APPLICATION OF LEF APPROACH IN THE CERTIFICATION OF AERONAUTICAL COMPOSITE STRUCTURES

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ABSTRACT

This paper presents a series of coupon-level fatigue tests on a novel composite system. Based on Joint Weibull estimation, scatter analysis is conducted on both fatigue life and residual strength to obtain shape parameters for different design details. Weibull distribution is applied to estimate the life shape parameter \( L \) and strength shape parameter \( R \) which describe the overall scatter performance of fatigue and static property. LEF is computed using \( \alpha_L \) and \( \alpha_R \) and is compared with conventional LEF values.

1 INTRODUCTION

During the latest 30 years, composite materials have been increasingly applied in advanced aeronautical structures due to their high strength/weight and stiffness/weight ratios, excellent fatigue and anti-corrosion performance, etc. However, compared to traditional metal counterparts, the certification of composite structures is more challenging due to the multiple damage forms and complex interaction mechanism of composite materials. As lacking of reliable analytical methods for fatigue and damage tolerance (F&DT), the certification of composite structures is currently heavily dependent on experiment. In addition, composite materials exhibit generally a much higher fatigue scatter, which leads to the demand of large amount of fatigue tests to achieve the same desired level of reliability in comparison to metals, Fig. 1.

![Typical fatigue behaviors: composites vs. metals](image)

Figure 1: Typical fatigue behaviors: composites vs. metals [1].

In the aeronautical industry, building block approach is commonly used for F&DT certification of composite airframe structure. In order to reduce the time and cost in full-scale component substantiation, the Load Enhancement Factor (LEF) approach, originally proposed by Whitehead [2], is used to interpret the data variability in lower levels (coupons, elements) of the building block testing
and translate the statistical significance into full-scale test substantiation under repeated load to achieve a desired reliability with one test article only, fig.2.

![Figure 2](image)

**Figure 2** a) Building block approach, b) SN curves for notched coupons

Fig.3 shows an illustrative graph of fatigue load vs. fatigue life for full-scale composite structures. In order to demonstrate desired Design Service Goal (DSG) under design maximum fatigue load, the fatigue testing load or/and the test duration should be adjusted to achieve B-basis reliability based on the scatter analysis results from coupon-level fatigue tests.

![Figure 3](image)

**Figure 3** Illustration of fatigue load vs. fatigue life for full-scale composite structures

This paper presents a series of coupon-level fatigue tests on a novel composite system. The selection of fatigue tests is based on different design details considered critical in the stress analysis of the composite structure. The generation of LEF follows the flow chart shown in fig.4. First, a scatter analysis based on Joint Weibull estimation is conducted on both fatigue life and residual strength to obtain shape parameters for different design details. Weibull distribution is applied to estimate the life shape parameter $\alpha_L$ and strength shape parameter $\alpha_R$. Based on $\alpha_L$ and $\alpha_R$ LEF is computed and then ready to be applied to the truncated full scale testing load spectrum.
Figure 4 Flow chart for generation of LEF [3]

2 TEST MATRIX

The definition of the LEF is based on the results of the coupon-level testing. All the applicable critical design detail, layups, R-Ratio and expected failure mode of the structure should be tested. In this work, test matrix includes Open Hole tension-Compression (OHC), Filled Hole tension-Compression (FHC) and Compression After Impact (CAI). In addition, different load ratios, lay-ups, damage during operation (BVID, VID) and environmental effects are also taken into account in the test matrix, see table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>No. of specimens</th>
<th>Code</th>
<th>Lay-up</th>
<th>Load ratio</th>
<th>Test environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27</td>
<td>OHC</td>
<td>A03</td>
<td>R= -1</td>
<td>RTD</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>OHC</td>
<td>A03</td>
<td>R= -1</td>
<td>RTW</td>
</tr>
<tr>
<td>3</td>
<td>27</td>
<td>OHC</td>
<td>B03</td>
<td>R= -1</td>
<td>RTD</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>OHC</td>
<td>C02</td>
<td>R= -1</td>
<td>RTD</td>
</tr>
<tr>
<td>5</td>
<td>27</td>
<td>FHC</td>
<td>A03</td>
<td>R= -1</td>
<td>RTD</td>
</tr>
<tr>
<td>6</td>
<td>27</td>
<td>FHC</td>
<td>A03</td>
<td>R= -1</td>
<td>RTW</td>
</tr>
<tr>
<td>7</td>
<td>27</td>
<td>FHC</td>
<td>B03</td>
<td>R= -1</td>
<td>RTD</td>
</tr>
<tr>
<td>8</td>
<td>27</td>
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<td>R= -1</td>
<td>RTD</td>
</tr>
<tr>
<td>9</td>
<td>27</td>
<td>CAI</td>
<td>A03</td>
<td>R= 10</td>
<td>RTD</td>
</tr>
<tr>
<td>10</td>
<td>27</td>
<td>CAI</td>
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<td>R= 10</td>
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<td>11</td>
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<td>RTD</td>
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<tr>
<td>12</td>
<td>27</td>
<td>CAI</td>
<td>C02</td>
<td>R= 10</td>
<td>RTD</td>
</tr>
</tbody>
</table>

Table 1: Coupon-level fatigue test matrix.

