FATIGUE LIFE PREDICTION OF COMPOSITE LAMINATES

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ABSTRACT
A method for the fatigue lifetime prediction of composite laminates is discussed. The method is based on the use of normalised fatigue curves obtained by an extensive re-analysis on a large number of fatigue data taken from literature. The available data were divided into several groups according to the following parameters: type of fibre, type of matrix, laminate behaviour, reinforcement architecture and load ratio, found to be those having the greatest influence on the fatigue behaviour of laminates. The main parameters of normalised fatigue curve and scatter band are reported for each group. The accuracy of the method was also verified, with good results, by using data sets taken again from literature.

1. INTRODUCTION

In the recent past, the fatigue behaviour of long fibre reinforced materials has deeply been investigated by many researchers with the aim of proposing criteria capable of predicting the fatigue life of composite laminate under cyclic loading. An extensive and accurate review on the subject has been presented in Ref. [1]. Unfortunately, it is recognised that, at present, methods of general validity are not yet available.

The only way to propose a general criterion would be the systematic study of the damage mechanisms evolution and to incorporate them in the prediction models [2]. The application of a cyclic load history can, in fact, activate different damage mechanisms, each of them playing an important role in the residual strength and stiffness properties of composite laminates. The most important mechanisms affecting the fatigue behaviour of composite materials turned out to be: the fibre failure, the layer delamination and the matrix cracking. Onset and growth of the different mechanisms, sequence of appearance and relative contribution to the laminate failure depend, however, on material lay-up and load ratio, as clearly shown for woven carbon/epoxy laminates [3]. By observing that laminate fatigue behaviour is generally controlled by a dominant damage mechanism only, a parameter defining the global laminate behaviour is probably more efficient than the laminate lay-up itself. From a practical point of view, this problem can be addressed classifying laminates into two categories: fibre-dominated and matrix-dominated. In the former, due to the greater number of layers aligned to the load direction, failures are controlled by the fibre properties, whereas in the latter the matrix properties play a more important role in the fatigue damage evolution. As far as the stress ratio influence is concerned, many experimental evidences show the more detrimental effect of negative stress ratio: a higher fatigue damage is associated to the presence of compressive components in the load history, usually resulting in steeper fatigue curves. It is also worthwhile to note the important role played by the type of reinforcement in the overall damage evolution, being glass fibres and GFRP much more sensitive to fatigue than carbon fibres and CFRP. Also the reinforcement architecture has a significant influence on the fatigue behaviour of the laminates. In fact, the mechanisms controlling damage onset and propagation are different in UD tape laminates with respect to woven fabric laminates. Environmental conditions, mainly temperature and moisture, have also found to strongly influence the fatigue strength of composites.

The development of a mechanistic model of general validity, incorporating the mechanics of the damage evolution, would require huge experimental efforts since data on the damage mechanisms are not yet available for all the possible material configurations and loading conditions. From a practical point of view, it could be of interest for the preliminary design of composite components the possibility of using a phenomenological model suitable to provide statistically meaningful results.

The present study reports on an attempt to propose a method for predicting the fatigue strength of laminates, in the absence of stress concentrations. The proposed approach was developed using a large DataBase of fatigue data taken from the literature. The different series of fatigue data were systematically re-analysed in order to assess, from a phenomenological point of view, the influence of each design parameter assumed here to be important in formulating a fatigue life prediction criterion.

2. RE-ANALYSIS AND CLASSIFICATION OF FATIGUE DATA

A preliminary analysis allowed us to identify the parameters having the greatest influence on the fatigue behaviour of composite laminates, at least from a macroscopic point of view. The parameters considered in the present study are:
- type of fibre (carbon, glass),
- type of matrix (thermosetting TS, thermoplastic TP),
- lay-up (fibre-dominated FD, matrix-dominated MD),
- reinforcement architecture (unidirectional UD, woven W),
- load ratio, $R=\sigma_{min}/\sigma_{max}$.

