}). This assumed the crack size approached 6 in. from the heel of the angle. This value was well above the estimated fracture resistance at the intermediate loading rate. Since no fracture occurred it was apparent that the frictional restraint between the cracked angle and the uncracked web had decreased the crack opening and the stress intensity factor.

The finite element model (see Fig. 67) yielded a maximum stress intensity factor of 42 ksi/\text{in} (46 MPa/\text{m}) which indicated that no crack instability should develop. This was in agreement with the test results. This value is plotted in Fig. 51 for test beam 3. The test results confirmed the applicability of the temperature shift, since the dynamic fracture toughness at \(-40^\circ F (-40^\circ C)\) is estimated to be almost 25 ksi/\text{in}. (see Fig. 51).

No adverse behavior was experienced at the cracked section when the flange angle of beam 3 fatigue cracked in two at the reduced temperature. The remaining cross section was able to carry the load without adverse affect.

The reduced temperature test of beam 6 resulted in cleavage fracture in all three components during the third and final crack extension at \(-40^\circ F (-40^\circ C)\). The fatigue cracks were extended from beach mark 3 (see Fig. 52) until fracture. At the time of fracture, the south angle vertical leg was cracked into the heel, with a crack length of 5.8 in. (147 mm). The web crack extended 7.4 in. (188 mm), and the north angle was cracked on its vertical leg and the outstanding leg crack extended 3.5 in (89 mm) from the angle heel.

The maximum stress in the cycle was 16.2 ksi (112 MPa) for the cracks in the two angles. The bending gradient reduced web crack stress to 6.5 ksi (44.6 MPa).

The crack growth rates observed in the angles of test beam 6 suggested that the stress intensity range was between 50-60 ksi/\text{in} (55 to 66 MPa m). Since the R-ratio was 0.2 this would imply a maximum stress intensity value between 60 and 72 ksi/\text{in} (66 to 79 MPa/\text{m}). If the finite element models are used to estimate the stress intensity factor, the predicted value for the south angle is about 70 ksi in (77 MPa/\text{m}). The value for the north angle with the 3.5 in (89 mm) crack from the angle heel was estimated to be 55 ksi/\text{in} (60.5 MPa/\text{m}). Since the estimated fracture toughness for the intermediate loading rate is 55 ksi in (60.5 MPa/\text{m}) crack instability was expected in both of the angles. Their fracture likely produced a significant increase in loading rate as well as increased stress in the web so that it fractured as well.
7. SUMMARY AND CONCLUSIONS

7.1 Literature Survey

A detailed review was carried out of available fatigue test data on riveted steel and wrought iron joints and on steel and wrought iron plates with open holes. Approximately 1100 test results were examined and evaluated. Following are the findings of that review.

1. The major variables observed to affect the fatigue resistance of riveted joints are the rivet clamping force and the rivet bearing ratio.

2. The variation in fatigue strength was found to be large. It is probable that this stems from the fact that the sources associated with these test data provided very diverse test conditions. In addition, many tests were discontinued before developing fatigue cracks, but without accumulating a sufficient number of stress cycles to justify the fatigue limit. It was customary to discontinue testing after 2 or 3 million cycles. All of the fatigue tests on steel specimens were conducted at stress ranges above 13.3ksi (92MPa). Hence, the fatigue limit was not defined as failures were observed to occur at all levels of applied stress range.

3. Plates with open holes tended to provide greater fatigue resistance than riveted joints. All plates yielded fatigue strengths that exceeded the Category C fatigue resistance curve.

4. The effect of different methods of hole preparation did not result in major differences in fatigue strength. Drilling, punching, subpunching and reaming, and subdrilling and reaming provided fatigue resistances that did not differ appreciably. However, the amount of test data on punched holes is very limited and does not represent the wide variation that is likely to exist in practice, as a result of punch wear, plate thickness and material. The tests on plates and joints with punched holes were carried out at relatively low bearing ratios (1.25 to 1.75). Reamed holes, whether sub-punched or -drilled, seemed to provide better performance than drilled holes.

