RESISTANCE AND LOADING FOR STEEL BRIDGE FATIGUE LIFE EVALUATION

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ABSTRACT

A fitness of purpose study lead to the conclusion that using a “Safe Life” philosophy was the most feasible way to ensure that critical details would be identified before there was serious risk of fracture.

The critical issues are:

- Interrupting trains
- Fatigue is not the issue, fatigue that leads to fracture is the issue
  - Secondary issues are cracks that cause train delays while needed inspections are carried out.
- Cannot calculate real safe life but can only estimate it
- Not structure life but estimate of a certain detail’s fatigue safe life

The paper will give a brief review of the resistance to fatigue damage followed by a review of appropriate loading criteria all within the bounds of a safe life evaluation methodology.

In very critical cases a proper load spectra and field strain measurements are necessary.

Probability of reaching calculated fatigue safe life was set at roughly 2.3% which will be shown to be consistent with other limit states.

Chapter 15 of the AREMA Manual of Recommended Practice (1) gives a number of detailed recommendations on what to do when the calculated safe life is exceeded.

The main ones are:

- Inspect details for fatigue cracks
- Good chance that since this is a fatigue safe life evaluation that cracking is yet to occur - that is why it is called safe life. Do not condemn if there are no critical cracks.
- BE SURE there are no critical cracks, inspect, inspect, inspect
- Use more sophisticated techniques if economically justified.

INTRODUCTION

Before the 1970s there was very little concern about fatigue in Railroad bridges.
In the 1970s there was a rash of failures in welded details due to fatigue that led to fracture. There was also a concern about riveted detail fatigue failures at some coal loading facilities and a number of railroad issues.

There was a need for a method of determining if a detail would be prone to fatigue failure and develop a methodology to reduce the structures of concern to a manageable size.

There was also a concern about the ability to find cracks soon enough. Figure 1 shows the concern with regard to a potentially critical rivet detail.

![Figure 1 Critical Crack at a Rivet](image)

Note that during fatigue a crack grows due to stress range but at fracture it is the maximum stress at that point that causes fracture. Assume a simple edge crack with $K = 1.12\sqrt{\pi a}$. At failure the fracture toughness was set at 40 ksi\(\sqrt{\text{in}}\) based on tests performed at that time and the maximum stress was assumed to be 0.8 $F_y$ which for $F_y = 33$ ksi is 26.4 ksi. Solving $a = 0.58$ inch, so that the visible portion of this critical crack would be $\frac{1}{4}$ inch past the rivet head. For $F_y = 30$ ksi it would be 3/8 inch past the rivet head. Cracks that small are very difficult to find.

A fitness of purpose study lead to the conclusion that using a “Safe Life” philosophy was the most feasible way to ensure that critical details would be identified before there was serious risk of fracture.

Committee 15 developed the Recommended Practice (1) that exists currently.

This paper describes how the recommendations should be applied with emphasis on riveted details.

**BASIC CONCEPT**

In theory a fatigue life evaluation is fairly simple. Get a load spectra, apply the appropriate cut-off, obtain stress ranges using influence lines, calculate an RMC (Root mean cube of stress range) and estimate when the calculated safe life has been reached. This may involve estimating future traffic. See Figure 2.
Figure 2  Estimating Fatigue Life

At this point the evaluator ideally has a 95% confidence that the detail being evaluated has a 95% chance of survival. This is often referred to as the 2.3% probability limit of “Safe Life”. Note, since it is a “Safe Life” calculation there is a good chance that there is more life remaining although the possibility of critical cracking is more likely. This is provided that the estimation is based on the most complete data possible.

The 2.3% probability limit of safe life is compared to other “Safety Factors” used in the AREMA Manual, Chapter 15-Steel Structures (1) in equations 1 to 5. The difference between the values recommended (1) for Category C (Equation 3), Category D (Equation 4), and Riveted details (equation 5) are consistent with the intended safety factors for Axial Tension, (equations 1 and 2).

