

PARAMETRIC INVESTIGATION OF FATIGUE LIFE PREDICTION METHODOLOGY

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ABSTRACT

The first of a sequel of papers, examining the influence of a number of parameters on the effectiveness of a life prediction methodology, is presented herein. The entire work is based on a well established methodology for the life prediction of GRP laminates under variable amplitude complex stress states. The process consists of the sequential execution of four main tasks, each one of which copes with a single subproblem in a straight forward manner. However, there exists a wide range of algorithms that could be used at each of these tasks. Thus, the problem becomes multiparametric and one has to find the optimal combination of all encountered parameters, cycle counting method, form of the constant life diagrams, fatigue criterion and finally damage summation rule. The aim of this on-going work is to create a generic software framework that will enable rapid prototyping of various life prediction schemes. The framework will define specifications on the representation of data, functional and behavioural specifications of the modules and a configuration scheme for the rapid interchange of the classes in the modules. Based on the software design, a software library is under development. In this first paper, the software framework will be presented analytically. Two different modules are already prepared for the first task of the entire procedure. The influence of two different cycle counting methods on life prediction will be examined. Theoretical predictions obtained using different cycle counting algorithms will be plotted against experimental data, for comparison, and pros and cons of each one of the algorithms will be discussed.

1. INTRODUCTION

The problem of fatigue life prediction is one of the most complicated in the major of fibre reinforced composite materials that is still unresolved. Lots of questions wait for answers, even for seemingly simple problems. For example, the form of S-N curves, to represent material's behaviour under constant amplitude loading. Nowadays, though a considerable number of solutions has been published, some of them have also been validated after extensive testing and construction of data bases e.g., [1,2], it is still a subject of discussion which is the most appropriate type of S-N curve to be used in life prediction formulations [3]. The last years, extensive constant amplitude fatigue testing on coupons made of fibre reinforced composite materials, has been accomplished. However, researchers understood that fatigue life of real structures, loaded under "real" loading patterns, i.e., variable amplitude irregular complex stress states, could be accurately predicted only if test results under the same conditions are available, or a valid fatigue life prediction methodology would be established. To this end, in the last five years, a limited number of methodologies have been proposed, some of them based on tests from constant amplitude and block loading e.g. [4] and others based solely on constant amplitude and static test results, e.g., [5, 6]. However, most of these methodologies cope with some of the tasks of the entire problem and need further development.

Any fatigue analysis method should contain routines for the counting of the events that produce damage, management of the available constant amplitude fatigue and static test data to derive the most suitable data base, possible use of valid failure criteria to enhance this database, and finally a damage accumulation rule to summarize all damage portions and compare the outcome with the predetermined criterion. However, though a single methodology consists of some certain steps, different techniques could be used in each one of them leading to different results, and the only way to evaluate the theoretical predictions is the comparison with valid experimental data from variable amplitude fatigue tests. It is self evident that certain and unique solutions for each step are not anticipated. The methodology

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should be flexible and should provide the end user with several potential solutions of each step. The selection of the best combination of routines, to form the entire methodology, is a task that is under examination. Only experimental evidence and experience gained after lots of iterations of the calculations for predicting the fatigue behaviour of several material systems would give answers to questions like this.

From the aforementioned paragraph it is concluded that a number of methods should be developed to solve each sub-problem of a fatigue life prediction methodology. And, when several methods exist for a simple task of the entire methodology, there should be a framework that would easily accommodate one or another partial solution to lead to the desired results.

Such a software framework is proposed in this paper, providing for this first phase only some specifications of the modules and input/output considerations for the good data interchange between the tasks of the methodology. By releasing a software framework like this one around the scientific community, and continuously feed the community with appropriate and adaptable fatigue and static test data, anyone that works on a specific subject of fatigue analysis would have the chance to compare it with others, been sure that other framework task results are not biased by the used of a new solution for a certain task. There is no need for open source for the software framework, not for the routines that could probably be proposed by other researchers to solve any of the sub-problems of the life prediction methodology, provided that anyone that wants to participate in this forum should follow the rules for input and output of the data.