5. The lower bound fatigue resistance of riveted steel connections is reasonably well represented by the Category D fatigue resistance curve, as it was exceeded by nearly all the test data. Exceptions were specimens with reduced clamping and high bearing ratios. These results apply primarily to simple connections and do not reflect the additional life observed for built-up members due to their inherent load redistribution capacity.
6. Steel connections with good clamping force and normal bearing ratios, i.e. smaller than 1.5, have a lower bound fatigue strength that is defined by Category C. A number of tests at high stress range fell below Category C probably due to yielding.

7. Specimens subjected to stress reversal provided a fatigue resistance significantly greater than other specimens. Apparently, the stress range is overestimated using the full stress amplitude. A portion of the compression part of the stress cycle can be neglected. Early drafts of the ECCS TC-10 specifications defined the stress range cycle as:

\[ \Delta \sigma_{\text{eff}} = \sigma_{\text{max}} - 0.6\sigma_{\text{min}} \]

This adjustment scales the data with \( R < 0 \) and provides reasonable agreement with the test data for \( R > 0 \).

8. Although only limited test data are available for wrought iron riveted members or plates with open holes, their fatigue resistance is affected by the same factors that influence steel specimens. Clamping force and bearing ratio are the main factors, while the state and age of specimens and holes play a part.

9. Wrought iron riveted connections exhibit a lower bound fatigue strength represented by Category E. A few test data fell below Category E, possibly as a result of their previous load history.

7.2 Tests on Weathered and Deteriorated Riveted Members

The experimental studies carried out on six weathered and deteriorated riveted members provided information on their extreme life behavior. In addition they also provided information on the behavior of severely corroded regions and their susceptibility to fatigue crack growth. Following are the principal findings:

1. The extreme life fatigue resistance of the web flange riveted connection appears to be close to the Category D fatigue limit. Several fatigue cracks were found to develop in the rivet details at stress ranges between 6.7 and 9.5 ksi (46-66MPa) after 8 to 36 million cycles.

2. The fatigue resistance of the corroded section was observed to vary between Category E and C, depending on the severity of the corrosion and the loss of cross-sectional area. The degree of severity cannot be accounted for by considering just the loss of area. The five test results suggest that when the thickness of the outstanding flange angle is reduced more than 50%, the roughness and proximity of the corroded area to the bottom surface of the angle reduced the fatigue resistance.
Those stringers that had more than half of their flange thickness removed by corrosion, initiated fatigue cracks near the Category E resistance curve. Only stringer 3 which had less corrosion loss (see Fig. 38) did not develop a crack in the corroded area.

3. Severing a component of the built-up section did not immediately impair the capacity of the members. Between 1/2 and 1 million additional cycles of stress range between 9 and 9.5 ksi (62-69 MPa) on the gross section were required before the load carrying capacity was completely destroyed. Cracks formed slowly in the other angle and in the web plate. All six test beams exhibited redundant behavior after cracks developed that severed a flange angle. Beam 6 fractured when large cracks formed in all components at the same section.

4. Significant bond was observed to exist between the angles and web plate as a result of their painted and corroded condition. This reduced the opening of the crack and extended the fatigue life.

5. Fatigue cracks that formed in the corroded legs of the compression flange were observed to arrest near the heel of the angle. None of these cracks affected the load carrying capacity and the fatigue resistance of the stringers.

6. Reduced temperature tests at periodic intervals of extension of a crack grown from a rivet hole into the outstanding leg of the angle, did not result in unstable crack growth. Even with 95% of the angle section cracked, the crack extension mode was stable. Beam 6 which had large cracks in all three tension elements fractured when crack instability developed in all three elements.

7.3 Analysis of the Cracked Rivet Detail

A finite element analysis was made to evaluate the behavior of a section of the built-up stringer when a crack developed in a flange angle. The multi-component built-up cross section and the presence of a frictional bond between the faying surfaces of the member components provided a complex condition not readily described by simple stress intensity factor equations.

