A PLAUSIBLE METHOD FOR FATIGUE LIFE PREDICTION OF BOATS IN A DATA SCARCE ENVIRONMENT

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SUMMARY

Within the marine world many boats are constructed from composite materials, that use classification society rules to predict their strength. As these vessels age, fatigue and remaining lifetime are of considerable interest to owners and operators. This paper seeks to identify an appropriate S-N curve and produce an example lifetime calculation.

Keywords: Composite Fatigue, Marine Vehicles, S-N Curve, Life Prediction, Damage

INTRODUCTION

Composite materials have played a part in the marine world for many years now specifically in the small craft applications. As with many other composite applications the range of materials used and the companies using composite materials range from the highly exclusive Sunseeker vessels to the high performance all weather rescue boats as used by search and rescue organisations around the world. The majority of these vessels are designed from the Lloyd's Register or DNV classification rules. As these vessels age some owners and operators are becoming increasingly concerned with the fatigue life associated with their particular vessel as it will have an impact on maintenance schedules, operations future resale values and the possibility of life extension.

This poses a difficult question as operators, boat builders and owners do not necessarily have the time or resources to conduct rigorous fatigue tests of each of the materials used within their vessels, the range of composites used within marine structures varies from simple CSM hand layup's, through to woven prepreg laminate systems to high performance autoclaved components. In addition to the variation in construction process, there are also variations in the materials used with glass, aramid and carbon fibre all used to reinforce various different matrix types including epoxy, poly and vinyl esters.

This paper seeks to provide a start point for composite boat owners and operators to predict the fatigue life of their vessels using limited open literature data gathered from a variety of sources.

LITERATURE REVIEW

Composite Fatigue

In the early 1970's research into composite fatigue concluded that components designed using these materials would have superior fatigue properties to other materials in use at the time, superior to the point that composite fatigue was not considered a limiting factor [1]. Data sets for a variety of glass reinforced polyester materials that were then mainly used in marine composites have been recorded by Smith [2] and Shenoi and Wellicome [3] .

There have been many fatigue investigations into axial compression and tension fatigue of composite materials, as well as limited investigations into the flexural fatigue of carbon and hybrid composite materials to support the work on composite fatigue life, however there is little or no published data available on the flexural fatigue of glass fibre composites.

Several investigations into the fatigue failure mechanisms have found significant differences between bending and tension, compression and fully reversed fatigue.[4,5,6]

Life Prediction Methodologies

Within homogenous materials the Pamlgren-Miner's rule damage accumulation methodology has been used successfully, though for composite structures it has been found that a Miner's rule approach can be un-conservative in some instances [7]. This has caused many authors to investigate alternative life prediction methodologies. The methods vary from damage accumulation, residual stiffness and strength to micro-mechanics and modulus based approaches. Several authors have carried out reviews of the composite fatigue methodologies.

Read [8] discussed the generation and use of applied stress divided by ultimate stress versus Log(N) (S-N) graphs and found that for glass fabric/polyester resin layup the log-linear straight line theory was the best overall fit, although at the extreme ends of the graph, extremely low and high cycle fatigue, an alternative fit was more applicable. A comparison of several fatigue damage laws found that the Pamlgren-Miner rule and Hashin-Rotem methods of life prediction were the most accurate tested, although errors in the region of 30% or more were still found. Recently Post [7] reviewed various different methodologies used to model the variable amplitude fatigue of composite materials. This review discovered that the models proposed required use of experimental fatigue fitting data for the material in question, making their prediction accuracy questionable.

Damage accumulation fatigue models are characterised by their use of a non-dimensional damage accumulation parameter, typically D, this parameter is initially 0 but as the fatigue of the material develops it increases until final failure where $D = 1$, the Pamlgren-Miner law is an example of a damage accumulation fatigue model. The important advantage of these rules is that they are often relatively easy to implement with few parameters which require calculation, but those that do make use of static properties for evaluation [8].

