A fatigue design methodology for GRP composites in offshore underwater applications

Dr P. A. FRIEZE

P A F A Consulting Engineers Limited, Hampton, Middx, UK
INTRODUCTION

Norsk Hydro Troll C field - floating production facility - 42 risers

Risers are supported by two 80 m high underwater jackets, in 340 m water depth

Each riser has its own support tray atop a jacket - R.A.T.

To reduce tray weight and installation time/cost, GRP used (E-glass with isophthalic polyester resin)

Trays classified to NPD as safety critical and inaccessible (for inspection and maintenance) - fatigue life safety factor = 10

Thus 250-year fatigue design life for 25 year service life.
INTRODUCTION (cont.)

At the time, no formal offshore fatigue requirements existed for composite offshore structures.

A two-staged approach to develop appropriate fatigue design criteria eventuated.

This presentation concentrates on the first in which basic GRP fatigue failure mechanisms drive the process.

The second stage exploits reasonably extensive data determined for another application, and is briefly discussed.
STAGE 1 - Basic Phenomena

Background

Read and Shenoi - Palmgrem-Miner rule is a reasonable basis for predicting the life of composite materials although it can be unconservative.

Curtis - ideal life estimation technique is one that enables the prediction of fatigue life and residual strength from a minimum amount of data, such as static strength and fatigue data on a small number of laminates.

Enables fatigue life prediction to be made for various laminate lay-ups and loading modes through extrapolation.
Stress Range

For steel structures, only dynamic stress range of importance

For GRP, long-term level of static loading also damages laminates

This damage acts as stress-raisers and contributes to fatigue development

Thus, stress variation important as well as average long-term stress

Catered for by stress ratio $R$, the ratio of minimum to maximum stress; a minus sign denotes compression

$R = -1$ represents equal compression and tension

$R = 0.1$ defines tension (or compression) with a minimum value near zero.
Two equations used to determine stress range from the ULS analysis results:

FLS stress range = ULS stress x (Max. Tension/ULS Riser Tension) \hspace{1cm} (1a)

Applies to R.A.T. locations dominated by riser forces

At supports, stress is result of overall R.A.T. action

Stresses alternate as tension oscillates about the long-term average, thus

FLS stress amp. = ULS stress x (Max. tens. – mean)/(ULS Riser Tension) \hspace{1cm} (1b)

Mean is 60 kN - see text and Table 1

Use maximum of (1a) or 2 x (1b)

D from Palmgren-Miner summation - Fatigue life = 25/D
S-N Curve

Outside aerospace industry, composites generally designed for static loading

High cycle fatigue data limited because of time involved

Fatigue tests are normally conducted up to $10^6$ cycles or, at most, up to $10^7$

Here, for life of 250 years, number of cycles is $10 \times 1.096 \times 10^8 = 1.096 \times 10^9$ (Table 1), i.e., two orders of magnitude longer than most test data

Care is required when extrapolating beyond $10^7$ cycles

Here, loading at supports is reversible so test data should also relate to fully reversed loading, i.e., $R = -1$
S-N Curve (cont.)

At high cycles, is there an endurance limit?

Issue complicated as most tests conducted under constant amplitude loading

Real sea conditions demand variable amplitude loading

Variable loading can eliminate the endurance limit or change the slope of the S-N curve beyond the endurance limit

At worst, no change of slope occurs for cycling beyond the endurance limit
S-N Curve (cont.)

Angle of loading relative to the ply direction important

Summary of the effects of off-axis loading and ply make-up, uni-directional (UD), cross-plies, or angle-plies - Talreja

R.A.T. laminates mainly comprise quadraxial plies interlaced with UD plies

For UD$s$ loaded parallel to the fibres ($0^\circ$), Talreja identifies three fatigue failure mechanisms:

- composite fracture strain $\varepsilon_c$ corresponding to fibre breakage and resulting interfacial debonding
- matrix cracking and interfacial shear failure
- fatigue limit of the resin $\varepsilon_m$ that represents the lower bound of fatigue failure
S-N Curve (cont.)

For UD laminates loaded at 90°, transverse fibre debonding ($\varepsilon_{db}$) occurs.

Between 0 and 90°, fatigue failure mechanisms vary from $\varepsilon_m$ at 0° to $\varepsilon_{db}$ at 90°.