The analytical studies demonstrated that:

1. A frictional bond between the faying surfaces of the cracked angle and the web plate was responsible for significant load transfer from cracked to uncracked components. This reduced the crack growth rate and extended the fatigue life. Bond was destroyed in the immediate vicinity of the crack.
2. It was observed that fatigue cracks initiated from the top of the rivet holes and advanced to the top edge of the angle before cracking developed elsewhere in the riveted section. During this stage of crack growth very little change in the growth rate occurred. The shape of the unbonded area found to be most probable was an ellipse with its center at the middle of the crack. The short axis length decreased with increasing crack length.

3. The presence of the frictional bond between section components reduced the crack growth rate of the crack in the outstanding angle leg advancing from the heel of the angle towards the tip. The increase in the crack growth rate was small when the crack length was less than two thirds of the angle leg. The unbonded area was found to approach the nearest rivet as the crack extended to the tip of the angle.

4. The finite element model provided good estimates of the maximum stress intensity factor when cleavage fracture developed in one of the beams during a reduced temperature test.
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16. Kloeppel, K., Gemeinschaftsversuche zur Bestimmung der Schwellzugfestigkeit voller, gelochter und genieteter Staebe aus St.37 und St.52, Der Stahlbau, 9(13/14):97-112, June, 1936, Additional Publication to 'Die Bautechnik'.


18. Nederlandse Spoorwegen, (Various Fatigue Tests on Steel and Wrought Iron Specimens), Test Reports, Nederlandse Spoorwegen, 1974-82, (not published)


<table>
<thead>
<tr>
<th>Test</th>
<th>$\Delta \sigma$ Gross MPa</th>
<th>$\Delta \sigma$ Net MPa</th>
<th>$N(\times 10^5)$</th>
<th>Comment</th>
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<tr>
<td>1</td>
<td>73.4</td>
<td>75.2</td>
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<tr>
<td></td>
<td>10.5</td>
<td>10.9</td>
<td>4.40</td>
<td>Angle Severed</td>
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<td></td>
<td></td>
<td></td>
<td>4.99</td>
<td>Section Failed</td>
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<td>2</td>
<td>62.1</td>
<td>64.8</td>
<td>0.85</td>
<td>Angle Severed</td>
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<td>9.0</td>
<td>9.4</td>
<td>1.45</td>
<td>Section Failed</td>
</tr>
<tr>
<td>3</td>
<td>62.1</td>
<td>63.4</td>
<td>(39.71)</td>
<td>No Failure</td>
</tr>
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<td>4</td>
<td>55.2</td>
<td>57.2</td>
<td>1.19</td>
<td>Crack Found &gt; 7.6 mm, 0.3 in.</td>
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<td>8.3</td>
<td>5.37</td>
<td>First hole drilled, ($\phi = 25$ mm, 1 in.)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>(7.61)</td>
<td>58 mm, 2.3 in.</td>
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<td></td>
<td>84 mm, 3.3 in, Section spliced</td>
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<td>5</td>
<td>70.3</td>
<td>73.1</td>
<td>3.00</td>
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<td>6.82</td>
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<td>(7.52)</td>
<td>57 mm, 2.25 in.</td>
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<td>Section Spliced</td>
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<td>97.4</td>
<td>0.080</td>
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<td>(0.174)</td>
<td>Hole Drilled, ($\phi = 32$ mm, 1.25 in.)</td>
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<td></td>
<td></td>
<td>Section Spliced, 66 mm, 2.6 in.</td>
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Ratio $R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \approx 0.1$ except Test 6 With $R \approx 0.2$
<table>
<thead>
<tr>
<th>Test</th>
<th>$\Delta \sigma_{net}$ (MPa ksi)</th>
<th>$N_c$</th>
<th>$N_f$</th>
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<td>69.6 10.1</td>
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<td>6.61</td>
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<td>Angle, Bottom Hole, Top of Hole</td>
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<td>7.34</td>
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<td>7.38</td>
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<td>Angle, Bottom Hole, Bottom of Hole</td>
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<td></td>
<td>8.70</td>
<td></td>
<td>- Same Detail, Top of Hole</td>
</tr>
<tr>
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<td></td>
<td>18.25</td>
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<td>Angle, Bottom Hole, Top of Hole</td>
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<td></td>
<td>12.29</td>
<td></td>
<td>- Same Detail, Bottom of Hole</td>
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<td></td>
<td></td>
<td>12.98</td>
<td></td>
<td>- Same Section, Opposite Angle, Top of Hole</td>
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<td></td>
<td></td>
<td>16.74</td>
<td></td>
<td>- Same Section, Opposite Angle, Top of Hole</td>
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</table>

