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THE FATIGUE STRENGTH OF WEATHERED AND DETERIORATED
RIVETED MEMBERS

by

Johannes M. M. Out

A thesis
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the degree of

Master of Science

in

Civil Engineering

Lehigh University
1984

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This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

May 7, 1984
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Professor in Charge

Chairman of Department
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This thesis is dedicated to Nicolaas J. Out and Maria J. Tromp.
# Table of Contents

**ACKNOWLEDGEMENTS**

**ABSTRACT**

1. **INTRODUCTION**

2. **REVIEW OF EXISTING TEST DATA ON RIVETED STEEL COMPONENTS**
   2.1 Procedure and Approach
   2.2 Factors influencing the Fatigue Resistance
      2.2.1 General remarks
      2.2.2 Influence of the R-ratio
      2.2.3 Influence of Yield Stress
      2.2.4 Influence of Clamping Force and Bearing Ratio
      2.2.5 Influence of Method of Hole Preparation
      2.2.6 Influence of Specimen State
   2.3 The Fatigue Resistance of Steel Plate Specimens with Open Holes
      2.3.1 General Remarks
      2.3.2 Influence of Method of Hole Preparation
      2.3.3 Influence of Specimen State

3. **REVIEW OF EXISTING TEST DATA ON WROUGHT IRON COMPONENTS**

4. **FATIGUE TEST PROGRAM**
   4.1 Introduction
   4.2 Test Specimens
   4.3 Test Set-up
   4.4 Results of the Fatigue Tests
      4.4.1 General Remarks
      4.4.2 Fatigue Resistance of the Corroded Region
      4.4.3 The Fatigue Resistance of the Rivet Details
      4.4.4 The Cracking of Deteriorated Compression Flanges

5. **THE REDUCED TEMPERATURE TEST**
   5.1 Objective and Procedure
   5.2 Material Fracture Characteristics
   5.3 Results of the Reduced Temperature Test

6. **ANALYTICAL FATIGUE CRACK GROWTH PREDICTION USING FINITE ELEMENTS**
   6.1 Introduction
   6.2 Analytical approach
      6.2.1 Finite Element Program QIFEVCAN, possibilities and limitations
      6.2.2 Preliminary Analysis
   6.3 The formulation of the Finite Element models
      6.3.1 Crack tip located in vertical leg of angle
      6.3.2 Crack tip located in outstanding angle leg

---

The text is not shown in the image.
6.4 Results of the analysis
   6.4.1 Crack tip located in vertical angle leg
   6.4.2 Crack tip located in outstanding angle leg

7. SUMMARY AND CONCLUSIONS
   7.1 Literature Survey on Fatigue of Riveted Members
   7.2 Fatigue and Reduced Temperature Tests on Weathered and
   Deteriorated Riveted Members
   7.3 Analysis of the cracked rivet detail