The transition occurs rapidly with angle as seen in Figure 1.
Figure 1. Effects on fatigue limits of off-axis loading and angle between plies.

UD glass epoxy, off-axis loading

angle-plied glass epoxy

\( \varepsilon_{db} \) (\( = \varepsilon_m \))
S-N Curve (cont.)

For cross-ply (ie, biaxial) laminates loaded parallel to one fibre, debonding initiates failure

However, because the orthogonal plies arrest the debonding cracks, delamination ($\varepsilon_{dl}$) controls failure

Strain to cause delamination ($\varepsilon_{dl}$) is smaller than the fatigue limit of resin ($\varepsilon_m$) but greater than the debonding strain ($\varepsilon_{db}$)
Table 2. Typical values for glass-epoxy failure strain

<table>
<thead>
<tr>
<th>Failure Mechanism</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin fatigue limit $\varepsilon_m$</td>
<td>0.0060</td>
</tr>
<tr>
<td>Delamination $\varepsilon_{dl}$</td>
<td>0.0043</td>
</tr>
<tr>
<td>Transverse fibre debonding $\varepsilon_{db}$</td>
<td>0.0010</td>
</tr>
</tbody>
</table>
S-N Curve (cont.)

Thus, delamination strain in biaxial laminates is a function of loading axis.

Delamination strain is also a function of the angle between the fibre directions as demonstrated by the fatigue behaviour of cross-ply laminates.

Tests conducted on symmetric cross-ply laminates with fibre orientations between ±30° and ±60° are illustrated in Figure 1.
Figure 1. Effects on fatigue limits of off-axis loading and angle between plies

UD glass epoxy, off-axis loading

angle-plied glass epoxy

Strain at fatigue limit

Off-axis loading angle or angle between plies

$\varepsilon_{db}$

$= \varepsilon_m$
S-N Curve (cont.)

They demonstrate no apparent fatigue degradation for orientations less than $\pm 35^\circ$

Then, relatively rapid reduction in fatigue strength to the debonding limit for orientations approaching $\pm 60^\circ$

Delamination strain for quadraxial laminates should correspond to the $\pm 45^\circ$ cross-ply results, ie, $\varepsilon \approx 0.004$

This is confirmed by Telreja where the delamination limit for two laminates composed of combinations of $0, +45, -45, 90^\circ$ plies is $\varepsilon_{dl} = 0.0046$
S-N Curve (cont.)

This observation of the variation of delamination limit with loading axis and ply angle explains the result presented in Figure 10 [Boller]

Here the fatigue behaviour of a cross-ply laminate subject to loading at 45° to the warp was noted to be significantly different from the fatigue behaviour of the same material loaded at 0°

At 45°, a knee (change in slope) in the curve occurs at around $10^4$ cycles whereas at 0° and more generally, it occurs at $10^5$ cycles

The trays are reinforced with plies at no more than $\pm 22.5°$ so it seemed reasonable to assume that the knee occurs at $10^5$ cycles
S-N Curve (cont.)

On the basis of the above, the S-N curve for the E-glass/polyester laminates was determined as bilinear with the stresses plotted as linear and the number of cycles to failure as log-linear (to the base 10)

\[ S = S_{\text{max}} - m \log N \]  \hspace{1cm} (4)

where \( S \) is stress, \( S_{\text{max}} \) is the intercept for \( N = 1 \), ie \( \log N = 0 \), and \( m \) is the slope of the curve

\( S_{\text{max}} \) and \( m \) are established from test data
S-N Curve (cont.)

Mean curve is found as a fit to data

To account for the spread of data, the design S-N curve is the mean minus two standard deviations

When insufficient data exist by which to determine the scatter, a lower bound serves the same purpose

Here a generic approach to determine the lower bound curve is adopted and then demonstrated to provide a lower bound through comparison with fatigue test data
Mean S-N Curve (cont.)

Test data demonstrate at \( N = 1 \) FLS strength in excess of the ULS.

To generalise the S-N curve, this increase is ignored and \( S_{\text{max}} \) is taken as the ULS in the direction of loading.

Thus, for \( N = 1 \) and \( \log N = 0 \), \( S = S_{\text{ult}} \).