Residual strength models use the assumption that as the number of fatigue cycles increases, the amount of strength left in the laminate (the residual strength), decreases. Within the residual strength group of models there are several different methods, including the strength life equal rank assumption, which is difficult to prove experimentally as all the tests required of the same specimen are destructive, a residual strength model interaction, which has been found to cope well with both long cycle fatigue and short cycle fatigue modes and several others utilising several different fatigue parameters [7].

Micromechanics models, which mimic the approaches proven successful in metallic materials, have been applied to fibre reinforced plastics. The major drawback to these methods is the required material testing to apply the various models. Results have been mixed for those models that do not require a large amount of experimental data; although working for their specific case, either no further cases have been explored or results have been questionable [7].

Although the Pamlgren-Miner law has been shown in some cases to be un-conservative [9] it is still often used as the standard to test against, it is also an extremely easy model to implement with knowledge of the ultimate failure strength and a rudimentary S-N graph. This and the fact that more complicated models do not produce a significant improvement in accuracy [7]means that for this investigation the Pamlgren-Miner rule will be used to evaluate the fatigue life of a representative plate of a typical hull construction.

DERIVATION OF S-N CURVES

Table 1 shows the extent of fatigue data collected for the present research. The S-N curves have been created by collecting as much data from literature as possible and plotting a common S-N graph followed by graphs of tension, compression and fully reversed fatigue, and flexural fatigue separately and finally splitting the graphs further according to material type. This approach allowed a direct comparison of simple parameters such as mean line equation and y-axis intercept to help draw any similarities or differences.

Table 1: Table showing current experimental data as found in literature.
(√ = 1 - 2 papers reviewed, √√ = 3-5 papers reviewed √√√ = 5 + papers reviewed)

Fibre type		Glass Fibres		Carbon Fibres		Combined/Other	
Testing Regime		UD	MD	UD	MD	UD	MD
Tension-Tension	On Axis	√	√√√	√	√√		
	Off Axis	√	√√	√	√√		
Compression-Compression	On Axis		√		√		
	Off Axis		√		√		
Fully Reversed	On Axis	√	√	√	√√		
	Off Axis	√	√	√	√√		
Flexural	On Axis				√		√√
	Off Axis						√
WISPER/WISPERX			√				
Double Cantilever Beam			√				
Torsion			√				

The data varies in the application of load, the frequency of loading, the R ratio used and material type. It has been grouped into areas according to fibre type and construction (UD = Uni-Directional and MD = Multi Directional), testing and angle of application, Table 1 shows this grouping. Of major interest to this study is the flexural fatigue of glass fibre and aramid reinforced epoxy composites with multi directional layups. This investigation concentrates on the differences between flexural and tension/compression type fatigue with the initial results shown in Figure 1 (a).

As can be seen by the highlighted section in Table 1 the author was unable to find any flexural fatigue tests of glass fibre reinforced composites. This prompted the comparative study between flexural and other loading for carbon fibre. Knowledge of the flexural fatigue behaviour of GFRP's is required because loading on boat hulls, of which the majority are GFRP, is a pressure loading over the hull, which bends the hull plate.

Linear Regression

In order to produce a prediction line for the material cyclic life from the data collected, linear regression analysis was used. The linear mean regression line was found from the following equations:

$$y = a + bx \text{ ,where } a = \bar{y} - b\bar{x},\ b = \frac{S_{xy}}{S_{xx}},\ S_{xy} = \sum(x-\bar{x})(y-\bar{y}) \text{ and } S_{xx} = \sum(x-\bar{x})^2 \quad (1)$$

The $(100-2P)\%$ confidence limit for the mean value of y at $x = x_0$ is given by:

$$y = a + bx_0 \pm t_c S\sqrt{\frac{1}{n} + \frac{(x_0-\bar{x})^2}{S_{xx}}},\ \text{where } S = \sqrt{\frac{\sum(y-a-bx)^2}{n-2}} \quad (2)$$

The $(100-2P)\%$ confidence limits for a predicted value of an individual y-observation when $x = x_0$ is given by:

$$y = a + bx_0 \pm t_c S\sqrt{1 + \frac{1}{n} + \frac{(x_0-\bar{x})^2}{S_{xx}}} \quad (3)$$

Where $\bar{x}$ is the mean value of x, $\bar{y}$ is the mean value of y, and the appropriate values for the t - distribution, t_c, can be found in many sources.