TABLES  63
FIGURES  70
REFERENCES  133
VITA  137
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Observed Cracking - Corroded Area</td>
<td>64</td>
</tr>
<tr>
<td>2</td>
<td>Summary of Test Results at the Rivet Details</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>Reduced Temperature Test Results</td>
<td>66</td>
</tr>
<tr>
<td>4</td>
<td>Measured Crack Growth Rates for Crack Tip in Vertical Angle Leg</td>
<td>67</td>
</tr>
<tr>
<td>5</td>
<td>Measured Crack Growth Rates for Crack Tip in Outstanding Angle Leg</td>
<td>68</td>
</tr>
<tr>
<td>6</td>
<td>Predicted Crack Growth Rates for Crack Tip in Vertical Angle Leg</td>
<td>69</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Summary of Test Data on Riveted Steel Connections (Failures)</td>
<td>71</td>
</tr>
<tr>
<td>2</td>
<td>Summary of Test Data on Riveted Steel Connections (Failures and Run-outs)</td>
<td>72</td>
</tr>
<tr>
<td>3</td>
<td>Fatigue Resistance of Riveted Steel Connections under Reversal Loading</td>
<td>73</td>
</tr>
<tr>
<td>4</td>
<td>Fatigue Resistance of Riveted Steel Connections at Low R Ratios (0 ≤ R &lt; 0.3)</td>
<td>74</td>
</tr>
<tr>
<td>5</td>
<td>Fatigue Resistance of Riveted Steel Connections at High R Ratios (R ≥ 0.3)</td>
<td>75</td>
</tr>
<tr>
<td>6</td>
<td>Adjusted Fatigue Resistance of Riveted Steel Connections at High R Ratios (ECCS)</td>
<td>76</td>
</tr>
<tr>
<td>7</td>
<td>Fatigue Resistance of Riveted Connections of Plate Materials with ( \sigma_y &lt; 275 \text{ MPa} )</td>
<td>77</td>
</tr>
<tr>
<td>8</td>
<td>Fatigue Resistance of Riveted Connections of Plate Materials with ( 275 \leq \sigma_y &lt; 345 \text{ MPa} )</td>
<td>78</td>
</tr>
<tr>
<td>9</td>
<td>Fatigue Resistance of Riveted Connections of Plate Materials with ( \sigma_y \geq 345 \text{ MPa} )</td>
<td>79</td>
</tr>
<tr>
<td>10</td>
<td>Fatigue Resistance of Riveted Steel Connections with Normal Clamping Force and Low Bearing Ratio (≤ 1.5)</td>
<td>80</td>
</tr>
<tr>
<td>11</td>
<td>Fatigue Resistance of Riveted Steel Connections with Normal Clamping Force and High Bearing Ratio (≥ 1.5)</td>
<td>81</td>
</tr>
<tr>
<td>12</td>
<td>Fatigue Resistance of Riveted Steel Connections with Reduced Clamping Force and Low Bearing Ratio (&lt; 1.5)</td>
<td>82</td>
</tr>
<tr>
<td>13</td>
<td>Fatigue Resistance of Riveted Steel Connections with Reduced Clamping Force and High Bearing Ratio (≥ 1.5)</td>
<td>83</td>
</tr>
<tr>
<td>14</td>
<td>Fatigue Resistance of Riveted Steel Connections with Drilled Holes</td>
<td>84</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>15</td>
<td>Fatigue Resistance of Riveted Steel Connections with Punched Holes</td>
<td>85</td>
</tr>
<tr>
<td>16</td>
<td>Fatigue Resistance of Riveted Steel Connections with Subpunched and Reamed Holes</td>
<td>86</td>
</tr>
<tr>
<td>17</td>
<td>Fatigue Resistance of Riveted Steel Connections with Subdrilled and Reamed Holes</td>
<td>87</td>
</tr>
<tr>
<td>18</td>
<td>Fatigue Resistance of Riveted Steel Connections, Specially Fabricated for Laboratory Tests</td>
<td>88</td>
</tr>
<tr>
<td>19</td>
<td>Fatigue Resistance of Riveted Steel Connections, Fabricated from Existing Structures</td>
<td>89</td>
</tr>
<tr>
<td>20</td>
<td>Fatigue Resistance of Steel Plates with Open Drilled or Punched Holes</td>
<td>90</td>
</tr>
<tr>
<td>21</td>
<td>Fatigue Resistance of Steel Plates with Open Subpunched and Reamed Holes</td>
<td>91</td>
</tr>
<tr>
<td>22</td>
<td>Fatigue Resistance of Steel Plates with Open Subdrilled and Reamed Holes</td>
<td>92</td>
</tr>
<tr>
<td>23</td>
<td>Fatigue Resistance of Steel Plates with New or Existing Holes, Fabricated for Laboratory Tests</td>
<td>93</td>
</tr>
<tr>
<td>24</td>
<td>Fatigue Resistance of Steel Plates with New or Existing Open Holes, Fabricating from Existing Structures</td>
<td>94</td>
</tr>
<tr>
<td>25</td>
<td>Fatigue Resistance of Wrought Iron Riveted Connections</td>
<td>95</td>
</tr>
<tr>
<td>26</td>
<td>Fatigue Resistance of Wrought Iron Plates with Open Holes</td>
<td>96</td>
</tr>
<tr>
<td>27</td>
<td>Stringers of the French Broad Ivy River Bridge</td>
<td>97</td>
</tr>
<tr>
<td>28</td>
<td>View of Compression Flange Showing Significant Reduction in Outstanding Legs</td>
<td>98</td>
</tr>
<tr>
<td>29</td>
<td>Flange Angle Corrosion at Cross-Frame Connections</td>
<td>99</td>
</tr>
<tr>
<td>30</td>
<td>Flange Angle Corrosion at Cross-Frame Connections</td>
<td>100</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>31</td>
<td>Preexisting Crack in Compression Flange Next to Bracing Connections</td>
<td>101</td>
</tr>
<tr>
<td>32</td>
<td>Fatigue Testing Setup</td>
<td>102</td>
</tr>
<tr>
<td>33</td>
<td>Crack at Corroded Area of Test Beam 1</td>
<td>103</td>
</tr>
<tr>
<td>34</td>
<td>Set of Cracks Developed Due to Force Redistribution in Section</td>
<td>104</td>
</tr>
<tr>
<td>35</td>
<td>Surface of Crack in Corroded Area of Test Beam 1</td>
<td>105</td>
</tr>
<tr>
<td>36</td>
<td>Cracked Section at Corroded Area of Test Beam 2</td>
<td>106</td>
</tr>
<tr>
<td>37</td>
<td>Initial Crack in Corroded Area of Test Beam 2</td>
<td>107</td>
</tr>
<tr>
<td>38</td>
<td>Corroded Area of Test Beam 3</td>
<td>108</td>
</tr>
<tr>
<td>39</td>
<td>Corroded Area of Test Beam 4 with Crack Reinitiation from Drilled Holes</td>
<td>109</td>
</tr>
<tr>
<td>40</td>
<td>The Fatigue Resistance of Corroded Area Details</td>
<td>110</td>
</tr>
<tr>
<td>41</td>
<td>Crack in Corroded Area of Beam 4 at Top Surface</td>
<td>111</td>
</tr>
<tr>
<td>42</td>
<td>Crack in Corroded Area of Beam 4 at Bottom Surface</td>
<td>112</td>
</tr>
<tr>
<td>43</td>
<td>Crack Surface of Crack at Rivet Hole Running into Bottom Flange</td>
<td>113</td>
</tr>
<tr>
<td>44</td>
<td>The Fatigue Resistance of the Rivet Details</td>
<td>114</td>
</tr>
<tr>
<td>45</td>
<td>The Fatigue Resistance of Riveted Members</td>
<td>115</td>
</tr>
<tr>
<td>46</td>
<td>Fatigue Crack in the Deteriorated Compression Flange of Test Beam 1</td>
<td>116</td>
</tr>
<tr>
<td>47</td>
<td>Surface of Compression Flange Fatigue Crack</td>
<td>117</td>
</tr>
<tr>
<td>48</td>
<td>Insulating and Cooling System at Fatigue Cracked Section of Test Beam 3 Used During Fracture Test</td>
<td>118</td>
</tr>
<tr>
<td>49</td>
<td>Tube System for Liquid Nitrogen Distribution During Reduced Temperature Test</td>
<td>119</td>
</tr>
<tr>
<td>50</td>
<td>Insulating Box Containing Section Cooled During Reduced Temperature Test</td>
<td>120</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>51</td>
<td>Charpy V-Notch Characteristics of the Flange Angle</td>
<td>121</td>
</tr>
<tr>
<td>52</td>
<td>Geometry of Beam Section with Cracked Rivet Detail with Crack Tip in Vertical Angle Leg</td>
<td>122</td>
</tr>
<tr>
<td>53</td>
<td>Geometry of Beam Section with Cracked Rivet Detail with Crack Tip in Outstanding Angle Leg</td>
<td>123</td>
</tr>
<tr>
<td>54</td>
<td>Crack Growth Rate as Function of Position of Crack Tip in Vertical Angle Leg</td>
<td>124</td>
</tr>
<tr>
<td>55</td>
<td>Crack Growth Rate as a Function of Position of Crack Tip in Outstanding Angle Leg</td>
<td>125</td>
</tr>
<tr>
<td>56</td>
<td>Infinite Strip Model with Half Infinite Crack</td>
<td>126</td>
</tr>
<tr>
<td>57</td>
<td>Finite Width Model with Center Through Crack</td>
<td>127</td>
</tr>
<tr>
<td>58</td>
<td>Finite Element Mesh for Crack Tip in Vertical Angle Leg With Unbonded Area of Constant Width</td>
<td>128</td>
</tr>
<tr>
<td>59</td>
<td>Mesh Detail - Conical Unbonded Area</td>
<td>129</td>
</tr>
<tr>
<td>60</td>
<td>Mesh Detail - Unbonded Area with Constant Width</td>
<td>129</td>
</tr>
<tr>
<td>61</td>
<td>Finite Element Mesh for Crack Tip in Vertical Angle Leg With Elliptical Unbonded Area</td>
<td>130</td>
</tr>
<tr>
<td>62</td>
<td>Mesh Detail - Elliptical Unbonded Area</td>
<td>131</td>
</tr>
<tr>
<td>63</td>
<td>Mesh Detail - Elliptical Unbonded Area</td>
<td>131</td>
</tr>
<tr>
<td>64</td>
<td>Finite Element Mesh for Crack Tip in Outstanding Angle Leg</td>
<td>132</td>
</tr>
</tbody>
</table>
ABSTRACT

This thesis describes a study that has been performed on the fatigue and fracture resistance of corroded and deteriorated riveted members. The validity of AASHTO/AREA Design Category D that is generally used for the evaluation of riveted connections is uncertain, particularly around the fatigue limit.