(18.25) Test Stopped

| 2    | 59.3 8.6                       | 36.50|      | Web Plate, Bottom Hole, Bottom of Hole |

(36.50) Test Stopped

| 3    | 56.2 8.15                      | 18.26|      | Angle, Bottom Hole, Top of Hole        |
|      |                               | 37.67|      | - Same Detail, Bottom of Hole           |
|      |                               | 39.29|      | - Same Section, Web, Bottom of Hole     |
|      |                               | 39.51|      | - Same Section, Web, Top of Hole        |
|      |                               | 39.66|      | - Same Section, Opposite Angle, Top of Hole |
|      |                               | 39.72|      | - Same Detail, Bottom of Hole           |
| 4    | 46.8 6.79                      | 25.94|      | Angle, Bottom Hole, Top of Hole, Shear Span |
| 5    | 45.8 6.65                      | 25.94|      | Angle, Bottom Hole, Top of Hole, Shear Span |

(39.72) Test Stopped

(continued)
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<th>Test</th>
<th>MPa</th>
<th>ksi</th>
<th>$\Delta \sigma_{net}$</th>
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<th>Nf</th>
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<td>4</td>
<td>54.7</td>
<td>7.9</td>
<td>105.23</td>
<td>6a</td>
<td>10</td>
<td>No Cracking Observed, Test Stopped</td>
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<td>5</td>
<td>67.6</td>
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<td>(35.80) Test Stopped</td>
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<td>89.6</td>
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<td>2.61</td>
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<td>2.90</td>
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<td>3.16</td>
<td>3.16</td>
<td>3.16</td>
<td>Angle, Bottom Hole, Top of Hole</td>
</tr>
</tbody>
</table>

$N_c$: Life until first cracking  
$N_f$: Life until failure of component  

Net section stress range ($\Delta \sigma_{net}$) defined as net section stress range at top of bottom hole
### TABLE 3  REDUCED TEMPERATURE TEST RESULTS

<table>
<thead>
<tr>
<th>N (Cycles)</th>
<th>ΔN</th>
<th>Beam 3 a (in)</th>
<th>Notes</th>
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</thead>
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<td>x10⁶</td>
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<td>(Crack in Angle Fillet)</td>
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<tr>
<td>38.69</td>
<td>490,000</td>
<td>1.55</td>
<td>Fatigue Crack Extension</td>
</tr>
<tr>
<td>39.18</td>
<td>22,000</td>
<td>--</td>
<td>Reduced Temperature Test 1</td>
</tr>
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<td></td>
<td>150,000</td>
<td>2.40</td>
<td>Fatigue Crack Extension</td>
</tr>
<tr>
<td>39.352</td>
<td>12,000</td>
<td>--</td>
<td>Reduced Temperature Test 2</td>
</tr>
<tr>
<td></td>
<td>160,000</td>
<td>3.5</td>
<td>Fatigue Crack Extension</td>
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<tr>
<td>39.524</td>
<td>9,000</td>
<td>--</td>
<td>Reduced Temperature Test 3</td>
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<td>114,000</td>
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<td>Fatigue Crack Extension</td>
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<td>39.647</td>
<td>15,000</td>
<td>--</td>
<td>Reduced Temperature Test 4</td>
</tr>
<tr>
<td></td>
<td>40,000</td>
<td>5.6</td>
<td>Fatigue Crack Extension</td>
</tr>
<tr>
<td>39.702</td>
<td>17,000</td>
<td>6.0</td>
<td>Reduced Temperature Test 5</td>
</tr>
<tr>
<td>39.72</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>N x10⁶</th>
<th>ΔN</th>
<th>Beam 6 NB</th>
<th>ST</th>
<th>WT</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.953</td>
<td>22,300</td>
<td>a (in) .79</td>
<td>4.49</td>
<td>5.91</td>
<td>Beginning of Beach Mark 1*</td>
</tr>
<tr>
<td>3.975</td>
<td>48,300</td>
<td>a   1.38</td>
<td>5.20</td>
<td>7.01</td>
<td>End of Beach Mark 1</td>
</tr>
<tr>
<td>4.0237</td>
<td>8,400</td>
<td>a    1.42</td>
<td>5.28</td>
<td>7.01</td>
<td>Beginning of Beach Mark 2</td>
</tr>
<tr>
<td>4.0321</td>
<td>14,800</td>
<td>a    2.20</td>
<td>5.43</td>
<td>7.29</td>
<td>End of Beach Mark 2</td>
</tr>
<tr>
<td>4.0469</td>
<td>5,200</td>
<td>a    2.36</td>
<td>5.43</td>
<td>7.33</td>
<td>End of Beach Mark 3</td>
</tr>
<tr>
<td>4.0521</td>
<td>25,900</td>
<td>a    3.54</td>
<td>5.98</td>
<td>7.56</td>
<td>Fracture</td>
</tr>
<tr>
<td>4.078</td>
<td></td>
<td>a    3.54</td>
<td>5.98</td>
<td>7.56</td>
<td>Fracture</td>
</tr>
</tbody>
</table>