Axial Tension
   Design or Normal Rating
   
   \[ 0.74F_u \ or \ 1/0.47 = 2.13 \times \ or \ 0.55F_y \ or \ 1/0.55 = 1.82 \times \]  
   \hspace{1cm} (1)

   Maximum Rating
   
   \[ 0.67F_u \ or \ 1/0.67 = 1.49 \times \ or \ 0.8F_y \ or \ 1/0.8 = 1.25 \times \]  
   \hspace{1cm} (2)

Fatigue 2.3% probability limit of safe life
   Category C:  1.3 \times \ N to mean life \hspace{1cm} (3)  
   Category D:  1.60 \times \ N to mean life \hspace{1cm} (4)  
   Rivet Tests:  1.33 \times \ N to mean life \hspace{1cm} (5)

Figure 3 shows test results for various welded stiffeners showing an upper bound on the top of the diagram, a mean value and a lower bound which is the 2.3% probability limit of safe life.
The above procedure is appropriate for welded details and any other fatigue details characterized by Categories A to E'. The Manual (1) has good resistance data on most welded details with less reliable data on pin connections and the effect of corrosion on fatigue (See articles 9.7.3.3.2.c 6 and 7) (1).

The data used in the Manual (1) to develop the “Fatigue Detail Categories” are based only on full size beam tests relevant to railroad bridges. Small scale tests used in Codes for many other structures are not used. For riveted details, tests on ¾” diameter rivets (used primarily on highway structures) were generally eliminated except for some punched hole data and some of the wrought iron beam tests due to lack of sufficient 7/8 diameter data. Failure criteria for most of the lower stress range ($\sigma_r$ below 18 ksi) riveted details were when the crack propagated into another component or when the beam could no longer carry the load (3,6,7).

Using the RMC Stress range may not be appropriate for detailed evaluations of riveted details where the slope of the 2.3 % probability limit of safe life changes with different stress ranges.

Since the most common type of steel railroad bridges is a two plate girder (DPG) riveted structure, the rest of the paper will concentrate on that type of structure to illustrate various issues with fatigue life evaluation in accordance with the AREMA Manual, Chapter 15-Steel Structures (1).

Fatigue tests were correlated to simple calculated stress ranges using $\sigma_r$=M/S as shown in figure 4a. Real structures tend to look more like figure 4b, hence real stress ranges may be less than first calculated. The Manual (1) conservatively ignores this possibility although the writer’s review of the unpublished tests results by CN indicated $\sigma_r = 0.83$ M/S as a mean value. The evaluator would have to confirm this in order to take advantage of this situation either through field testing or more sophisticated analysis on a particular structure.
Fig 4a Full Size Beam Fatigue Test (4a) and (4 b) Typical DPG

The Manual (1) suggests that if the annual gross tonnage over a structures is less than 5 Million Gross Tons that a fatigue analysis is not necessary assuming normal traffic.

Furthermore for riveted details, if the stress range at Normal Rating is equal or less than 9 ksi and the structure meets certain conditions listed in the Manual (1), then a fatigue life analysis is not necessary.

Similarly for riveted details, if the RMC stress range is equal or less than 9 ksi and the structure meets certain conditions listed in the Manual (1), then a fatigue life analysis is also not necessary.

If a fatigue life analysis is required then the first task is to obtain a load spectra.

As a quick check use the Normal Rating Cooper load or Alternate load and if the structure is OK with this loading then it meets current design criteria for its Normal rating. This is not very likely except for recently designed structures.

Using the appropriate load spectra (see figure 5) is critical. The loading applied in case “c” is far more critical than any of the others assuming similar tonnages.

Most railroads provide a list of cars with weights to their train crews and bill customers on ton-miles moved. If this data can be obtained it is relatively easy to develop a good load spectra. The problem is that most railroads do not keep the data for very long and it has to be extracted and stored in real time.
If a Load Spectra is not available, make use of the Gross ton mile data combined with train type data. A detailed example follows.

**EXAMPLE OF DEVELOPMENT OF LOAD SPECTRA**

The table 1 show estimated tonnages in million gross tons for trains composed of specific car types that the evaluator can manipulate to match the traffic on the structure being evaluated. Check with the railroad to be sure the assumptions in the table are correct for that routing.

A sample calculation for a heavy unit train is:

- 2 – 420 kip locomotives and 150 cars at 315 kips gross: 24000 tons per train
- 2 – 420 kip locomotives and 150 cars empty: 5300 tons per train
- 1 – 315 kip loaded unit train as above 365 days: 8.76 MGT/ Annum
- 1 – 315 kip empty unit train as above 365 days: 1.934 MGT/ Annum
TABLE 1 Annual Tonnage for trains composed of specific car types