A detailed literature study is included which examines test data on the fatigue behaviour 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 extend they influence the fatigue life. Category D remains the applicable lower bound for a stress range above the fatigue limit. 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.

A series of fatigue tests were carried out on eighty 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. The stress ranges that were applied were selected between the fatigue limits provided for the 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 the rivet detail studied. 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.

A series of reduced temperature tests on a cracked stringer did not induce fracture of the component. These tests and the behaviour observed during the fatigue tests confirmed the redundancy of riveted built up sections fabricated from mild steel.

An analytical study using linear elastic fracture mechanics concepts has been performed to characterize the frictional bond and the way it restrains the crack growth rate. The agreement between predictions and measurements was good.
Chapter 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 increasing importance as ever intensifying 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 of 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 is needed to establish better estimates of the fatigue resistance of riveted built up sections.

Most of the previous laboratory work 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 97 [MPa]. Both the AASHTO and the 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 cor-
responds to category D in the joint classification system. A
description and summary of the database used is given in the com-
mentary to the AREA specifications.

This thesis contains a detailed literature survey which con-
firms 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
stem from several independant sources eliminates sometimes unrecog-
nized influences on the studied phenomenon, that are specific to
the test program. It appears that the majority of test results
that fall short of category C exhibit low clamping and high bearing
eratio.

Next, this thesis describes a pilot test program on the high
cycle fatigue behaviour and fracture resistance of riveted built up
members in their weathered and deteriorated state. 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 an enor-
mous penalty on the fatigue resistance. It is of particular interest to investigate the applicability of this category around the fatigue or endurance limit.

The research project discussed here provides information thereon. Four stringers taken from a railroad bridge have been tested, subjected to a constant amplitude load cycle. 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 behaviour of the rivet details and the cross-sections that were significantly affected by corrosion. The latter detail proved to be a problem of greater size than had been expected. An attempt was made to cause fracture of a section which contained a large fatigue crack.

A final part of this thesis is an analytical study on the behaviour of a cracked rivet detail and its environment. The object was to find the relation 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 immediately adjacent to and ahead of the crack.
Investigated are the shape and size of the unbonded area. Calibration is made with the crack growth measurements made. 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. The results of the analysis are plausible.
Chapter 2

REVIEW OF EXISTING TEST DATA ON RIVETED STEEL COMPONENTS

2.1 Procedure and Approach

A detailed review of all the available data on the fatigue behaviour of riveted steel members or components is provided in this chapter. Data are included from studies performed in the United States and Europe from 1934 to date [3, 4, 5] [6, 7, 8] [9, 11, 13] [14, 15, 16] [17, 18, 20] [22, 21, 24] [28, 29]. 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 \( R = \frac{S_{\text{min}}}{S_{\text{max}}} \) 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 by the information given 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 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 database.

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 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 regard to any of the control variables. Most test results exceed design Category D, although a small number of data points fall below Category D or E. Note that no test have been conducted at stress ranges below 97 [MPa]. Figure 2 shows the same fatigue data supplemented by the run-out test results. Very few specimens were subjected to more than 2 million cycles.

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

The test data mainly concern shear splices. Figure 45 highlights the available data on more complex connections.

2.2.2 Influence of the $R$-ratio

In most of the fatigue tests, the $R$-ratio was used as a controlled variable. The published tests were divided into three categories: $-1 < R < 0$, $R=0$, $R > 0.3$.

Figure 3 summarizes the test data for alternating loading, when $R < 0$. A large number of specimens did not exhibit failure in the section and are identified by the symbol 'o' in figure 3. The data indicate that the fatigue strength exceeds the Category C resistance line.

Figure 4 shows the test data with low $R$-ratios. 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 5 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 138 [MPa]. It seems likely that this is the primary reason for the reduction in fatigue resistance of these specimens. An examination of figures 3, 4 and 5 indicates that the alternating stress condition is not as critical as a positive \( R \)-ratio. This has been recognized in the 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

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

where \( \sigma \) is the tension component of the stress cycle and \( \sigma_{\text{min}} \) is the compression component. The adjusted stress cycle values for the alternatingly loaded test specimens are displayed in figure 6. 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 3.
2.2.3 Influence of Yield Stress

Figures 7, 8 and 9 summarize the fatigue resistance as a function of the material yield point. Little difference can be seen between figures 7 and 8. 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 higher yield strength material is seen to generally lie above the Category C resistance curve as seen in figure 9. 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 10-13. Test specimens with normal clamping force do not seem to be greatly affected by wide variations in the bearing ratio according to figures 10 and 11. Category D can be seen to provide a lower bound resistance for both low and high bearing ratios. 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 12 and 13 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 10 and 12 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 11 and 13. The fatigue resistance is less than Category E in two instances. Significant scatter in the test data is apparent in figure 13.

The results summarized in figures 10-13 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 14-17.

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 14 and 15 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 13 mm.

Punch alignment and wear can result in minute cracks around the hole [19, 26]. 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 16 and 17. Both subdrilled and subpunched holes seem to be
less susceptible to fatigue than the drilled holes. Nearly all the test data with subdrilled or punched holes can be seen to plot above the Category C resistance line.

On the whole it seems that the manner of hole preparation is 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 18. Figure 19 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 18.
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 has 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 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 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 20 shows the test results for specimens with drilled and with punched holes, while figures 21 and 22 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 20 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. 14-17) shows 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 23 and 24. Figure 23 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 24.

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 24. 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.
Chapter 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 behaviour of riveted wrought iron until in the recent past national railroads started investigating this behaviour [9, 18, 24].

Figures 25 and 26 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 25 and 26 learns that there is no major difference between the behaviour of riveted specimens and of specimens with open holes. For both types 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 \(90 \text{ [MPa]}\), had been tested before at lower stress ranges and conceivably contained cracks hidden by the rivet head that were not reported \[18\].

On comparison of the figures 1 and 25 one observes that riveted wrought iron connections have a fatigue strength lower than riveted steel connections: between Categories D and E.
Chapter 4

FATIGUE TEST PROGRAM

4.1 Introduction

Fatigue tests were conducted on four 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.

The 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 cycle fatigue limit of AASHTO/AREA Categories C and D, respectively 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 for being obsolete rather than for malfunctioning. It was in service until demolition. 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, 1 [m] deep and .32 [m] wide 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 7.32 [m]. As cut from the bridge, they were about 6.10 [m] long.