To evaluate the software framework, two already established methods are used to solve the first step of the methodology, cycle counting, and theoretical predictions from both solutions are compared to experimental data from variable amplitude fatigue tests on glass fibre/polyester straight edge coupons using two different loading spectra. Unique solutions are currently used for the other steps of the methodology, as mentioned in [6]

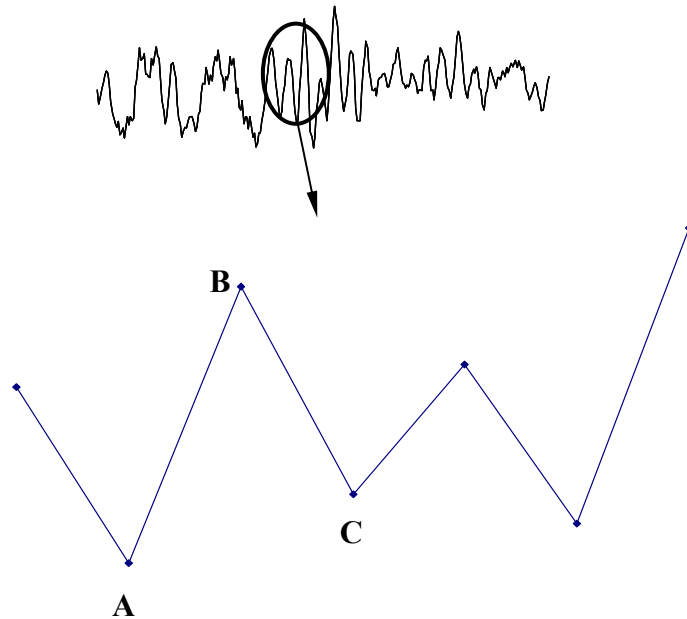
2. THEORETICAL BACKGROUND

2.1 Fatigue life prediction methodology

The whole analysis is based on a well established and validated life prediction methodology presented in the last years by the present author [5, 6]. This methodology has been introduced in order to provide accurate theoretical predictions of the fatigue life of fibre reinforced composite materials loaded under irregular multiaxial stress patterns. The entire algorithm that was developed consists of four routines, each one of which copes with a different, sub-problem of the analysis, namely;

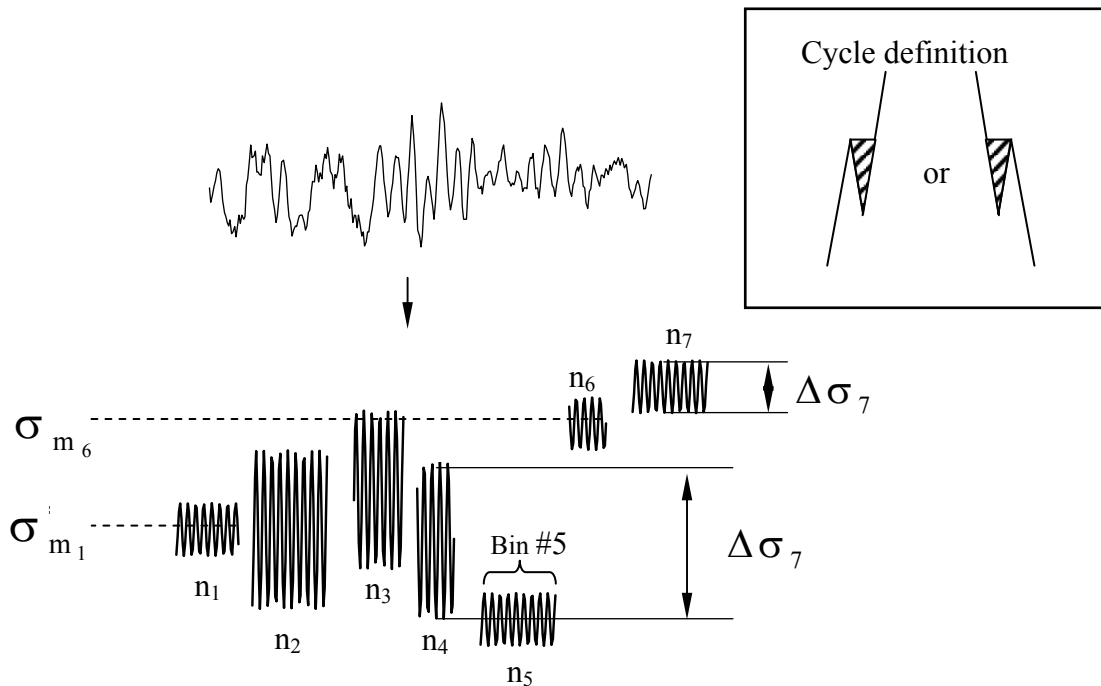
- Cycle counting; to convert VA time series into cycles of constant amplitude and mean values, i.e., events that produce damage that can be estimated. Cycles of amplitude and mean values between certain upper and lower bound are usually put together and form a bin
- Constant life diagrams (CLDs); to calculate S-N curves at any stress ratio resulting from cycle counting analysis
- Fatigue failure criterion; to calculate allowable number of cycles for each one of the aforementioned bins, i.e., the number of cycles of each single bin of constant amplitude and mean value that the virgin coupon could sustain until failure
 - In case of uniaxial loading patterns there is no need for any multiaxial fatigue failure criterion to calculate number of cycles to failure; The S-N curves, obtained from constant life diagram scheme, are enough for the calculations
- Damage summation rule; to summarize, linearly or not, partial damage coefficients, i.e., coefficients that correspond to each cycle bin.