<table>
<thead>
<tr>
<th>Heaviest Car kips</th>
<th>Car/train</th>
<th>Locomotive Wt. kips</th>
<th>Number Locomotives</th>
<th>Tons per train</th>
<th>Annual Tonnage MGT 365 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>315</td>
<td>150</td>
<td>420</td>
<td>2</td>
<td>24000</td>
<td>8.76</td>
</tr>
<tr>
<td>286</td>
<td>150</td>
<td>420</td>
<td>2</td>
<td>21885</td>
<td>7.988</td>
</tr>
<tr>
<td>Empty Return</td>
<td>150</td>
<td>420</td>
<td>2</td>
<td>5300</td>
<td>1.934</td>
</tr>
<tr>
<td>263</td>
<td>110</td>
<td>395</td>
<td>2</td>
<td>14860</td>
<td>5.424</td>
</tr>
<tr>
<td>Empty return</td>
<td>110</td>
<td>395</td>
<td>2</td>
<td>3860</td>
<td>1.409</td>
</tr>
<tr>
<td>Auto rack</td>
<td>95</td>
<td>395</td>
<td>2</td>
<td>9210</td>
<td>3.362</td>
</tr>
<tr>
<td>Empty return</td>
<td>95</td>
<td>395</td>
<td>2</td>
<td>2200</td>
<td>0.804</td>
</tr>
<tr>
<td>Heavy Passenger 75T</td>
<td>20</td>
<td>260</td>
<td>2</td>
<td>1760</td>
<td>0.642</td>
</tr>
<tr>
<td>Lighter Pass 75T</td>
<td>11</td>
<td>260</td>
<td>1</td>
<td>955</td>
<td>0.349</td>
</tr>
<tr>
<td>Gen Merchandise 263 k</td>
<td>75</td>
<td>395</td>
<td>2</td>
<td>10260</td>
<td>3.744</td>
</tr>
</tbody>
</table>

Given the annual tonnage on a line, combined with the various train types an estimate of the number of vehicles and weights can be made.

Line with 62 MGT and Train Data

As an example consider a line with 62 MGT per annum and the information in Table 2 that should be available from the railroad.

TABLE 2 Train Data

<table>
<thead>
<tr>
<th></th>
<th>Trains/day</th>
<th>Days operating</th>
<th>Cars/train</th>
<th>Loco/train</th>
<th>Max Car weight kips</th>
<th>Loco weight kips</th>
<th>Min Car Weight kips</th>
</tr>
</thead>
<tbody>
<tr>
<td>286 k</td>
<td>2</td>
<td>350</td>
<td>150</td>
<td>2</td>
<td>286</td>
<td>410</td>
<td>65</td>
</tr>
<tr>
<td>263 k</td>
<td>3</td>
<td>355</td>
<td>110</td>
<td>2</td>
<td>263</td>
<td>395</td>
<td>63</td>
</tr>
<tr>
<td>auto</td>
<td>1</td>
<td>310</td>
<td>95</td>
<td>2</td>
<td>220</td>
<td>395</td>
<td>46</td>
</tr>
<tr>
<td>Gen Merch 122</td>
<td>2</td>
<td>290</td>
<td>74</td>
<td>1</td>
<td>263</td>
<td>395</td>
<td>63</td>
</tr>
<tr>
<td>Gen Merch. 115</td>
<td>2</td>
<td>300</td>
<td>75</td>
<td>1</td>
<td>220</td>
<td>395</td>
<td>60</td>
</tr>
<tr>
<td>Gen Merch 67</td>
<td>10</td>
<td>345</td>
<td>74</td>
<td>1</td>
<td>144</td>
<td>395</td>
<td>44</td>
</tr>
<tr>
<td>Pass Reg.</td>
<td>2</td>
<td>345</td>
<td>20</td>
<td>2</td>
<td>150</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>Pass Summer</td>
<td>1</td>
<td>40</td>
<td>11</td>
<td>1</td>
<td>150</td>
<td>248</td>
<td></td>
</tr>
</tbody>
</table>
Combine the information in Tables 1 and 2, in Table 3.