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. 29 and 30). The bottom inside flange angle is seen to be severely corroded, so that a reduced thickness resulted as well as a partly eliminated 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, which shows a thickness reduction of the flange 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 245 [kN] hydraulic jacks and one pulsator, as illustrated in figure 32. The distance between the jacks was 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 variable 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

Four of the stringers have been 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. Results are tabulated for the number of cycles until first detected cracking, until failure of the corroded angle as well as the number of cycles until failure of the section, if 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 progressing 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 four stringers tested all had the 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. 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 existing crack had been detected in the corroded section which was removed by grinding. This segment is shown in figure 37.

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 centered on the crack tip after it had grown to a length of about 64 [mm]. The crack finally reinitiated after 2.2 million additional stress cycles and the section was spliced to permit continued testing of the stringer.

The fatigue test data of the corroded region detail of the flange angle are graphically shown in figure 40. The stress range is defined on the net section.

The corroded areas of stringers 2 and 4 (figs. 36 and 39) had a fatigue life, at first observed cracking, lower than provided
by Category E. The corroded detail of stringer 1 (see fig. 32) had a fatigue resistance slightly lower than Category C. Stringer 3 (see fig. 38) did not crack at this location.

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 and 4 was greater than predicted by considering the loss of cross-sectional area only, as the results plot well below Category A. Apparently, the roughness of the surface and the associated stress concentrations are the major factors in making this detail more severe than anticipated.

The mechanism of crack formation in the corroded area was as follows. First, several small cracks formed on the rough surface at the deeper notches close to the angle 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, while small cracks continued to form in the corroded surface and to coalesce with the edge crack. The crack length measured at the bottom surface significantly lagged behind the length at the corroded top surface, as illustrated in the figures 41 and 42.
A final note should be made on the 'crack length at discovery' in the various cases. For beam 4, the crack was very small when detected: 7.6 [mm]. This condition is identified in figure 40 as "cracking". The condition where the crack length has increased to approximately the length at discovery for beam 1, is represented by point C'. Hence, the fatigue strength of the corroded sections of beams 1 and 4 are comparable.

All three stringers that developed cracks in the corroded section, sustained a substantial number of additional stress cycles before the section failed. The numbers of cycles at failure of the angle resp. the cross-section are indicated by "angle failure" and "section failure".

4.4.3 The Fatigue Resistance of the Rivet Details

Fatigue cracks formed at rivet holes, as illustrated in figure 48. The crack surface of one of these details is shown in figure 43. The fatigue strengths of the rivet details which cracked independently of each other are summarized in Table 2 and plotted in figure 44 as a function of the net section stress range. In figure 44, "cracking" denotes first observed cracking. Failure of the flange angle developed for stringer 3 only. The cracked angles of the remaining stringers were retrofitted before failure could occur. No tests were continued until failure of the riveted section.
due to cracking at rivet holes.

Fatigue cracking was observed to occur below the fatigue limit for category C (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 behaviour of riveted joints. Most of the cracked rivet details are located in a constant moment region, so that the rivets do not transmit a bearing force. This is a favourable condition. At the same time, the rivets appeared to be tight, which is favourable as well.

The available shop drawings do not indicate the method of hole preparation. The apparent distortion of the holes may be a result of punching or driving of the rivets.

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

The majority of the rivet details were observed to develop first cracking at the top of the hole, even though the nominal stress range is higher at its bottom. Most cracks initiated at the inner surface between web plate and angle, at the edge of the hole. It is possible that fretting has aided crack initiation.

Observations during the test indicated that there was a significant influence of a frictional bond between web plate and angles. This bond was due to a paint and corrosion product. The significance of this influence lies in the effect it had on the propagation velocity 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 indicate that the crack growth rate was fairly constant with increas-
ing crack length, as long as the crack propagated in the vertical leg of the angle. This phenomenon is treated in more detail in chapter 6.

The fatigue resistance of the riveted stringers is compared with the Category C and D resistance lines, shown to represent riveted members \([2]\), in figure 45. 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.

4.4.4 The Cracking of Deteriorated Compression Flanges

The significant loss of section of the compression flange apparent in figure 28 was typical of every test beam. In extreme cases, this loss was sufficient to result in the development of fatigue cracking in the outstanding legs of the angle. Figure 46 shows one such a fatigue crack. The crack surfaces are shown in figure 47.
The cracks always started at the section that had the largest thickness reduction. The explanation for this phenomenon is that the compressional stress cycle resulted in yielding on the net ligaments of the reduced section as a result of stress concentration and reduced area. During the unloading part of the stress cycle, a residual tension stress field formed, permitting crack initiation. In these circumstances the crack propagated towards the heel of the angle and arrested after having grown out of the region of yielding. None of the cracks propagated past the heel. Hence, the cracks in the compression flange did not adversely affect the load carrying capacity of any of the test beams.
Chapter 5  
THE REDUCED TEMPERATURE TEST

5.1 Objective and Procedure

A reduced temperature test was carried out on the third stringer. The objective was to evaluate the behaviour of the member, given a fatigue crack, under low temperatures. More specifically, the objective was to determine if brittle fracture of a cracked component would occur and how that would affect the behaviour of the cross-section. At the start of the test a fatigue 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, as illustrated in figure 48. No cracking was observed in the other flange angle or in the web plate at that cross-section.

The test procedure was as follows. The cyclic test was interrupted so that an insulating box of styrofoam could be built around the section, which contained a grid of copper tubes with openings at regular distance, through which liquid nitrogen could be injected into the closed space, as illustrated in the figures 49 and 50. By injecting the nitrogen, the temperature of the enclosed section of the stringer was decreased to approximately -40 [°C]. The temperature was monitored by three temperature gages, attached to the web plate at mid depth and to the top and bottom angles.
After reaching the required temperature, the temperature was maintained by regulating the nitrogen flow.

With the cracked section being at this low 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 [cyc/min]. The crack front advanced in a stable, fatigue mode. The cyclic loading was continued for a period of approximately half an hour at the reduced temperature. Then the crack was propagated at room temperature for an additional 12.5 to 25 [mm]. This procedure was then repeated.

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 -18 to 66 [°C]. The results are summarized in figure 51.

A large variation in absorbed impact energy can be seen at test temperatures between 21 and 44 [°C]. The estimated 20.3 [J] (15 [ft-lbs]) transition temperature was about 20 [°C]. Hence, the material would satisfy the impact energy requirement for Zone 2 of the AASHTO and AREA Specifications.
5.3 Results of the Reduced Temperature Test

The reduced temperature test was performed for a number of different crack lengths. These lengths and the number of stress cycles experienced under reduced temperature are recorded in Table 3.

No unstable crack extension occurred in the cracked angle at any stage. 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.

The maximum estimated stress intensity factor during the test was \( 45 \, [ \text{MPa(m)}^{1/2} ] \), if an edge crack were assumed from the heel of the angle. The test results suggest that a significant temperature shift is applicable, since the dynamic fracture toughness at 21 [°C] was this order of magnitude [23].