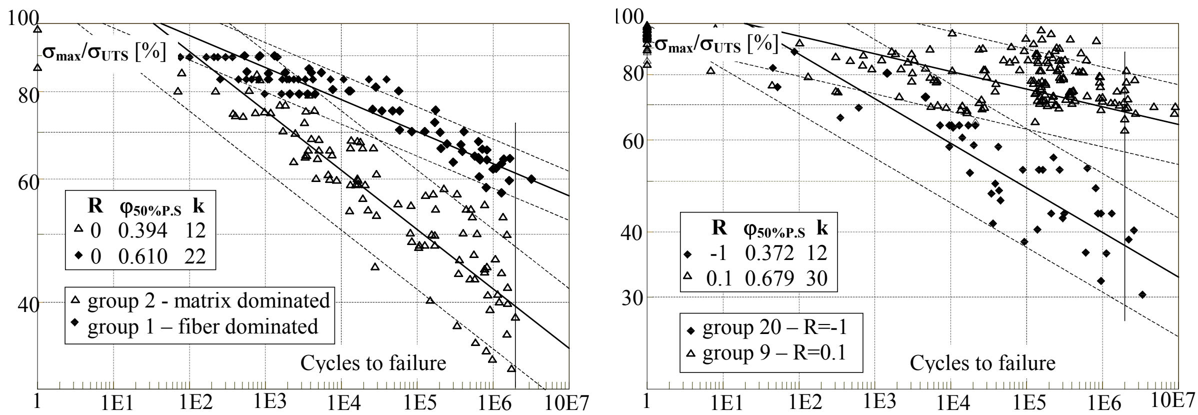
The environmental conditions have not been taken into account due to the difficulties of finding enough data for correctly accounting for their effects. Moreover the investigation has been focused only to data obtained from plain specimens (that is, without any notch or cut-out creating stress concentration phenomena).
About 140 different series of fatigue data were considered in the analysis and the data available were subdivided into 29 different groups according to the aforementioned parameters. All the fatigue data, expressed in terms of maximum applied stress, were normalised with respect to the relevant static strength. A fatigue curve was calculated for each group, assuming a log-normal distribution of the number of cycles to failure for each stress level. Being the data normalised, the average fatigue ratio $\varphi_{50\%}$ at $2 \cdot 10^6$ cycles was calculated for each group.
Therefore, the average fatigue ratio $\varphi_{50\%}$ was defined as:

$$\varphi_{50\%} = \left(\frac{\sigma_{MAX,50\% P.S.}}{\sigma_{UTS}} \right)_{N_f = 2 \cdot 10^6} \tag{1}$$

In order to provide statistically reliable design data, during the analysis of the data the scatter band at 10% and 90% probability of survival associated to the fatigue curve of each group was also evaluated. This allowed us to calculate the fatigue ratio at 90% probability of survival, $\varphi_{90\%}$.
The groups into which the collected data were subdivided are listed in Table 1 together with the relevant parameters and the results of the statistical re-analysis. The results are concisely presented only in terms of the fatigue ratios $\varphi_{50\%}$ and $\varphi_{90\%}$ and the T_σ parameter. This last parameter, defined as $T_\sigma=\sigma_{MAX,\ 10\%}/\sigma_{MAX,\ 90\%}$, allowed the intrinsic scatter of the data to be quantified. Unfortunately, for some groups, very few data were found in literature and this could result harmful for the statistical reliability of the prediction. The search and collection of data, however, is a continuous process still in progress and therefore continuous improvements are expected. A much greater number of experimental data related to a wider range of testing conditions would allow also the data to be classified with a higher precision. More groups could be therefore created, maybe reducing the scatter found in some groups, highlighted by the greatest values of the T_σ ratio.
Examples of the normalised scatter bands obtained for some groups are presented in Fig.1, where the influence of some of the characterizing parameters can also be seen.

“**Table 1.** Fatigue groups, distinguishing parameters and normalised scatter band data.”