**TABLE 3 Estimate of Number of Vehicles and Annual Train Tonnage**

<table>
<thead>
<tr>
<th></th>
<th>MGT</th>
<th>Cars</th>
<th>Empties</th>
<th>Trains/day</th>
<th>Locos</th>
</tr>
</thead>
<tbody>
<tr>
<td>286 k 2 per day</td>
<td>15.302</td>
<td>105000</td>
<td></td>
<td>2</td>
<td>1400</td>
</tr>
<tr>
<td>263k 3 per day</td>
<td>15.826</td>
<td>117150</td>
<td></td>
<td>3</td>
<td>2130</td>
</tr>
<tr>
<td>Auto 1 per day</td>
<td>3.362</td>
<td>29450</td>
<td></td>
<td>1</td>
<td>620</td>
</tr>
<tr>
<td>Empty 286 k</td>
<td>3.700</td>
<td>105000</td>
<td></td>
<td>2</td>
<td>1400</td>
</tr>
<tr>
<td>Empty 263 k</td>
<td>4.111</td>
<td>117150</td>
<td></td>
<td>3</td>
<td>2130</td>
</tr>
<tr>
<td>Empty auto</td>
<td>0.800</td>
<td>29450</td>
<td></td>
<td>1</td>
<td>620</td>
</tr>
<tr>
<td>Loco Gen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gen 122</td>
<td>2.879</td>
<td>21460</td>
<td>21460</td>
<td>2</td>
<td>580</td>
</tr>
<tr>
<td>Gen 115</td>
<td>2.534</td>
<td>22500</td>
<td>22500</td>
<td>2</td>
<td>600</td>
</tr>
<tr>
<td>Pass Hwy.</td>
<td>1.2144</td>
<td>13800</td>
<td></td>
<td>2</td>
<td>1380</td>
</tr>
<tr>
<td>Pass Summer</td>
<td>0.038</td>
<td>440</td>
<td></td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>Gen 67</td>
<td>11.874</td>
<td>127650</td>
<td>127650</td>
<td>10</td>
<td>3450</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td>61.6</td>
<td>437450</td>
<td>432210</td>
<td>29</td>
<td>14350</td>
</tr>
</tbody>
</table>

In the first attempt, the writer obtained 73 MGT assuming all trains loaded. The writer then assumed that the unit trains would be fully loaded, as would the auto trains. The General merchandise trains Gen 122, and Gen 115 were assumed to carry half the possible tonnage and Gen 67 to carry 2/3 of the tonnage but in half the cars. These assumptions made the result come close to the known tonnage of 62 MGT/Annum.

A sample calculation for the Passenger heavy is \(0.6424\) (from Table 1) \(\times\) 2 (trains) \(\times\) 345 (days from Table 2)/365 days = 1.2144 MGT.

The next step is to apply the information in Table 3 to obtain the number of cycles of loading for each vehicle type.

**Apply to a Specific Bridge**

To illustrate this process consider a 60 foot open deck DPG, Normal rating E 60, \(F_y = 33\) ksi, dead load 0.65 Kips per lineal foot (klf), 7:c/c Girders, Section Modulus 2096 in\(^3\).

Impact for fatigue (1) is \(0.35 \times (40-3 \times 60^2/1600 + 100/7) = 16.6\%\). (7)

From Table 1.15.1, Chapter 15 (1) Moment for E 80 is 2597.8 kip ft / rail.

For E 60, Stress range is \(M/S = (2597.8 \times (60/80) \times 12/2096) \times 1.166 = 13\) ksi. (8)

Since this exceeds 9 ksi a further analysis is recommended to see if the RMC from a load spectra would be less than or equal 9 ksi.
The 286 kip cars in this example have about 2/3 of a cycle per car (See figure 6) and a 93’10 auto rack has one cycle per car. The number of cycles for each vehicle can be derived from influence lines. Two examples of Moment on a 60 foot span are shown in Figure 6.

Figure 6a and b Influence Lines for 58’6 Coal Car (a) and 93’10 Auto Carrying Car (b)

Apply the information from Table 3 to estimate the Root mean cube stress range as shown in Table 4. For rivets, stress ranges below 6 ksi are not counted. The number of cycles are for particular car types and may not be representative of other cars in the same weight classes. The reader would need to develop influence lines for the car types actually in operation over a certain structure.