Results of Comparison

Figure 1 (a) contains data for carbon fibre composite tension, compression and fully reversed fatigue tests at numerous frequencies and R ratio's, the spread of this data is quite significant with the upper and lower prediction limits cutting the y axis at 1.27 and 0.56 respectively, the slope of the mean line is found to be -0.0614. Figure 1 (b) contains data for carbon fibre composite flexural fatigue at various different frequencies and R ratio's, the spread of the data is less than that of Figure 1 (a) with the upper and lower prediction limits cutting the y axis at 1.34 and 0.8 respectively, the slope of the mean line is also significantly larger at -0.0963, a difference of 49%. This data was obtained from the sources used to create Table 1.

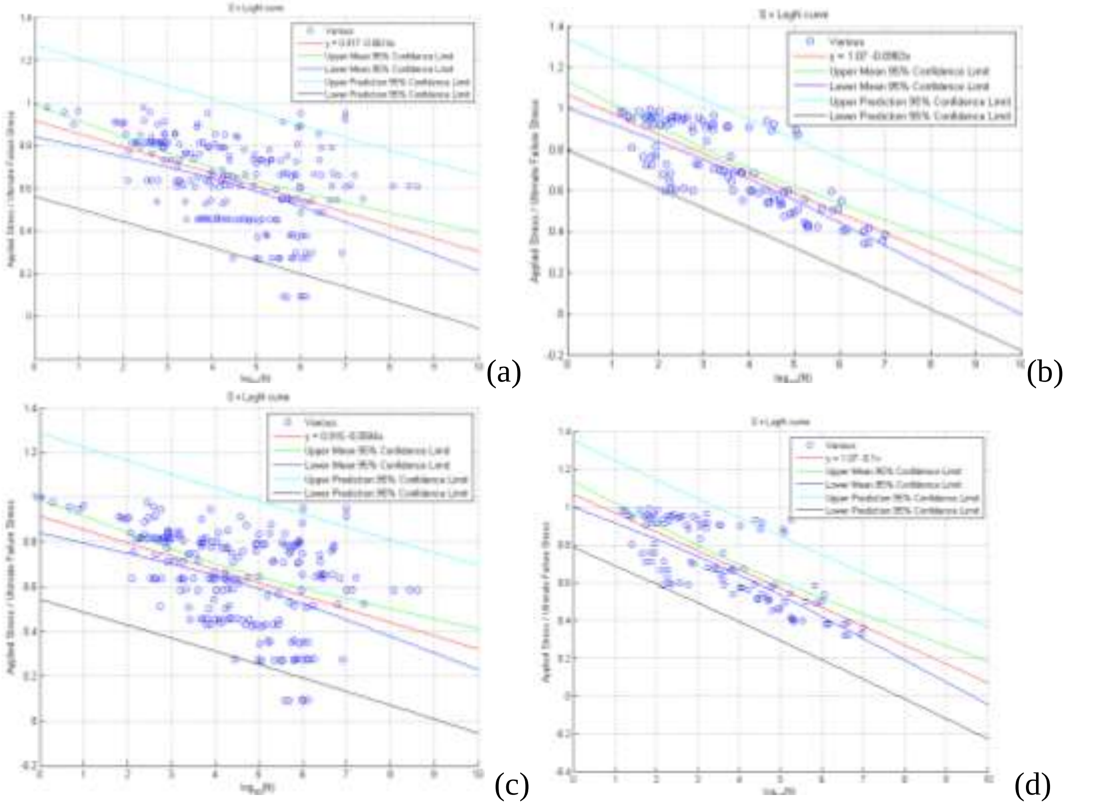


Figure 1: Graphs showing fatigue data of carbon fibre composites in compression and tension (a) and bending (b) and the data after the application of the Rotem model for compression and tension (c) and bending (d)