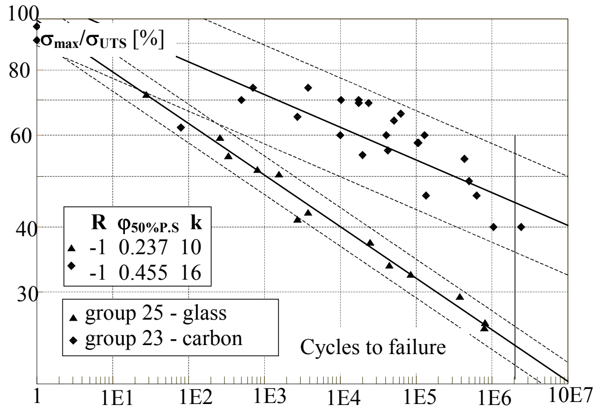
Group	R	Fibre	Matrix	Behav.	Fibre archit.	$\varphi_{,50\%}$	$\varphi_{,90\%}$	Tσ	N° data	N° series
1	0	Carbon	TP	FD	UD	0.611	0.563	1.177	47	9
2	0	Carbon	TP	MD	UD	0.394	0.324	1.480	106	13
3	0	Glass	TS	FD	UD	0.365	0.287	1.620	29	3
4	0	Glass	TS	MD	UD	0.267	0.199	1.927	86	13
5	0	Glass	TS	MD	W	0.311	0.228	1.870	186	16
6	0	carbon	TS	FD	W	0.680	0.584	1.356	73	11
7	0	carbon	TP	FD	W	0.811	0.781	1.067	7	1
8	0	glass	TP	FD	W	0.507	0.446	1.296	23	2
9	0.1	carbon	TS	FD	UD	0.679	0.570	1.417	217	11
10	0.1	carbon	TS	MD	UD	0.418	0.292	2.037	97	10
11	0	glass	TS	FD	W	0.266	0.198	1.808	108	5
12	0.5	carbon	TS	FD	UD	0.698	0.553	1.593	32	3
13	0.5	carbon	TS	MD	UD	0.714	0.580	1.516	13	1
14	>1	carbon	TP	FD	UD	0.557	0.533	1.235	6	1
15	>1	carbon	TP	MD	UD	0.404	0.319	1.603	16	3
16	>1	glass	TS	FD	UD	0.510	0.406	1.572	28	2
17	>1	glass	TS	MD	UD	0.394	0.300	1.720	44	3
18	-0.5<R<0	carbon	TS	FD	UD	0.489	0.375	1.705	57	3
19	-1<R<-0.5	carbon	TS	FD	UD	0.379	0.329	1.324	21	2
20	-1	carbon	TS	FD	UD	0.372	0.284	1.704	50	4
21	-1	glass	TS	FD	UD	0.316	0.270	1.374	27	2
22	-1	glass	TS	MD	UD	0.300	0.242	1.540	29	2
23	-1	carbon	TS	FD	W	0.455	0.358	1.547	29	2
24	-1	carbon	TS	MD	W	0.246	0.211	1.359	14	1
25	-1	glass	TS	FD	W	0.237	0.218	1.185	13	2
26	-1	glass	TS	MD	W	0.187	0.157	1.424	14	1
27	<-1	carbon	TS	FD	UD	0.242	0.182	1.783	35	3
28	-∞	carbon	TP	FD	UD	0.530	0.487	1.185	16	2
29	-∞	carbon	TP	MD	UD	0.316	0.225	1.973	48	7



(a) Influence of the laminate behaviour for thermoplastic, carbon fibre, UD laminates at R=0

b) Influence of the load ratio R for thermosetting, fibre-dominated, carbon fibre, UD laminates

“**Fig. 1.** Comparison of the normalised fatigue scatter bands for some groups.”