Additionally, the results indicated that the frictional restraint between the cracked angle and the uncracked web, which was noted in Chapter 4, was beneficial, as the crack opening was small. The associated stress intensity factor was probably smaller than predicted by assuming an edge crack. Chapter 6 will give a
more detailed analysis of this phenomenon.

No adverse behaviour was experienced at the section when the flange angle cracked in two under the reduced temperature. The remaining resistance of the cross-section was sufficient to carry the applied load.
Chapter 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, showed a remarkably small opening displacement. This was one of the reasons why these cracks were only discovered when they were 40 to 50 [mm] long. The geometry of the cracked detail is shown in figure 52. 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.

In addition, the reduced temperature test 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 1.1 * 62 [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 76 [mm]
away from the crack. Also, it should be noted that no cracking developed at those rivets. The geometry of the cracked detail with the crack tip in the outstanding angle leg is shown in figure 53.

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 products which developed between these components. 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 propagation is stable fatigue crack growth. Once the fracture toughness is exceeded, crack instability must occur in the cracked component.

Measurements of crack propagation during the test on the third stringer provide experimental data to compare the predicted results with.

6.2 Analytical approach

The analysis of the detail makes use of concepts from linear elastic fracture mechanics. The detail and its environment form 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 handles two dimensional problems only. 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 made the analysis possible of the stage of crack propagation when the crack was confined to the angle leg attached to the web plate.

When the crack is turning the corner at the heel of the angle, the problem becomes an essentially three-dimensional problem and can not be directly analyzed with this program. The subsequent stage 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 modelled by truss elements.
6.2.2 Preliminary Analysis

The crack growth rate was determined from measurements of the crack length as a function of 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, resulting in movement of the specimen.

A graphical summary of the estimated crack propagation rates as a function of crack length is provided in the figures 54 and 55, respectively for the crack growing in the web of the angle and for the crack in the outstanding leg. 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 propagation. It should be noted that a relative 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 54 represents the regression line of the data points. The regression line is a flatly sloping line and demonstrates that the crack growth rate is increasing slowly with increasing crack length.
The crack growth rate is directly related to the stress intensity factor, under certain restrictions, by the functional relationship known as the Paris Power Law:

\[ \frac{da}{dN} = C \cdot (\Delta K)^n \]

(6.1)

Rolfe and Barsom have suggested an upper bound estimate \( C = 6.9 \times 10^{-12} \) for ferrite-pearlite steel, with \( n = 3 \), \( a \) in [m] and \( K \) in [MPa(m)^{1/2}] [23].

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 56 [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:

\[ K = \sigma \cdot (h)^{1/2} \]

(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 20 to 32 [mm], for the crack tip at mid height respectively extended to the full height of the leg of the angle. This is sig-
nificantly smaller than the 76 [mm] 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 have to vary likewise along the crack length, which causes the bond between elements to be broken in an elliptic fashion. The estimates of the width of 20 to 30 [mm] provide a helpful estimate of the short axis length.

Figure 55 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 centre through crack (see figure 57) [27]. The finite width \( b \) was taken as the flange width, equal to 152 [mm], and the nominal
stress range to which the plate is subjected was 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 50 [mm] long) in the outstanding leg, the crack driving force is underestimated by the centre cracked specimen. Apparently the completely severed vertical leg of the angle is of considerable influence driving the crack. For larger crack sizes, the centre 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 beam adjacent to the cracked rivet detail is shown in figure 58. The immediate area around the crack is shown enlarged in figure 60. 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 is constant in the middle section and the rivets transmit no shear force. In the presence of a crack the closest rivets might be loaded in bearing, if the frictional bond would not be 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 by 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 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. Possible shapes were selected on the basis of rational descriptions as numerous solutions were possible.
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 mesh was flexible as shown in figures 58 to 63 providing an element configuration which permitted the crack to step by step propagate up 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 64 shows a mesh for the condition that the 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

For the condition that the crack tip was located between the lower rivet hole and the top edge of the angle (see fig. 52), the following considerations were made.

The estimate of the width was initially based on the semi-infinite crack specimen (see fig. 56). 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 centre 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 60 was examined. Next, this shape was modified to a region of conical shape (see fig. 59). 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 second examined 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 the figures 52 and 61 to 63. The shape was related to the approximately elliptical opening displacement of the crack when unrestrained. The ellipse was centred midway between the centre 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 62 and 63.

The loading on the modelled section was imposed at the edge where the section 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. In other words, the section was taken big enough so that the increase of compliance due to the existence of the crack was negligible compared to the total compliance. This condition was shown to be fulfilled when the modelled half length of the section was approximately four times the length of the angle legs.
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 until half depth and then be tapered out towards the heel of the angle, as shown in figure 53. Width $w_1$ was taken as 46 [mm] and width $w_2$ as 76 and 91 [mm]. A typical mesh is shown in figure 64. The length of half the section was taken four times the length 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 section equal to the gross section strains integrated over the length of the section. In the second stage, contributions were added to the imposed displacements corresponding to the opening displacements along the crack as calculated in the first stage. 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 using the models described in the previous section yielded the crack growth rates tabulated in table 6. These crack growth rates were calculated from the stress intensity factors $K_I$ by eq. (6.1).

An unbonded area with a constant width (fig. 60), yields results that suggest that an increase of width is required in order to match the measured values of crack growth. By linear interpolation the widths are found to vary between 18 and 30 [mm]. These results are in good agreement with the estimates made using the infinite strip model of figure 56 as discussed in section 6.2.2.

The results for an increasing width with increasing crack-length suggest that the unbonded area grows in both width and length direction. This is confirmed by the results for the conically shaped unbonded area (fig. 59). It is found that if the width behind the advancing cracktip does not increase as a result of the increasing crack opening, the predicted crack growth decreases. The crack opening displacement is maximal near the midpoint of the crack and likewise should the width of the unbonded area be maximal near that point.
An elliptical shape is a more probable alternative (fig. 52 and 61 to 63). By interpolation, the short axis lengths can be seen to increase from 20 to 33 [mm]. The short axis/crack length ratio decreases from 56 to 41 % with increasing crack length. Those values are fairly close to the values for the constant width computed earlier, but the ellipse has a total area of the unbonded region which is smaller, making the elliptic shape more likely.

6.4.2 Crack tip located in outstanding angle leg

Figure 55 shows the results of the finite element analysis when the crack tip resides in the outstanding leg of the angle. The crack growth rate is 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. As before, the Paris power law (6.1) was used to relate the crack growth rate and stress intensity factor.

Figure 55 summarizes the three sets of results (see (6.3.2)):

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

2. those assuming width $w_2 = 91.4$ [mm] (3.6 [in]) and subjected
to a first stage loading only;

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

The agreement between the analysis and the measurements is good. As was indicated by the measurements, the analytical predictions show 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 centre through cracked idealization.