TABLE 4 Estimate of RMC Stress Range

<table>
<thead>
<tr>
<th>Car Category</th>
<th>Cars</th>
<th>Cycles n</th>
<th>Avg wt. kips</th>
<th>Length Ft.</th>
<th>Avg. Cooper E</th>
<th>$\sigma_r$ E 60 = 13 ksi</th>
<th>$N(\sigma_r)^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empties 432210</td>
<td>432210</td>
<td>31</td>
<td>11.4</td>
<td>2.47</td>
<td>&lt; 6 ksi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gen67 127650</td>
<td>127650</td>
<td>42126</td>
<td>144</td>
<td>34’5</td>
<td>6.08</td>
<td>9468056</td>
<td></td>
</tr>
<tr>
<td>Auto 29450</td>
<td>29450</td>
<td>220</td>
<td>93’10</td>
<td>5.9</td>
<td>&lt; 6 ksi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gen115 22500</td>
<td>22500</td>
<td>7425</td>
<td>220</td>
<td>43’10</td>
<td>8.99</td>
<td>5394835</td>
<td></td>
</tr>
<tr>
<td>Gen 122 21460</td>
<td>21460</td>
<td>7082</td>
<td>263</td>
<td>9.58</td>
<td>6226489</td>
<td></td>
<td></td>
</tr>
<tr>
<td>263k unit train cars 117150</td>
<td>117150</td>
<td>78490</td>
<td>263</td>
<td>9.61</td>
<td>69660549</td>
<td></td>
<td></td>
</tr>
<tr>
<td>286 k unit train cars 105000</td>
<td>105000</td>
<td>70350</td>
<td>286</td>
<td>10.13</td>
<td>73129162</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pass Cars 14240</td>
<td>14240</td>
<td>12530</td>
<td>150</td>
<td>32.1</td>
<td>6.96</td>
<td>4224534</td>
<td></td>
</tr>
<tr>
<td>Summer pass locos</td>
<td>40</td>
<td>20</td>
<td>248</td>
<td>37.0</td>
<td>8.02</td>
<td>10317</td>
<td></td>
</tr>
<tr>
<td>Hvy. Pass Locos 1380</td>
<td>1380</td>
<td>700</td>
<td>260</td>
<td>39.5</td>
<td>8.56</td>
<td>439055</td>
<td></td>
</tr>
<tr>
<td>263 train and less locos 11530</td>
<td>11530</td>
<td>7690</td>
<td>395</td>
<td>49.7</td>
<td>10.76</td>
<td>9579948</td>
<td></td>
</tr>
<tr>
<td>286 train locos 2800</td>
<td>2800</td>
<td>1867</td>
<td>410</td>
<td>51.6</td>
<td>11.16</td>
<td>2601515</td>
<td></td>
</tr>
</tbody>
</table>

| Sum cycles n = 228280 | Sum $N(\sigma_r)^3$ | $1.8 \times 10^8$ |
RMC $\sigma_r = (1.8 \times 10^9/228280)^{1/3} = 9.25$ ksi with 228280 cycles. Very close to 9 ksi. \hspace{1cm} (9)

Using the actual load spectra (see table 5) of loading over this bridge generated by the railroad using a procedure similar to that already illustrated gave, RMC $\sigma_r = 8.99$ ksi with 302662 cycles, in which case since it is less than 9 ksi, no further analysis is recommended.

Table 5 Actual Data for That Location vs. Estimated

<table>
<thead>
<tr>
<th>From tons</th>
<th>To tons</th>
<th>Actual No. Locos</th>
<th>Actual No. cars</th>
<th>Actual Avg. tons/car</th>
<th>Estimated Locos</th>
<th>Estimated Cars</th>
<th>Estimated Avg. tons/car</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>39</td>
<td>0</td>
<td>416880</td>
<td>31</td>
<td>0</td>
<td>432210</td>
<td>31</td>
</tr>
<tr>
<td>40</td>
<td>99</td>
<td>42</td>
<td>270254</td>
<td>67</td>
<td>0</td>
<td>141890</td>
<td>72</td>
</tr>
<tr>
<td>100</td>
<td>109</td>
<td>0</td>
<td>31626</td>
<td>106</td>
<td>0</td>
<td>29240</td>
<td>110</td>
</tr>
<tr>
<td>110</td>
<td>119</td>
<td>0</td>
<td>45227</td>
<td>115</td>
<td>0</td>
<td>22500</td>
<td>110</td>
</tr>
<tr>
<td>120</td>
<td>124</td>
<td>54</td>
<td>42830</td>
<td>122</td>
<td>40</td>
<td>21460</td>
<td>131</td>
</tr>
<tr>
<td>125</td>
<td>130</td>
<td>691</td>
<td>123021</td>
<td>128</td>
<td>1380</td>
<td>117150</td>
<td>131</td>
</tr>
<tr>
<td>131</td>
<td>142</td>
<td>20847</td>
<td>105690</td>
<td>135</td>
<td>12930</td>
<td>105000</td>
<td>143</td>
</tr>
</tbody>
</table>

Even though the estimated values are different than the actual reported values as shown in table 5, the effect of estimation errors on lighter vehicles is not as significant as those on the higher stress ranges. It is important to get the higher stress range data as close to actual as possible.