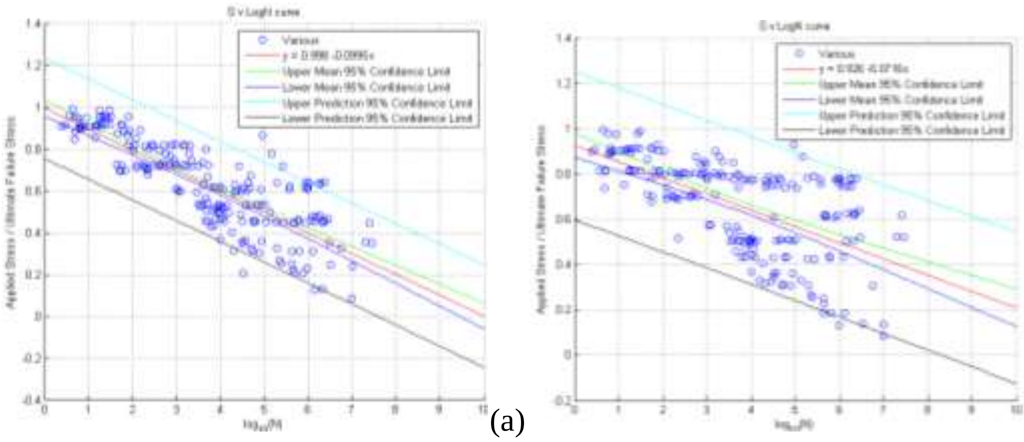
Scatter Reduction

There are many different elements within a composite material which can make it behave differently from other composite materials. On top of this there are several different parameters that can be changed whilst conducting a fatigue test on a particular laminate type. All of these different factors have a significant effect on the outcome of the test and therefore a method of taking these factors into account to enable a fair comparison between composite materials and tests is required. Rotem [10] tried to negate the influence of stress ratio on the fatigue curves and devised a method which allowed the user to estimate the fatigue behaviour of composite laminates under any stress ratio using equation 4.

$$\sigma_2 = \frac{1 - R_1}{(R_r - R_1)/\sigma_u + (1 - R_r)/\sigma_a} \qquad 4$$

Where σ_2 is the resultant stress level, R_1 is the stress ratio at which the original tests were carried out, R_r is the common stress ratio, σ_u is the ultimate stress of the material in question and σ_a is the applied stress. In this case for this paper R_r was chosen as 0.

However the reduction in scatter for these graphs in particular was minimal. This can be seen by comparing the un-normalised compression, tension and fully reversed fatigue data in Figure 1 (a) with the Rotem normalised data in Figure 1 (c). Comparing the y-intercept for the upper and lower confidence limits to obtain an obvious indication of the scatter of the data it can be seen there is very little reduction with the upper line intercepting the y axis at 1.27 on Figure 1 (a) and just less than 1.29 on Figure 1 (c), whilst the lower bound intercepts at just below 0.6 in Figure 1 (a) and Figure 1 (c). Comparison of Figure 1 (b) and (d), bending fatigue data reveals a very similar story, whilst comparison of Figure 2 (a) and (b) provides an interesting result.



(a) (b)

Figure 2: Graphs showing the tensile, compressive and fully reversed glass fibre laminate fatigue data (a) and after the application of the Rotem model (b)

Figure 2 (a) shows the glass fibre composite laminate tension, compression and fully reversed loading fatigue results. It displays a relatively small amount of scatter with the lower confidence limit intercepting the y axis just under a stress ratio of 0.8, Figure 2 (b) shows the same data after the application of the Rotem method, it is fairly obvious in this case that the scatter has in fact increased as a result of the normalisation process, however the process has also produced several very distinct data bands within the data set. It is postulated that this may be the result of the introduction into the same data plot of several materials of different matrix type, layup, thickness etc and that the bands produced are of materials of similar construction.