The analysis shows that the increase of the crack growth with increasing crack length was small compared to the increase of the growth rate for the centre through cracked model. When the crack length was larger than two thirds of the leg length, the crack length increased appreciably in the way it was observed in the measurements.

Figure 55 shows that the finite element analysis generally underestimated the crack growth rate for all three examined shapes and loading combinations. The predicted curves are smoother than the measured function. Hence, the highest computed value for the crack length of 10.16 [cm] exceeded the measurement. It is possible that the sudden increase in the measured crack growth rate was caused by a sudden expansion of the unbonded area due to the
brittleness of the bond product.

A comparison of the three analytical curves shows that an increased width $w_2$ raised the crack growth rate. The addition of the crack opening to the imposed displacements also raised the predicted crack growth rate as could have been expected. In both cases, however, the increase was fairly small compared to the discrepancy between the measured and predicted values.

The predicted crack growth rate could probably have been raised onto an arbitrary measured value but that might have required a width equal to or greater than the distance to the nearest rivet. Then rivet bearing would assist in the transfer of load from the cracked to the uncracked section components. This would have changed the problem essentially and would have required different models.

The predicted crack growth rates by the finite element analysis are in good agreement with the limited test data considering the complexity of the conditions and geometry.
Chapter 7
SUMMARY AND CONCLUSIONS

7.1 Literature Survey on Fatigue of Riveted Members

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. A total of 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 tests provided very diverse test conditions. In addition, many tests were discontinued before developing fatigue cracks, but without accumulating a sufficient amount of stress cycles to justify that the stress range was below the fatigue limit. It was customary to discontinue testing after 2 or 3 million cycles. Next, all of the fatigue tests on steel specimens were conducted at stress ranges above 92 [MPa]. Hence, the fatigue limit was not.
defined as failures were observed to occur at all of the applied stress ranges.

3. Plates with holes tended to provide greater fatigue resistance than riveted joints. All plates tested 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. It must be said that 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 approximately defined by Category C. A number of tests at a 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 specifications of the ECCS TC-10 recommended to define the stress cycle as:

$$\Delta\sigma_{\text{eff}} = \sigma_{\text{max}} - 0.6 \times \sigma_{\text{min}}$$

This recommendation scales the data with $R < 0$ appropriately, such that reasonable agreement exists with the test data for
8. Although only limited test data are available for wrought iron riveted members or plates with open holes, it seems that their fatigue resistance is affected by the same factors that influence steel specimens. Clamping force and bearing ratio are probably 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 Fatigue and Reduced Temperature Tests on Weathered and Deteriorated Riveted Members

The experimental studies carried out on four weathered and deteriorated riveted members provided information on the extreme life behaviour of such members. In addition they also provided information on the behaviour 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 46 and 66 [MPa] after 8 to 30 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. This degree of severity cannot be accounted for by considering just the loss of area. The four test results suggest that when the thickness of the outstanding flange angle is reduced until less than half remains, the proximity of the corroded area to the opposite surface reduces 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. A lesser level of thickness did not result in crack initiation.

3. Severing of a component of the built up section did not immediately impair the cyclic loading capacity of the members. Between .5 to 1. million additional cycles of a stress range of 62 to 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
four test beams exhibited redundant behaviour once cracks
developed that severed a flange angle.

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

5. Fatigue cracks that formed in the deteriorated 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.
7.3 Analysis of the cracked rivet detail

A finite element analysis was made to evaluate the behaviour of a section of the built up stringer after a crack in a flange angle initiated from a rivet hole. The complexity of this detail resides in the load redistribution capacity of the built up cross section and in the presence of a frictional bond between the faying surfaces of the member components.

The main effort was dedicated to characterizing the unbonded area between the cracked and uncracked components in the vicinity of the crack. A guideline was provided by crack growth measurements made during the test. It was possible to obtain good agreement between analytical results and these measurements.

The analytical studies demonstrated that:

1. A frictional bond between the faying surfaces of the cracked angle and the web plate was responsible for the load transfer from cracked to uncracked components. This reduced the crack growth rate and extended the fatigue life. The bond is absent in the immediate vicinity of the crack.

2. It was observed that the crack initiated from the top of the rivet hole and advanced to the top edge of the angle before
cracking occurred elsewhere in the section. During this stage of crack propagation the crack growth rate increased little. The shape of the unbonded area found to be the most probable was an ellipse with its centre on the middle of the crack. The short axis length decreased with increasing crack length from 56 to 41% of the crack length. This length is smaller than the distance to the nearest rivet, confirming the assumption that these rivets did not transfer any load in bearing.

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 tip was removed from the heel by less than two thirds of the angle leg length. The unbonded area at this stage was found to be approaching the nearest rivet.
TABLE 1: OBSERVED CRACKING - CORRODED AREA

<table>
<thead>
<tr>
<th>Test</th>
<th>Δσ_gross (MPa)</th>
<th>Δσ_net (MPa)</th>
<th>N (10^6)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>73.4</td>
<td>75.2</td>
<td>3.77</td>
<td>Crack Found &gt; 104 mm 4.1 in.</td>
</tr>
<tr>
<td></td>
<td>10.5</td>
<td>10.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>62.1</td>
<td>64.8</td>
<td>0.85</td>
<td>Angle Severed</td>
</tr>
<tr>
<td></td>
<td>9.0</td>
<td>9.4</td>
<td>1.45</td>
<td>Section Failed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>62.1</td>
<td>63.4</td>
<td>(39.71)</td>
<td>No Failure</td>
</tr>
<tr>
<td></td>
<td>9.0</td>
<td>9.2</td>
<td></td>
<td></td>
</tr>
<tr>
<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>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>8.3</td>
<td>5.37</td>
<td>First hole drilled</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(7.61)</td>
<td>Section spliced</td>
</tr>
</tbody>
</table>

Ratio R = \( \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \) \approx 0.1
TABLE 2: SUMMARY OF TEST RESULTS AT THE RIVET DETAILS