T = -40° C (-40° F)

(σ\(_{\text{max}}\))\(_{g}\) = 9.8 ksi for beam 3; (σ\(_{\text{max}}\))\(_{g}\) = 16.2 ksi for beam 6

*Beach marking at Sr/2 (6.4 ksi)

Crack length at NB | measured from angle corner of outstanding leg
Crack length at ST | and WT measured from angle corner of vertical leg
### TABLE 4  MEASURED CRACK GROWTH RATES FOR CRACK TIP IN VERTICAL ANGLE LEG OF BEAM 3

<table>
<thead>
<tr>
<th>$N \times 10^6$</th>
<th>$\Delta N$</th>
<th>$a$ (in.)</th>
<th>$\Delta a$</th>
<th>$\bar{a}$ (in.)</th>
<th>$\frac{da}{dN} \times 10^{-6}$</th>
<th>Rivet Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.741</td>
<td>1.85</td>
<td>0.35</td>
<td>2.03</td>
<td>0.128</td>
<td>1.85</td>
</tr>
<tr>
<td>2.741</td>
<td>2.20</td>
<td></td>
<td></td>
<td></td>
<td>2.70</td>
<td></td>
</tr>
<tr>
<td>2.672</td>
<td>0.30</td>
<td>2.35</td>
<td>0.112</td>
<td></td>
<td>$\geq 0.40$ $\geq 2.90$ $\geq 0.15$</td>
<td></td>
</tr>
<tr>
<td>5.413</td>
<td>2.50</td>
<td></td>
<td></td>
<td></td>
<td>$\geq 3.10$</td>
<td></td>
</tr>
<tr>
<td>2.272</td>
<td>0.45</td>
<td>2.73</td>
<td>0.198</td>
<td></td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>7.685</td>
<td>2.95</td>
<td>0.739</td>
<td>$\geq 0.15$</td>
<td>$\geq 3.03$ $\geq 2.03$</td>
<td>2.45</td>
<td></td>
</tr>
<tr>
<td>8.424</td>
<td>$\geq 3.10$</td>
<td></td>
<td></td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>11.248</td>
<td>---</td>
<td>2.824</td>
<td>---</td>
<td>---</td>
<td>2.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>---</td>
<td></td>
<td></td>
<td></td>
<td>$\geq 0.60$ $\geq 2.78$ $\geq 0.212$</td>
<td></td>
</tr>
</tbody>
</table>

$N$ is number of cycles

$a$, $\bar{a}$ is crack length

Note: The crack length is measured from edge of rivet head upward.