But even having the “exact load Spectra” and appropriate number of cycles still only gives an estimate.

To obtain a much better estimate, if it is needed, would require some field testing to determine actual stress ranges that are generally less than calculated and to determine an impact factor unique to the structure that most often will be less than that given in Table 15-1-8 of Chapter 15 (1). Figure 7 shows the result of analysis on AREMA Impact factors (5). The values recommended in Chapter 15 (7), Table 15-1-8 for fatigue are the 2.3 % probability of occurrence based on tests of 100 bridges but a particular structure might have less impact.

![Figure 7 Typical Impact Distribution on Steel Railroad Bridges Various Speeds (5)](image)

**Analysis Of Riveted Detail due to variable Slope of Stress Range – Cycle Diagram**

The Manual focuses on using the RMC Stress Range for all details and for riveted details to determine if any analysis can be waived if the RMC is below 9 ksi but if it isn’t then using the RMC may not be correct.
A sample calculation of how to apply the equations in the Manual Figure 15-9-10 (1) (See Figure 10) is shown in Table 6 based on the estimate made in Table 4.

![Fatigue Data](image)

**Figure 8** Fatigue Data used in The Manual (1) for Riveted Connections with Drilled Holes

**Table 6 Calculation due to Variable slopes in Figure 8**

<table>
<thead>
<tr>
<th>Stress ranges from Table 4</th>
<th>n from table 4</th>
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Sum 0.07613 n/N (10)

The damage per annum for the given load spectrum is 0.07613 and assuming the load spectrum is constant over time there is 1/0.07613 = 13 years of safe life. What this means is that there was a 2.3% chance of a serious fatigue crack but not a guarantee of one as it is safe life.

It is time to ensure the structure detail of concern is clean enough to inspect and then inspect to be sure cracking is yet to occur.

Using RMC = 8.99 ksi gives 0.049452 or 20 years of safe life which would not be correct.

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Note, in the above example it was already established that a fatigue analysis could be waived as the RMC Stress Range was below 9 ksi based on the actual railroad generated load Spectrum.

**FITNESS OF PURPOSE**

For riveted Structures the failure criteria used is roughly the 2.3% probability of fracture based on the assumption that the crack propagates to another element. The concern is whether after a fatigue life calculation shows the Safe Life is exhausted is the structure still fit for service. With good inspection it is likely to be fit for future service.

For the tests done for CN at Lehigh University (3) and the University of Alberta (6,7), the range of N at failure at a stress range of 7.8 ksi varied from 13.6 to 50.3 million cycles with a mean of 30.5 million cycles. Cautious engineering judgement needs to be exercised especially if the calculated stress ranges and cycles were not based on testing.

The AREMA Manual of Recommended Practice Chapter 15 (1) gives a number of detailed recommendations on what to do when the calculated safe life is exceeded.

- Inspect details for fatigue cracks
- Good chance that since this is a fatigue safe life evaluation that cracking is yet to occur - that is why it is called safe life. Do not condemn if there are no critical cracks.
- “BE SURE” there are no critical cracks, inspect, inspect, inspect on structures clean enough to see cracks
- Use more sophisticated techniques if economically justified.

Remember that Maximum Rating ignores fatigue.

**SUMMARY**

It is important to use:

- The right cars and locomotive for that loaded length,
- The correct number of cycles for each vehicle and weight,
- Proper load spectra (Easy if collected in real time)
- Real strains and measured impacts are needed to get the most realistic estimates
- Do not spend more on analysis or testing than a repair or retrofit would cost.

**FUTURE**

Currently there is not enough load or action information to develop a proper probability evaluation protocol. There is also a problem with compounding Probabilities such as:

- 2.3% on resistance side, perhaps over estimates on Live Load side
- 2.3% on fatigue impact
- Actual vs. Estimated stress range (0.83)
- Temperature- toughness effects (Less chance of fracture when it is very hot)
- Ability to find Ni crack reliably or what can be found reliably?
• From that develop safe inspection interval after some appropriate calculated N. The writer would recommend using when the Safe Life according to the Manual (1) has been reached.

• Pin Connections and serious corrosion

• Need more data to develop a proper partial probability evaluation protocol?

Although it is perhaps time for a new enhanced protocol sufficient data is not yet available.

CONCLUSIONS

• Current protocol, if properly applied is a good screening tool for problem structure details

• But only an estimate

• Good engineering judgement and

• thorough inspections are a must

ACKNOWLEDGEMENTS

CN who paid for most of the relevant rivet stress range testing and the testing of over 100 of their Railroad bridges.