<table>
<thead>
<tr>
<th>Test</th>
<th>Δσ net (*10⁶)</th>
<th>Nc</th>
<th>NF</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65.9 9.6</td>
<td>6.52</td>
<td></td>
<td>Angle, Bottom hole, Top of hole</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.34</td>
<td></td>
<td>Angle, Bottom hole, Top of hole</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.70</td>
<td></td>
<td>Angle, Bottom hole, Top of hole</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12.98</td>
<td></td>
<td>Angle, Bottom hole, Top of hole</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(18.25)</td>
<td>Test Stopped</td>
</tr>
<tr>
<td>2</td>
<td>59.3 8.6</td>
<td>36.50</td>
<td></td>
<td>Web plate, Bottom hole, Bottom of hole</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(36.50)</td>
<td>Test Stopped</td>
</tr>
<tr>
<td>3</td>
<td>56.2 8.15</td>
<td>18.26</td>
<td>38.69</td>
<td>Angle, Bottom hole, fillet, Top of hole</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(39.72)</td>
<td>Angle, Bottom hole, Fillet, Top of hole</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(--)</td>
<td>Angle, Bottom hole, Fillet, Top of hole</td>
</tr>
<tr>
<td></td>
<td>46.8 6.79</td>
<td>25.94</td>
<td></td>
<td>Angle, Bottom hole, Top of hole Shear span</td>
</tr>
<tr>
<td></td>
<td>45.8 6.65</td>
<td>25.94</td>
<td></td>
<td>Angle, Bottom hole, Top of hole Shear span</td>
</tr>
</tbody>
</table>

Nc: Life until first cracking  
NF: Life until failure of component

Note: Only cracks at rivet holes not affected by a cracked section are included
### TABLE 3: REDUCED TEMPERATURE TEST RESULTS

<table>
<thead>
<tr>
<th>Test</th>
<th>ai</th>
<th>mm</th>
<th>in.</th>
<th>ΔN.Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>*</td>
<td>27.9</td>
<td>1.1</td>
<td>19,000</td>
</tr>
<tr>
<td>2</td>
<td>39.4</td>
<td>1.55</td>
<td></td>
<td>Single static test</td>
</tr>
<tr>
<td>3</td>
<td>61.0</td>
<td>2.4</td>
<td></td>
<td>22,000</td>
</tr>
<tr>
<td>4</td>
<td>88.9</td>
<td>3.5</td>
<td></td>
<td>12,000</td>
</tr>
<tr>
<td>5</td>
<td>114.3</td>
<td>4.5</td>
<td></td>
<td>9,000</td>
</tr>
<tr>
<td>6</td>
<td>142.2</td>
<td>5.6</td>
<td></td>
<td>15,000</td>
</tr>
<tr>
<td>7</td>
<td>152.4</td>
<td>6.0</td>
<td>No Fracture</td>
<td></td>
</tr>
</tbody>
</table>

T = -40°C (-40°F)  
\( \sigma_{\text{max}} = 61 \text{ MPa} \) (8.9 ksi)  
\( \varepsilon = 2.6 \times 10^{-3} \text{ (s^{-1})} \)

\( a_i \) is: Crack length at start of test, measured at bottom of flange from angle corner to crack tip  
* crack in fillet
### TABLE 4 MEASURED CRACK GROWTH RATES FOR CRACK TIP IN VERTICAL ANGLE LEG

<table>
<thead>
<tr>
<th>Rivet Detail</th>
<th>8 Nt</th>
<th>12 St</th>
<th>4 St</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>ΔN</td>
<td>a</td>
</tr>
<tr>
<td></td>
<td>(mm)</td>
<td>*10^-6</td>
<td>(mm)</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>----</td>
<td>47.0</td>
</tr>
<tr>
<td></td>
<td>2.741</td>
<td>2.741</td>
<td>55.8</td>
</tr>
<tr>
<td></td>
<td>5.413</td>
<td>2.672</td>
<td>63.5</td>
</tr>
<tr>
<td></td>
<td>7.685</td>
<td>2.272</td>
<td>74.9</td>
</tr>
<tr>
<td></td>
<td>8.424</td>
<td>.739</td>
<td>≥78.7</td>
</tr>
<tr>
<td></td>
<td>11.248</td>
<td>2.824</td>
<td>---</td>
</tr>
</tbody>
</table>

N is number of cycles

a, Δa is crack length

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

\[ a_r = 22.9 \text{ (mm)} \] should be added to find the crack length wrt. center of hole.
### TABLE 5 MEASURED CRACK GROWTH RATES FOR CRACK TIP IN OUTSTANDING ANGLE LEG

<table>
<thead>
<tr>
<th>N</th>
<th>ΔN</th>
<th>a</th>
<th>Δa</th>
<th>$\bar{a}$</th>
<th>da/dN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>*10^6</td>
<td></td>
<td></td>
<td></td>
<td>*10^-6</td>
</tr>
<tr>
<td>0</td>
<td>---</td>
<td>*)</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>.380</td>
<td>.380</td>
<td>27.9</td>
<td>≈ 27.9</td>
<td>≈ 14.0</td>
<td>≈ 73.5</td>
</tr>
<tr>
<td>.466</td>
<td>.086</td>
<td>35.6</td>
<td>7.62</td>
<td>31.8</td>
<td>88.6</td>
</tr>
<tr>
<td>.490</td>
<td>.024</td>
<td>39.4</td>
<td>3.81</td>
<td>37.5</td>
<td>156.</td>
</tr>
<tr>
<td>.662</td>
<td>.172</td>
<td>61.0</td>
<td>21.6</td>
<td>50.2</td>
<td>125.</td>
</tr>
<tr>
<td>.834</td>
<td>.172</td>
<td>88.9</td>
<td>27.9</td>
<td>74.9</td>
<td>162.</td>
</tr>
<tr>
<td>.957</td>
<td>.123</td>
<td>114.</td>
<td>25.4</td>
<td>102.</td>
<td>207.</td>
</tr>
<tr>
<td>1.012</td>
<td>.055</td>
<td>142.</td>
<td>27.9</td>
<td>128.</td>
<td>508.</td>
</tr>
<tr>
<td>&lt;1.029</td>
<td>&lt;.017</td>
<td>152.</td>
<td>10.2</td>
<td>147.</td>
<td>&gt;598.</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>
<thead>
<tr>
<th>da/dN (*10^{-6} (mm))</th>
<th>35.6</th>
<th>50.8</th>
<th>66.0</th>
<th>81.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant width; width (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.8</td>
<td>3.90</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>19.1</td>
<td>4.31</td>
<td>3.12</td>
<td>2.36</td>
<td>1.98</td>
</tr>
<tr>
<td>25.4</td>
<td>--</td>
<td>4.82</td>
<td>3.71</td>
<td>3.22</td>
</tr>
<tr>
<td>30.5</td>
<td>--</td>
<td>--</td>
<td>4.84</td>
<td>4.32</td>
</tr>
</tbody>
</table>

| conical shape; width 17.6 + 4/30 \(a\) (mm) | | | | |
|------|------|------|------|
| 19.1 (.5) | 3.86 | -- | -- | -- |
| 20.3 (.53) | 4.22 | -- | -- | -- |
| 24.3 (.43) | -- | 4.00 | -- | -- |