Certain routines were proposed for each task of the entire methodology in [6]. Rainflow counting [7] was used for the cycle counting, linear interpolation between known curves in constant life diagrams for the second step, FTPF multiaxial failure criterion, [8] and Palmgren-Miner's linear damage rule for the last one. For more details, see refs [6, 8].



“Fig. 1. Schematic representation of *single range-mean* counting method”

The first enrichment of the procedure refers to the use of a completely different method for cycle counting, single range-mean counting, as described in [9]. According to this method, which is the most simple one, any transition from a valley, e.g., A, to a peak, e.g., B, in a time series, or from a peak, e.g., B, to a valley, e.g., C, forms half cycle with range= $ABS(A-B)$ and mean value, $mean=(A+B)/2$, or range= $ABS(B-C)$ and $mean=(B+C)/2$ accordingly, as schematically shown in Fig. 1.



“Fig. 2. Schematic representation of *rainflow* counting method”

Counting with this simple method results to so many half cycles as the number of load transitions, keeping the load sequence. On the other hand, rainflow counting algorithms categorize counted cycles, according to their range and mean values, without paying any attention to the location of the counted cycle in the time series, and put cycles of the same category in blocks, as can be seen in Fig. 2.

The routine for the development of the “simple range-mean” cycle counting method has been prepared taking into account the considerations for input/output of data from the already used routines, for rainflow counting, of the software framework.

2.2 Software framework

The first phase of this project is based on an already established computer code and only input/output requirements are set for each step of the entire methodology. Doing so, the articulated code will be easily adaptable, by replacing any one of the four aforementioned steps by a new, fully compliant, routine solving the same problem. Major input parameters for the calculations are: Time series, as row data, and material properties under static and fatigue loading. Input/output considerations taken into account from the existent code are as follows:

- Task one: Cycle counting
Input: Row data of the stress time series. The maximum expected stress should be equal to the maximum peak of the stress time series
Output: Sequential file containing three (3) columns; stress range, mean stress and number of counted cycles.
- Task two: Constant life diagram
Input: Output of task one, plus material static and fatigue properties. In the current version S-N curves that are used in calculations are of the form: $\sigma_a = \sigma_0 N^{-b}$. Curves for Compression-Compression (C-C) loading at R=10, Tension-Compression (T-C) loading at R=-1, and Tension-Tension (T-T) loading at R=0.1 are taken into account for the construction of constant life diagrams and thus needed for further implementation of the procedure. When complex stress state is present, those curves should be provided for normal, transverse and also for the shear directions of the material coordinate system.
Output: Sequential file containing eleven (11) columns; σ_{1a} , σ_{2a} , σ_{6a} , σ_{10} , $-b_1$, σ_{20} , $-b_2$, σ_{60} , $-b_6$, number of counted cycles and R-ratio.
Where: σ_{ia} , $i=1,2,6$, stress amplitude, at a specific R-ratio, along i-th material direction which is developed on the material for n-cycles, as counted from task one. 1 stands for longitudinal normal, 2 for transverse normal and 6 for shear stress component. σ_{i0} , b_i are fatigue parameters for the S-N of the type $\sigma_{ia} = \sigma_{i0} N^{-b_i}$ for longitudinal and transverse material directions and also for shear at the same R-ratio.
- Task three: Fatigue failure criterion
Input: Output of task two
Output: Sequential file containing two (2) columns; Allowable number of cycles, N_f , and number of counted cycles. Allowable number of cycles is calculated by solving the following nonlinear equation for N_f .
$$\frac{\sigma_{1a}^2}{X^2(N_f)} + \frac{\sigma_{2a}^2}{Y^2(N_f)} - \frac{\sigma_{1a}\sigma_{2a}}{X(N_f)Y(N_f)} + \frac{\sigma_{6a}^2}{S^2(N_f)} - 1 = 0. \quad (1)$$
In the above, X(N), Y(N) and S(N) are the corresponding S-N curves for the two normal and the shear stress components.
- Task four: Damage summation rule
Input: Output of task three
Output: Damage coefficient, D. When the linear Palmgren-Miner rule is used, D is calculated as:

$$D = \sum_{i=1}^k \frac{n_o}{N_f} \quad (2)$$

Where k is the number of blocks of cycles with the same range and mean value, as resulted by task one, n_o , number of operating cycles for each block and N_f , number of allowable cycles for each bin of operated cycles, as resulted from the third task.

Damage coefficient, D , is directly connected to fatigue life, L , which is presented in fatigue cycles or in spectrum passes.

$$L = \frac{1}{D} \quad (3)$$

It is evident that the methodology, in its present form, refers to plane stress states of variable amplitude. To evaluate the methodology, constant life diagrams for material properties along the three directions, namely longitudinal, transverse and shear, should be determined experimentally. When the stress state that arises on materials coordinate system is uniaxial, columns 2 and 3 of the sequential file, output of task 2, should contain zero values. In that case, columns 6, 7, 8, 9 of the same file could contain dummy values for fatigue parameters. For more information, about the entire methodology and the use of it, consult refs [6, 8].

3. EXPERIMENTAL

Variable amplitude (VA) tests using two different loading spectra were conducted in the course of this study. These tests are supplementary to others, under static and constant amplitude cyclic stress on the same materials, already reported elsewhere [10]. The complete database is now used for the establishment of a methodology that predicts fatigue life of GRP composite laminates under multiaxial fatigue loading of variable amplitude.

3.1 Materials and coupons

Straight edge coupons used for the tests were cut from a multidirectional laminated plate with a stacking sequence consisting of four layers, two unidirectional laminae of 100% aligned fibers, with a weight of 700 g/m² and two stitched ± 45 of 450 g/m², 225 g/m² in each off-axis direction. The lay-up is typical of laminates used in wind turbine rotor blade construction. The material system was a typical glass/polyester composite, E-glass from AHLSTROM GLASSFIBRE, while the polyester resin was CHEMPOL 80 THIX by INTERCHEM. This resin is a thixotropic unsaturated polyester and was mixed with 0.4%, Cobalt naphthenate solution (6% Co), accelerator and 1.5% Methyl Ethyl Ketone Peroxide, MEKP, (50% solution), catalyst. Rectangular plates were fabricated by hand lay-up technique under industrial conditions and cured at room temperature. Considering as 0° direction that of the UD layer fibers, the lay-up can be encoded as [0/(±45)₂/0]_T. Coupons were cut, by a diamond saw wheel, at 0°, on-axis, and 30°, 60° off-axis directions.