Chen [11] discovered that as the applied frequency increased, the associated S-N characteristics improved, that is for higher stress levels the specimens showed greater tolerance to damage and the number of cycles to failure improved. However in order to make use of this finding several curves and fatigue tests of the same materials at various frequencies are required which fall outside the scope of this paper.

S-N Curve modification

Although there were significant differences found between the carbon tension, compression and fully reversed loading S-N graph and the bending S-N curve, the marked difference in the glass tension, compression and fully reversed loading S-N graphs before and after the application of the scatter reduction method has led the author to believe that any comparisons drawn will be negated by other properties of the testing, such as frequency, 'R' ratio and matrix selection.

FATIGUE LIFE PREDICTION

The steps required to assess the life of a structure can be broken down into; the estimation of the life time operating conditions and frequency of operation, range of loading scenarios, load-structure interactions, appropriate S-N curve and finally a life prediction thereby collecting evidence for present and future designs.

Define Operating Conditions

The initial phase is to understand the type of loading the structure will see. There are many different loading spectra available for wind turbine and aircraft loading types [7]. For marine vehicles there is data available for the sea way spectrum which can be used to identify the typical wave encounters for a specific sea state, this combined with knowledge of the boat's expected operational duties allows gives the lifetime operating conditions for that particular vessel. In this case the operating conditions have been taken from Clark [12] and can be found in Table 4 and is represented by the number of cycles for each load.

Calculation of Typical Loading Scenarios

With knowledge of the operating conditions, the typical loading conditions can be found. For marine applications this involves identifying the expected dynamic pressures found at each individual wave height. The loading conditions for this work were also taken from Clark [12] and adapted for the boat in question by scaling the data against the design weight of a SAR vessel of 26 Tonnes displacement then scaling it up to43 Tonnes displacement for a geometrically similar vessel. The data is presented in Table 4.

Load Structure Interactions

The Load-Structure interactions were performed using third order shear deformation applied to a representative panel. The panel in question is chosen to be 1230mm x 460mm laminate plate which consists of 12 layers of unidirectional glass fibre and multidirectional glass/aramid hybrid laminates and is taken from a typical high performance composite SAR craft. The material properties for each lamina are shown in Table 2. The laminate layup is as follows.

$$[RE, UE, UE_{90}, XE, UE_{90}(4xQEA), UE_{90}, XE, UE_{90}]$$

Table 2:Table showing the constituent lamina boat hull.

Lamina Name	Materials	Ply angle	E_{xx} (MPa)	E_{yy} (MPa)
RE210 Vac	E-Glass / Epoxy	0^0	16890	16890
UE1200 Pre-Preg	E-Glass / Epoxy	0^0 and 90^0	38100	6530
XE 900 Vac	E-Glass / Epoxy	0^0	14500	14500
QEA1200 Pre-Preg	Aramid, E-Glass / Epoxy Hybrid	0^0	23150	8203

The properties of the laminate are calculated using classical laminate theory, with the ultimate failure stress taken from test data and presented in Table 3.