The Faculty and Students at Lehigh and Alberta Universities and other institutions that contributed to the knowledge base. In particular, Professors John W Fisher and Geoff Kulak and Researcher Yi (Ed) Zhou.

REFERENCES

1 Manual of Recommended Practice, Chapter 15, Steel Structures, 2015, AREMA, Washington, DC.


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2 Estimating Fatigue Life
3 Typical Upper Bound, Mean and Lower bound Stress Range to Cycles
4 Full Size Beam Fatigue Test (4a) and (4 b) Typical DPG
5 Various axle Load (kips) Spectra with Similar Annual Tonnages
6 Influence Lines for 58'6 Coal Car (a) and 93’10 Auto Carrying Car (b)
7 Typical Impact Distribution on Steel Railroad Bridges Various Speeds
8 Fatigue Data used in The Manual (1) for Riveted Connections with Drilled Holes

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2 Train Data
3 Estimate of Number of Vehicles and Annual Train Tonnage
4 Estimate of RMC Stress Range
5 Actual Data for That Location
6 Calculation due to Variable slopes in Figure 8.
RESISTANCE AND LOADING FOR STEEL BRIDGE FATIGUE LIFE EVALUATION

Robert A.P. Sweeney, Ph'd, D. Eng., P.Eng., Hon. Mbr. AREMA
Fitness of Purpose Study

Safe Life philosophy was the most feasible way to ensure that critical details would be identified before there was serious risk of fracture.

Critical Issues

- Interrupting trains
- Fatigue is not the issue, Fatigue that leads to fracture is the issue
  - Secondary issues are cracks that cause train delays while needed inspections are carried out.
- Cannot calculate real safe life but can only estimate it
- Not structure life but estimate of a certain detail’s fatigue safe life

What To Do When the Calculated Safe Life is Exceeded.

- Inspect details for fatigue cracks
- Good chance that since this is a fatigue safe life evaluation that cracking is yet to occur - that is why it is called safe life. Do not condemn if there are no critical cracks.
- BE SURE there are no critical cracks, inspect very thoroughly.
- Use more sophisticated techniques if economically justified.

When Fatigue Became a problem

- In the 1970s there was a rash of failures in welded details due to fatigue that led to fracture.
- There was also a concern about riveted detail fatigue failures at some coal loading facilities and a number of railroad issues

Critical Crack at a Rivet $K = 1.12\sigma\sqrt{\pi a}$

- Fatigue cracks grow with stress range
- Fracture occurs due to Maximum Stress at Material Fracture Toughness
- Solve for $a$, leaves only: $3/8$" visible for $\sigma = 0.8 \times 30$ ksi & $\frac{1}{4}$" visible for $\sigma = 0.8 \times 33$ ksi

fatigue life evaluation is fairly simple

Easy in Theory

- Get a load spectra, 
  - apply the appropriate cut-off,
- obtain stress ranges using influence lines,
- calculate an RMC (Root mean cube of stress range) except rivets and
- estimate when the calculated Safe life has been reached.
  - This may involve estimating future traffic.

Example
AREMA Chapter 15 Fatigue Limits

- At this point the evaluator ideally has a 95% confidence that the detail being evaluated has a 95% chance of survival.
  - This is often referred to as the 2.3% probability limit of Safe Life.
  - This is provided that the estimation is based on the most complete data possible.

Compare to Other AREMA Limits

- Axial Tension
  - Design or Normal Rating: $0.74F_u$ or $1/0.47 = 2.13X$ or $0.55F_y$ or $1/0.55 = 1.82X$
  - Maximum Rating: $0.67F_u$ or $1/0.67 = 1.49X$ or $0.8F_y$ or $1/0.8 = 1.25X$

- Fatigue 2.3% probability limit of safe life
  - Category C: $1.3X$ N to mean life
  - Category D: $1.60X$ N to mean life
  - Rivet Tests: $1.33X$ N to mean life

Typical Upper Bound, Mean and Lower bound Stress Range to Cycles

Data Used in AREMA Chapter 15

- Based only on full size beam tests relevant to railroad bridges.
  - Small scale tests used in Codes for many other structures are not used.
  - For riveted details $\frac{3}{8}$" diameter rivet tests were generally eliminated except for some punched hole data and some of the wrought iron beam tests.
- Failure criteria for most of the lower stress range (below 18 ksi) riveted details were when the crack propagated into another component or when the beam could no longer carry the load.