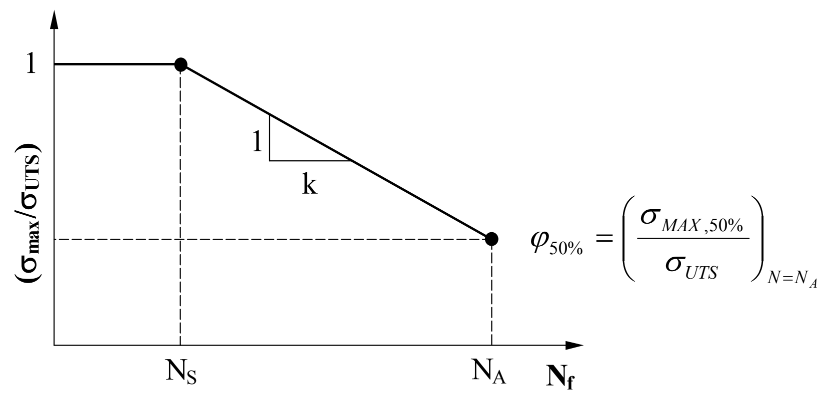


c) Influence of the type of reinforcement for thermosetting, fibre-dominated, woven laminates at R=-1

"**Fig. 1.** (contd.) Comparison of the normalised fatigue scatter bands for some groups."

3. THE METHOD FRAMEWORK

Extending the approach already proposed by Mandell [4], the model formulated here is mainly based on the concept of the fatigue ratio, which allows a normalised fatigue curve for each group to be built (Fig.2). The definition of the number of cycles N_S, at which the condition $\sigma_{max}/\sigma_{UTS}=1$ is fulfilled, can have some influence on the life prediction. According to Mandel's hypothesis, N_S was assumed to be equal to unity. This assumption was seen to be reasonably accurate by the independent analysis of each series of fatigue data taken into consideration. Moreover, the choice of assuming $N_S = 1$ allowed us to formalise a conservative approach suitable to deal with situations of practical interest. The number of cycles N_A, for the high cycle fatigue strength, was taken equal to $2 \cdot 10^6$ cycles.



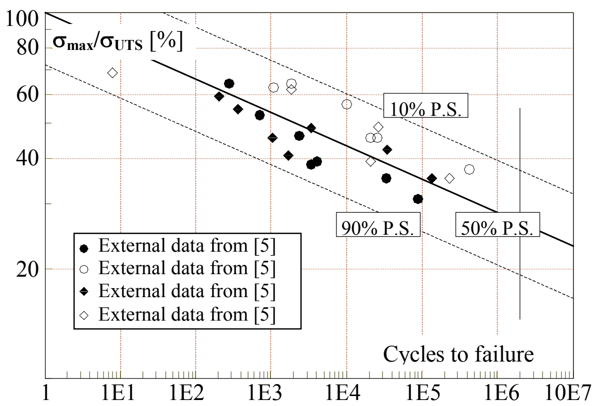
"**Fig. 2.** Normalised fatigue curve."

4. VALIDATION

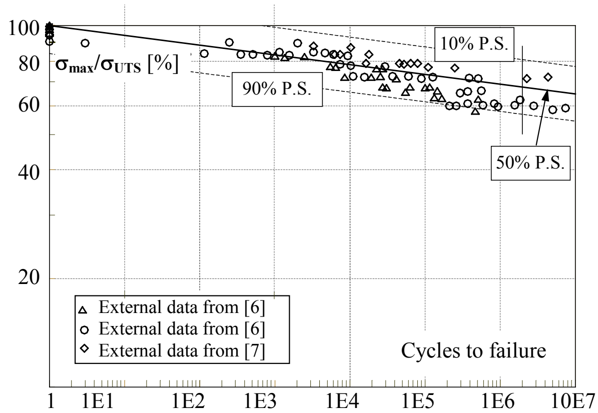
For the validation of the proposed model and to check the accuracy of the normalised scatter bands, some "external" series of data were selected again from the technical literature. It is not superfluous to highlight here that the data used for the validation are different to those considered in the statistical analysis to calibrate the model.