To determine the endurance limit, use is made of the observation in relation to test data for an isophthalic polyester laminate that at around \( 10^5 \) cycles, the mean stress approximates 0.4 of the stress at \( N = 1 \).

Follows, if \( S = 0.4 \ S_{\text{ult}} \) when \( N = 10^5 \), \( m = 0.12 \ S_{\text{ult}} \).

\[
S = S_{\text{ult}} - 0.12 \ S_{\text{ult}} \log N \tag{5}
\]
Mean S-N Curve (cont.)

Below the knee, delamination governs long fatigue life

For epoxy-based glass laminates with quadraxial reinforcement, the delamination strain is 0.0046 (noted above)

By reducing the delamination limit where polyester resins are involved suggests 0.004 is appropriate

However, Boller provides no indication of whether a corresponding limit on cycles exists
Mean S-N Curve (cont.)

Instead, use was made of:

(a) Results in McCabe et al covering curve-fits to fatigue data for a range of polyester resins including isophthalic

(b) Flexural fatigue test data for the same range of resins when reinforced with alternating plies of glass mat and woven roving

In both cases, the loading was $R = -1$. 
Figure 2. Curve-fit of ASTM D671 fatigue data for various unsaturated polyester resins (R = -1) [McCabe at al] extrapolated from $10^7$ cycles. At $10^{10}$ cycles, for isophthalic resin strain is 0.00714.
Figure 3. Comparison of isophthalic polyester laminate fatigue data with mean isophthalic polyester resin S-N curve (Fig. 2) & proposed design curve.
Mean S-N Curve (cont.)

In Figure 3 (McCabe at al), a comparison is presented between flexural test results for reinforced isophthalic polyester and the corresponding unreinforced resin curve from Figure 2.

Close correspondence between the resin-only-based curve and the test results is clear and supports a limiting strain of $0.004$ at $10^{10}$ cycles (based on $\varepsilon_{dl}$) as appropriate for the mean curve.

Solving the generalised S-N equation for a typical tensile modulus of 17,100 MPa and recalling that $S = 0.4 S_{ult}$ at $N = 10^5$ cycles

$$S = 0.517 S_{ult} - 0.0234 S_{ult} \log N$$  \hspace{1cm} (6)
Design (Lower Bound) S-N Curve

Found by assuming that

(a) for upper curve - at $N = 1$ $S$ is limited to $0.9 \, S_{ult}$

(b) for the lower curve, a larger safety margin is provided by adopting a limiting strain of 0.002, ie, half the value adopted for the mean curve

Thus

\[ S = 0.9 \, S_{ult} - 0.12 \, S_{ult} \log N \quad \leq 10^5 \text{ cycles} \quad (7) \]

\[ S = 0.459 \, S_{ult} - 0.0317 \, S_{ult} \log N \quad > 10^5 \text{ cycles} \quad (8) \]
Figure  Comparison of LR orthophthalic polyester laminate (CSM) fatigue test data with R.A.T. S-N curve (R = -1)
Comparisons with test data

Figure Comparison of HR orthophthalic polyester laminate (CSM) fatigue test data with R.A.T. S-N curve (R = -1)
Comparisons with test data

Figure Comparison of HR orthophthalic polyester laminate (CSM) fatigue test data with R.A.T. S-N curve (R = -1)
Comparisons with test data

Figure Comparison of HR orthophthalic polyester laminate (CSM) fatigue test data with R.A.T. S-N curve (R = -1)
STAGE 2 - $\varepsilon$-N CURVE

The chosen $\varepsilon$-N fatigue curve is independent of laminate ULS strength and so applies to all laminates.

The $R = 0.1$ design curve, based on wind turbine blade test data (Echtermeyer et al), is

$$\log \varepsilon = 0.063 - 0.101 \log N \quad (9)$$

where $\varepsilon$ is % and given in amplitude terms.

$R = -1$ curve also provided (Echtermeyer et al)

Figure 4 presents a comparison of all three curves.
Figure 4. Comparison of fatigue design curves

- - - - Standard fatigue curve $R = -1$ [11]
- - - - Standard fatigue curve $R = 0.1$ [11]
- - - - R.A.T. fatigue design curve

Strain (%) vs. Number of cycles