Full Size Beam Fatigue Test and Typical DPG

Fatigue Analysis is Not Necessary

- Less than 5 Million Gross tons assuming normal traffic.
- Furthermore for riveted details
  - if the stress range at Normal Rating is equal or less than 9 ksi and the structure meets certain conditions listed in the Manual
  - if the RMC stress range is equal or less than 9 ksi and the structure meets certain conditions listed in the Manual.
First Obtain Load Spectra

Axle Loads kips

AREMA 2015 Annual Conference
Minneapolis, MN | October 4-7, 2015

First Obtain Load Spectra

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Ideal Load Spectra

- Most railroads provide a list of cars with weights to their train crews and bill customers on ton-miles moved.
- If this data can be obtained it is relatively easy to develop a good load spectra.
  - The problem is that most railroads do not keep the data for very long and it has to have been extracted and stored in real time.

Load Spectra not available

- Estimate Load Spectra
- Use Railroad Gross ton mile data
- combined with train type data
- Next Slides show example for a line with 62 MGT

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Minneapolis, MN | October 4-7, 2015

Typical Annual Data for typical trains with specific car types

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<th>Max. Weight</th>
<th>Min. Weight</th>
<th>Loco weight</th>
<th>Max. Loco</th>
<th>Max. Car/Train</th>
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Apply to 60 Foot Open Deck DPG

- Normal rating E 60, $F_r = 33$ ksi, dead load 0.65 Kips per lineal foot (klf), 7’c/c Girders, Section Modulus 2096 in³.
- Impact for fatigue is $0.35 \times (40-3 \times 60^{2/1600} + 100/7) = 16.6 \%$.
- Moment for E 80 is 2597.8 kip ft / rail.
- For E 60, Stress range is $M/S = (2597.8 \times (60/80) \times \frac{12}{2096}) \times 1.166 = 13$ ksi $> 9$ ksi.

Example Influence Lines for Two Cars

2/3 cycles per car Coal Gon.
1 cycle per car auto rack

Estimate of Load Spectra

- Using the actual load spectra of loading over this bridge generated by the railroad, RMC $\sigma_r = 8.99$ ksi with 302662 cycles, in which case since it is less than 9 ksi, no further analysis is recommended.
- Our Estimate $\sigma_r = 9.25$ ksi, but 228 280 Cycles – Even though the values estimated are different than the actual data the effect of estimation errors on lighter vehicles is not as significant as those on the higher stress ranges.
- It is important to get the higher stress range data as close to actual as possible.

To get a much better estimate

- field testing to determine actual stress ranges
  - that are generally less than calculated and
- determine an impact factor unique to the structure
  - that most often will be less than that given in Table 15-1-8 of Chapter 15.

Analysis of Variable Slope of Stress Range – Cycle Diagram

Fatigue impact based on 2.3% probability
**RMC vs. n/N**

- The damage per annum for the given load spectrum is 0.07613 and assuming the load spectrum is constant over time there is $\frac{1}{0.07613} = 13$ years of safe life.
  - What this means is that there was a 2.3% chance of a serious fatigue crack but not a guarantee of one as it is safe life.
  - It is time to ensure the structure detail of concern is clean enough to inspect and then inspect to be sure cracking is yet to occur.
- Using RMC = 8.99 ksi gives 0.049452 or 20 years of safe life which **would not be correct**.
  - Note, in the above example it was already established that a fatigue analysis could be waived as the RMC Stress Range was below 9 ksi based on the actual railroad generated load Spectrum.

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  - The correct number of cycles for each vehicle and weight,
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  - Do not spend more on analysis or testing than a repair or retrofit would cost.

**FUTURE: Need to Deal with**

- 2.3% on resistance side, perhaps over estimates on Live Load side
- 2.3% probability for impact,
- Actual vs. Estimated stress range (0.83 ?)
- Temperature- toughness effects (Less chance of fracture when it is very hot)
- More data for Pin Connections and serious corrosion

**Future Finding Cracks Reliably**

- Ability to find crack reliably or what can be found reliably?
- From that develop safe inspection interval after some appropriate calculated N.
  - The writer would recommend N be when the Safe Life according to the Manual (?) has been reached.
- Need more data to develop a proper partial probability evaluation protocol?
  - Although it is perhaps time for a new enhanced protocol, sufficient data is not yet available.

**CONCLUSIONS**

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- But only an estimate
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• Modjeski & Masters for Support to attend this Conference.