A common approach in the validation of life prediction models is the comparison between the actual fatigue life of each experimental results and the average life predicted by the model for the same stress level. This way of working, however, is not suitable to properly account for the intrinsic scatter of the data used for the model calibration. To overcome this limitation, the external series of data were directly compared, after normalisation, with the relevant fatigue scatter band, plotting external data and scatter band in the same fatigue diagram. If the data

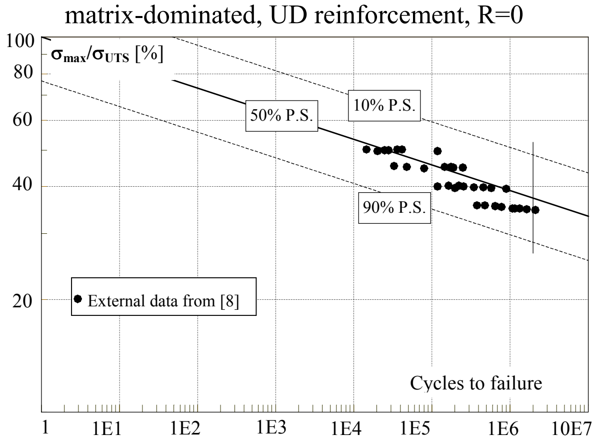
fall within the scatter band of the relevant group, the accuracy of the scatter band can be considered acceptable.
Some examples are reported in Fig.3. Despite the strong simplifications introduced by classifying the data according to five parameters only, the sound agreement found between the validation data and the relevant scatter band is well promising.



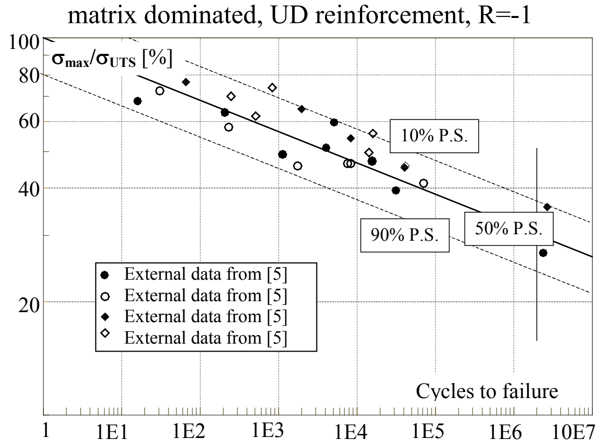
a) Group 4: Glass fibres, thermosetting matrix, matrix-dominated, UD reinforcement, R=0



b) Group 9: Glass fibres, thermosetting matrix, matrix dominated, UD reinforcement, R=-1



c) Group 20: Carbon fibres, thermosetting matrix, fibre-dominated, UD reinforcement, R=0.1



d) Group 22: Carbon fibres, thermosetting matrix, fibre-dominated, UD reinforcement, R=-1

"**Fig. 3.** Comparison between the reference scatter band for some groups and external data."

4. LIFE PREDICTION PROCEDURE

The fatigue behaviour of a generic composite material can be predicted according to the following procedure:

1. The laminate strength, σ_{UTS}, should be known or may easily be evaluated by static tensile tests.
2. On the basis of the laminate constituents and characteristics as well as on the loading conditions, the proper fatigue group can be selected and the values of the fatigue ratios $\varphi_{50\%}$, and $\varphi_{90\%}$ can be directly obtained from Table 1.
3. The reference fatigue strengths, $\sigma_{max,50\%}$ and $\sigma_{max,90\%}$, at $2{\cdot}10^6$ cycles to failure for a probability of survival equal to 50% and 90% can be obtained by simply multiplying the laminate strength σ_{UTS} by the fatigue ratios $\varphi_{50\%}$, and $\varphi_{90\%}$, respectively.
4. Assuming $\sigma_{max}=\sigma_{UTS}$ at N equal to 1 cycle and joining with a straight line this value to the reference strength, $\sigma_{max,50\%}$, at $2{\cdot}10^6$ cycles to failure the fatigue curve of the considered laminate can be plotted. The equation of this curve, associated to a probability of survival equal to 50%, is:

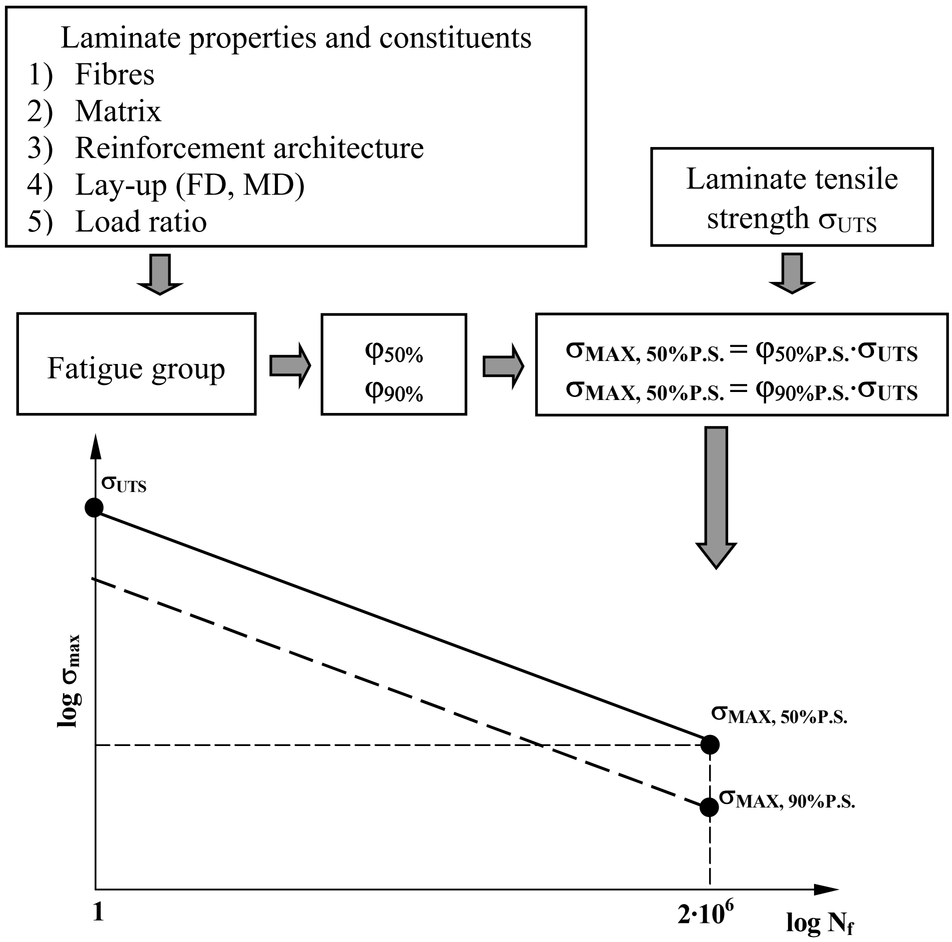
$$N \cdot (\sigma_{\max})^k = N_A \cdot (\sigma_{MAX})^k = \text{cost} \tag{2}$$

and its inverse slope can be calculated as follows:

$$k = \log_{10}\left(\frac{N_A}{N_S}\right) \Big/ \log_{10}\left(\frac{\sigma_{UTS}}{\sigma_{MAX,50\%}}\right) \tag{3}$$

5. The fatigue curve having a probability of survival equal to 90% can be determined by plotting a straight line having an inverse slope equal to k and passing through the estimated strength, $\sigma_{\max,\,90\%}$, for P_S= 90%.

The flowchart summarising the procedure is sketched in Fig.4.



"**Fig.4.** Procedure for the construction of the fatigue curve of a generic laminate."

5. CONCLUSIONS

A phenomenological model for predicting fatigue lifetime of composite laminates has been presented. The proposed model was based on the concept of the fatigue ratio. The overall effect of the different damage mechanisms on the fatigue behaviour and strength of composite laminates is, at least for a certain extent, incorporated into the model through the results of the statistical re-analysis of a large number of data taken from different sources.

The available data were classified according to five parameters only, type of fibre, type of matrix, laminate behaviour, reinforcement architecture and load ratio; for each resulting group the normalised fatigue curve and the associated scatter band were calculated.
The validation of the procedure by external, experimental data provided very good and well promising results.
The proposed model can therefore be considered a powerful engineering tool suitable for assessing composite materials in situations of practical interest reducing the costs of the design process, at least at its preliminary stage.

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