According to CMH17, the following guidelines should be considered in the test matrix in support of the LEF computation:

- Specimens should be fabricated from a minimum of three distinctive material batches.
- A minimum of three fatigue load levels should be included for one SN curve.
- A minimum of 6 datasets for residual strength should be included in the strength scatter analysis for generating the strength shape parameter $\alpha_R$.
- A minimum of 6 datasets for fatigue life should be included (at least 6 Weibull Life shape parameters) in the fatigue-life scatter analysis for generating the life shape parameter $\alpha_L$. 

3 SCATTER ANALYSIS

To reduce cost and test duration while maintaining the required reliability of data, it is recommended that the fatigue scatter analysis should be conducted using pooling methods such as the joint Weibull method. Weibull distribution is used in statistical analysis of composites, especially for small samples, due to its simple functionality and ease of interpretation. The shape parameters for life and residual strength are derived respectively using eq.1 and eq.2.

\[
\sum_{i=1}^{M} \left( n_i \beta_i \left[ \frac{\sum_{j=1}^{n_i} x_{ij}^{\hat{a}_i} \ln(x_{ij})}{\sum_{j=1}^{n_i} x_{ij}^{\hat{a}_i}} - \frac{1}{\tilde{a}_i} \sum_{j=1}^{n_i} \ln(x_{ij}) \right] \right) = 0
\]

Where:
- \(X_{ij}\): is the number of fatigue cycles to reach failure or run-out condition for the jth coupon of the ith group
- \(\hat{a}_i\): shape parameter estimate for fatigue data
- \(n_{fi}\): number of coupons reaching failure
- \(n_i\): number of coupon in the ith group
- \(M\): total number of stress levels (groups)

\[
\sum_{i=1}^{M} \left( n_i \beta_i \left[ \frac{\sum_{j=1}^{n_i} x_{ij}^{\hat{a}_i} \ln(x_{ij})}{\sum_{j=1}^{n_i} x_{ij}^{\hat{a}_i}} - \frac{1}{\tilde{a}_i} \sum_{j=1}^{n_i} \ln(x_{ij}) \right] \right) = 0
\]

Where:
- \(X_{ij}\): is the each coupon residual strength
- \(\hat{a}_i\): shape parameter estimate for strength data
- \(n_{fi}\): number of coupons undergoing residual strength
- \(n_i\): number of coupon in the ith group
- \(M\): total number of stress levels (groups)

The weibull distribution for life and strength shape parameters is estimated based on \(\hat{a}_L\) and \(\hat{a}_R\) obtained previously. The modal and mean value of \(\hat{a}_L\) and \(\hat{a}_R\) distribution represent in some degree the typical scatter properties of the material system, with modal values being more conservative values noted as \(\alpha_L\) and \(\alpha_R\), fig.5.
In-house code FATools are developed to conduct scatter analysis presented hereby for composite fatigue life and static strength based on Weibull distribution. It generates A/B basis SN curves with a data diagnostics function which ensures certification requirements are met for a valid analysis, fig. 6.

**4 LEF COMPUTATION**

Based on $\alpha_L$ and $\alpha_R$ obtained in the previous section, the computation of LEF is straight forward by using eq.3.

\[
\text{LEF} = \left( \frac{N_F}{N} \right)^{\alpha_R/\alpha_L} \\
N_F = \left[ \frac{\Gamma \left( \frac{\alpha_L+1}{\alpha_L} \right)}{\chi^2(p/2n/2n)} \right]^{\alpha_L/\alpha_R}
\]

(3)

Where:

- $N_F$ is the resulting life factor for LEF=1
- $\alpha_L$ = life shape parameter (modal life shape parameter )
- $\alpha_R$ = strength shape parameter (modal strength shape parameter )
- $p$=survival probability (90% reliability for B-basic value)
- $\gamma$=confidence (95% for B-basic value)
- $N$=test duration coefficient (N = Life Factor when LEF = 1)
- $n$=number of test articles
According to eq.3, given the reliability and confidence, the LEF on single full-scale structure testing remains also function of test duration. For illustrative purpose, using conventional values of obtained by Whitehead[2] where $\alpha_L = 1.25$ and $\alpha_R = 20$, fatigue load on full-scale structure testing should be enhanced to 1.17 times the design fatigue load to reach B basis reliability if test duration is limited to 1 design life time.

![LEF vs. test duration](image)

Figure.7 LEF vs. test duration

Fig.7 shows a comparison of LEF obtained in this study and the conventional values obtained by Whitehead[2]. For both results, load enhancement decreases as test duration is prolonged. At N=1 DSG, fatigue testing load should be increased by around 15% (17% for Whitehead[2]) of maximum design fatigue load for the material system studied in this paper. At N=2 DSGs, load enhancement is a comparable. When test duration exceeds 2 DSGs, LEF for Whitehead[2] is smaller.

5 CONCLUSION

This paper presented a series of coupon-level fatigue tests on a novel composite system. Scatter analysis based on Joint Weibull estimation is conducted on both fatigue life and residual strength to obtain shape parameters for different design details. Weibull distribution is applied to estimate the life shape parameter $\alpha_L$ and strength shape parameter $\alpha_R$. Based on $\alpha_L$ and $\alpha_R$, LEF is computed.

Compared to LEF obtained by Whitehead[2], it is worth noting that for test duration shorter than 2 DSGs (most commonly used test duration is 1DSG or 1.5DSG), LEF presented in this paper is smaller than conventional LEF, which lessens the severity of load enhancement and facilitates the application of fatigue test load.
REFERENCES