Table 3: Properties of the hull laminate

	E_x (MPa)	E_y (Mpa)	G_{xy} / G_j (MPa)	Ultimate Failure Stress (MPa)
In Plane Properties	17001	25119	5424 / -	289
Flexural Properties	15869	24518	- / 3971	-

In order to obtain the stresses in the laminate third order shear deformation theory was applied. For this simple case it is assumed that the plate is simply supported 1230mm x 460mm x 11.06 mm, from equation 5

$$U_0\,(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} U_{mn}\,\cos\alpha x \sin\beta y \quad (5)$$

Where U_0 can be vertical, horizontal or rotational displacements, , $\alpha = \pi m/L$, $\beta = \pi n/B$, where L and B are the length and breadth of the panel.

$$q(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} Q_{mn}\,\cos\alpha x \sin\beta y \quad (6)$$

Equation 6 gives the loading at a specific point where Q_{mn} is the lateral loading on the plate and is given by

$$Q_{mn} = \frac{16q_0}{\pi^2 mn} \quad (7)$$

Where q_0 is the load on the plate. By substituting equations 5 to 7 into the stiffness matrix [C] the relationships between the stress and strains can be calculated, by determining the strains from the displacement relations and substituting them into the stiffness matrix the stresses caused by the loading can be calculated [13]. The stresses calculated for this paper are shown in Table 4.

Identify Appropriate S-N curves

The S-N curve used for the life prediction was that shown in Figure 2 (a) since the raw data provides a curve with reasonable spread, and a mean line which cuts the applied stress/ultimate failure stress axis at 1, this makes it a better option than the graphs for carbon composite or Figure 2 (b) which has an increased spread.

Calculate Life

The life of the selected hull panel laminate has been predicted using the simple Miners Rule summation and literature data collected providing the appropriate S-N curve.

$$D = \sum_{i}^{\infty} \frac{n_i}{N_i} \quad (8)$$

Where D is the damage sustained, n_i is the number of cycles at loading condition i and N_i is the number of cycles to failure at loading condition i taken from an appropriate S-N graph. To obtain the predicted total life of the plate equation 9 is used

$$\text{Expected Life}_{\text{Years}} = {}^{1}/_{D_{years}} \times \text{years} \qquad (9)$$

From 8 the total damage predicted to be sustained by this representative plate under the identified loading conditions is 6.66% over 20 years. From 9 the total life of this plate under these conditions is found to be 300 years.

Table 4: Table showing the loading spectrum from [12] modified for a 43 tonne boat over 20 years.

Applied Pressure, 26 Tonne SAR craft, (kPa)	Applied Pressure, 43 tonne boat, (kPa)	Calculated Stress (N/mm^2)	Number of applied Cycles (n)	Number of Cycles to Failure (N)	% Life Used
5	8	0.52	1,400,000	36,307,805	3.86
17	27	1.77	577,500	35,481,339	1.63
39	61	3.99	208,500	28,183,829	0.74
64	101	6.61	54,300	23,442,288	0.23
113	178	11.66	13,770	15,848,932	0.09
113	178	11.66	13,770	15,848,932	0.09
152	239	15.65	2,535	11,481,536	0.02
206	325	21.28	500	7,244,360	0.01
245	386	25.28	100	5,370,318	<0.01
294	463	30.32	15	3,548,134	<0.01
378	596	39.03	1	1,778,279	<0.01
				Total Used Life	6.66

CONCLUSION

This paper has sought to identify the data available for application to marine composite fatigue. It has found that although there is a wealth of fatigue data for tension-tension, compression-compression and fully reversed loading for both carbon and glass fibre composites there are no published results for glass fibre flexural fatigue that the author has been able to find. This data is essential to the present research as the literature shows significant differences in failure mechanisms between each loading regime in carbon. It is assumed here that the results will be similar for glass fibre composites.

Pulling in a large variety of data from numerous sources fatigue data for different laminate's, layups and loading conditions has produced S-N curves with large scatter. Scatter reduction using the Rotem method [10], has shown that although bands of data have been produced the overall scatter has not been reduced and in one particular case it has been increased. This leads to the conclusion that the interacting effects of the wide variation in cloth types, fibre orientation and loading scenarios dictate the scatter of a general composite material.

Although a method for the life prediction of marine composite materials has been suggested it is advised that boat owners and operators generate additional S-N data points for the materials to be used in their boats to be compared with and added to the data set that exists in published literature to satisfy themselves that the proposed S-N curve is suitable for their vessels.

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