$a_r = 22.9$ (mm) should be added to find the crack length wrt. center of hole

* These indicate the identification of rivet in north or south angles
TABLE 5  MEASURED CRACK GROWTH RATES FOR CRACK TIP
IN OUTSTANDING ANGLE LEG OF BEAM 3

<table>
<thead>
<tr>
<th>N</th>
<th>ΔN</th>
<th>a</th>
<th>Δa</th>
<th>ȧ</th>
<th>da/dN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x10^6</td>
<td>(in.)</td>
<td>x10^-6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>.380</td>
<td>=1.1</td>
<td>≈0.55</td>
<td>≈2.89</td>
<td></td>
</tr>
<tr>
<td>0.380</td>
<td>1.1</td>
<td>.086</td>
<td>0.30</td>
<td>1.25</td>
<td>3.49</td>
</tr>
<tr>
<td>.466</td>
<td>1.40</td>
<td>.024</td>
<td>0.15</td>
<td>1.48</td>
<td>6.14</td>
</tr>
<tr>
<td>.490</td>
<td>1.55</td>
<td>.172</td>
<td>0.85</td>
<td>1.98</td>
<td>4.92</td>
</tr>
<tr>
<td>.662</td>
<td>2.40</td>
<td>.172</td>
<td>1.10</td>
<td>2.95</td>
<td>6.38</td>
</tr>
<tr>
<td>.834</td>
<td>3.50</td>
<td>.123</td>
<td>1.0</td>
<td>4.0</td>
<td>8.15</td>
</tr>
<tr>
<td>.957</td>
<td>4.49</td>
<td>.055</td>
<td>1.10</td>
<td>5.04</td>
<td>20.</td>
</tr>
<tr>
<td>1.012</td>
<td>5.59</td>
<td>&lt;.017</td>
<td>0.40</td>
<td>5.79</td>
<td>&lt;23.5</td>
</tr>
<tr>
<td>&lt;1.029</td>
<td>5.98</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N is number of cycles
a is crack length measured from the corner to the crack tip
at the bottom of the outstanding angle leg
*) crack in angle fillet, not visible at bottom of the outstanding angle leg
TABLE 6  PREDICTED CRACK GROWTH RATES FOR CRACK TIP IN VERTICAL ANGLE LEG OF BEAM 3

<table>
<thead>
<tr>
<th>Geometry of Unbonded Region</th>
<th>Crack Size a (in.)</th>
<th>1.4</th>
<th>2</th>
<th>2.6</th>
<th>3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>da/dN $\times10^{-7}$</td>
<td>$\Delta K$ (ksi/in)</td>
<td>da/dN $\times10^{-7}$</td>
<td>$\Delta K$ (ksi/in)</td>
<td>da/dN $\times10^{-7}$</td>
</tr>
<tr>
<td>(a) Constant Width Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band Width = 1.0 (in.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.70</td>
<td>1.54</td>
<td>7.52</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>0.75</td>
<td>1.70</td>
<td>7.77</td>
<td>1.23</td>
<td>6.98</td>
<td>0.93</td>
</tr>
<tr>
<td>(b) Conical Shaped Region</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width = 0.69 + 4/30 $xa$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.75 (.56)*</td>
<td>1.52</td>
<td>7.49</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>0.80 (.53)</td>
<td>1.66</td>
<td>7.72</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>0.96 (.43)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c) Elliptical Shaped Region</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>short axis $b_2$ = $(\frac{b_2}{b_1}) (\text{in})$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0 (.46)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 (.44)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.15 (.36)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 (.48)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3 (.41)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured Crack Growth Rates</td>
<td>1.58</td>
<td>7.59</td>
<td>1.60</td>
<td>7.62</td>
<td>1.63</td>
</tr>
</tbody>
</table>

a  is crack length measured from center of hole
b_1  is long axis length
b_2  is short axis length
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No Failure

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No Detectable Cracking in Corroded Area

Test No.

Cracking

Angle Failure

Section Failure

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- ○ Baker and Kulak '82
- □ Reemsnyder '75
- ▲ Present Tests
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\[ K_I = \sigma \sqrt{\pi a} \ F(a/b) \]
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Fig. 66 Mesh Detail - Elliptical Unbonded Area
Fig. 67 Finite Element Mesh for Crack Tip in Outstanding Angle Leg
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