| elliptical shape; short axis length \(b_2\) (mm) | | | | |
|------|------|------|------|
| 25.4 (.46) | -- | 4.32 | -- | -- |
| 27.9 (.44) | -- | -- | 3.68 | -- |
| 29.2 (.36) | -- | -- | -- | 3.43 |
| 30.5 (.48) | -- | -- | 4.21 | -- |
| 33.0 (.41) | -- | -- | -- | 4.19 |

| estimated from measured crack growth rates | | | | |
|------|------|------|------|
| 4.01 | 4.06 | 4.13 | 4.19 |

a is crack length measured from center of hole

\(b_1\) is long axis length

\(b_2\) is short axis length
FIGURES
Fig. 1 Summary of Test Data on Riveted Steel Connections (failures)
Fig. 2 Summary of Test Data on Riveted Steel Connections (Failures and Run-Outs)
Fig. 3 Fatigue Resistance of Riveted Steel Connections under Reversal Loading
Fig. 4. Fatigue Resistance of Riveted Steel Connections at Low R Ratios (0 \leq R < 0.3)
Fig. 5 Fatigue Resistance of Riveted Steel Connections at High R Ratios (R ≥ 0.3)
Fig. 6 Adjusted Fatigue Resistance of Steel Connections at High R Ratios (ECCS)
Fig. 7  Fatigue Resistance of Riveted Connections of Plate Materials with $\sigma_y < 275$ MPa
Fig. 8 Fatigue Resistance of Riveted Connections of Plate Materials with $275 \leq \sigma_y < 345$ MPa
Fig. 9  Fatigue Resistance of Riveted Connections of Plate Materials with $\sigma_y \geq 345$ MPa
Fig. 10  Fatigue Resistance of Riveted Steel Connections with Normal Clamping Force and Low Bearing Ratio ($\leq 1.5$)
Fig. 11 Fatigue Resistance of Riveted Steel Connections with Normal Clamping Force and High Bearing Ratio (≥ 1.5)
Fig. 12 Fatigue Resistance of Riveted Steel Connections with Reduced Clamping Force and Low Bearing Ratio (< 1.5).
Fig. 13 Fatigue Resistance of Riveted Steel Connections with Reduced Clamping Force and High Bearing Ratio ($\geq 1.5$)
Fig. 14  Fatigue Resistance of Riveted Steel Connections with Drilled Holes
Fig. 15 Fatigue Resistance of Riveted Steel Connections with Punched Holes
Fig. 16 Fatigue Resistance of Riveted Steel Connections with Subpunched and Reamed Holes
Fig. 17 Fatigue Resistance of Riveted Steel Connections with Subdrilled and Reamed Holes
Fig. 18 Fatigue Resistance of Riveted Steel Connections, Specially Fabricated for Laboratory Test
Fig. 19 Fatigue Resistance of Riveted Steel Connections, Fabricated from Existing Structures
Fig. 20 Fatigue Resistance of Steel Plates with Open Drilled or Punched Holes
Fig. 21 Fatigue Resistance of Steel Plates with Open Subpunched and Reamed Holes
Fig. 22 Fatigue Resistance of Steel Plates with Open Subdrilled and Reamed Holes
Fig. 23 Fatigue Resistance of Steel Plates with New or Existing Holes, Fabricated for Laboratory Tests
Fig. 24 Fatigue Resistance of Steel Plates with New or Existing Open Holes, Fabricating from Existing Structures
Fig. 25 Fatigue Resistance of Wrought Iron Riveted Connections
Fig. 26 Fatigue Resistance of Wrought Iron Plates with Open Holes
Fig. 27 Stringers of the French Broad Ivy River Bridge
Fig. 28 View of Compression Flange Showing Significant Reduction in Outstanding Legs
Fig. 29 Flange Angle Corrosion at Cross-Frame Connections
Fig. 30 Flange Angle Corrosion at Cross-Frame Connections
Fig. 31 Preexisting Crack in Compression Flange Next to Bracing Connections
Fig. 32 Fatigue Testing Setup
Fig. 33 Crack at Corroded Area of Test Beam 1
Fig. 34 Set of Cracks Developed Due to Force Redistribution in Section
Fig. 35 Surface of Crack in Corroded Area of Test Beam 1
Fig. 36  Cracked Section at Corroded Area of Test Beam 2
Fig. 37 Initial Crack in Corroded Area of Test Beam 2
Fig. 38 Corroded Area of Test Beam 3
Fig. 39 Corroded Area of Test Beam 4 with Crack Reinitiation from Drilled Holes
No Detectable Cracking in Corroded Area

Test No.

Cracking

Angle Failure

Section Failure

Fig. 40 The Fatigue Resistance of Corroded Area Details
Fig. 41 Crack in Corroded Area of Beam 4 at Top Surface
Fig. 42  Crack in Corroded Area of Beam 4 at Bottom Surface
Fig. 43 Crack Surface of Crack at Rivet Hole Running into Bottom Flange
Fig. 44 The Fatigue Resistance of the Rivet Details
Fig. 45 The Fatigue Resistance of Riveted Members
Fig. 46 Fatigue Crack in the Deteriorated Compression Flange of Test Beam 1
Fig. 47 Surface of Compression Flange Fatigue Crack
Fig. 48  Fatigue Cracked Riveted Section in Test Beam 3, After Several Reduced Temperature Tests
Fig. 49  Tube System for Liquid Nitrogen Distribution During Reduced Temperature Test
Fig. 50  Insulating Box Containing Section Cooled During Reduced Temperature Test
Fig. 51 Charpy V-Notch Characteristics of the Flange Angle
Fig. 52  Geometry of Beam Section with Cracked Rivet Detail with Crack Tip in Vertical Angle Leg
Fig. 53 Geometry of Beam Section with Cracked Rivet Detail with Crack Tip in Outstanding Angle Leg
Fig. 54 Crack Growth Rate as Function of Position of Crack Tip in Vertical Angle Leg
Fig. 55 Crack Growth Rate as a Function of Position of Crack Tip in Outstanding Angle Leg
Fig. 56 Infinite Strip Model with Half Infinite Crack

\[ K_I = \sigma \sqrt{h} \]

\[ V = \sigma h/E; \quad \tau_{12} = 0 \]
Fig. 57 Finite Width Model with Center Through Crack

\[ K_I = \sigma \sqrt{\pi a} F(a/b) \]
Fig. 58  Finite Element Mesh for Crack Tip in Vertical Angle Leg With Unbonded Area of Constant Width

128
Fig. 59 Mesh Detail - Conical Unbonded Area

Fig. 60 Mesh Detail - Unbonded Area With Constant Width
Fig. 61 Finite Element Mesh for Crack Tip in Vertical Angle Leg With Elliptical Unbonded Area
Fig. 62 Mesh Detail - Elliptical Unbonded Area

Fig. 63 Mesh Detail - Elliptical Unbonded Area
Fig. 64 Finite Element Mesh for Crack Tip in Outstanding Angle Leg
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