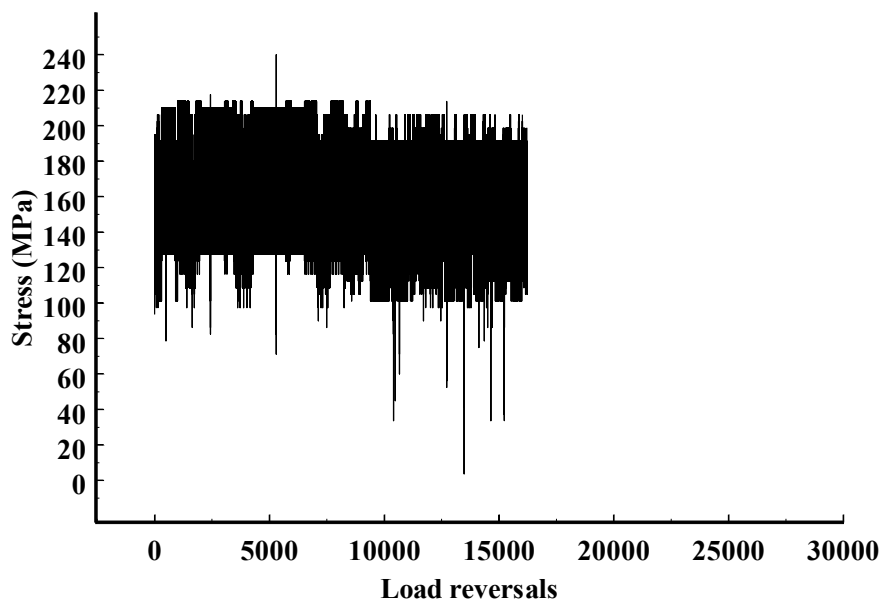
All coupons were prepared according to ASTM 3039-76 standard, their edges were trimmed with sandpaper and aluminum tabs were glued at their ends. Nominal dimensions in mm (length x width x thickness): 250 x 25 x 2.6. The length of the tabs, 2 mm thick, was 45 mm leaving a gauge length of 160 mm. All fatigue tests were conducted in a servo-hydraulic MTS test rig of 250 kN capacity, under load control at a frequency of 10 Hz.

3.2 Loading spectra

Two load spectra were used in applying variable amplitude loading on the coupons. For the application of the load, it was decided to keep the frequency constant and not the loading rate in order to obtain data under similar loading conditions as those for CA loading. Constant frequency results in higher loading rates, at high stress levels, while the opposite holds true

for lower loading levels. However, this is also the case in CA tests, during the determination of an S-N curve. Nevertheless, as it has been also reported [11], there is no significant difference in fatigue life of similar material as the ones examined in this study, if either constant frequency or constant loading rate is used.

The first loading spectrum was a modified version of the standardized for wind turbine rotor blades, WISPERX, henceforth denoted MWISPERX (MWX). It is in fact a shifted version of the original to induce only tensile loads. Time series for MWX of a maximum applied stress of 240 MPa is presented in Fig. 3. This load spectrum has been applied on 30 coupons cut at 0°, 30° and 60° from the multidirectional laminate. 15 coupons cut at 0°, on-axis, have been tested at three different maximum stress levels, 10 coupons cut at 30°, off-axis, also at three different maximum stress levels and finally 5 coupons cut at 60°, off-axis, at two different stress levels. The test frequency was kept constant at 10 Hz and thus, time required from a peak to valley and vice-versa, was equal to 0.05 sec, irrespective of the load range.



“Fig. 3. MWISPERX time series, maximum value at 240 MPa”

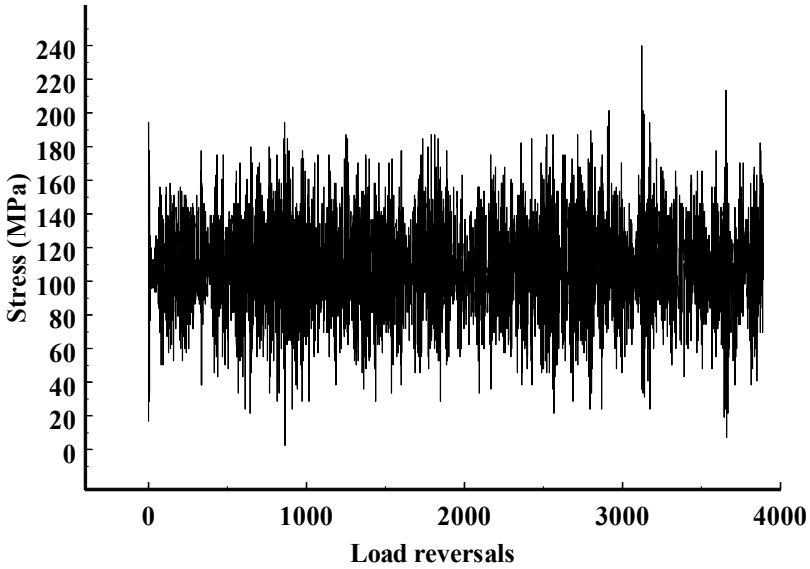
The second VA series used in the present experimental program was a more realistic spectrum, as it was derived through aeroelastic simulation for a loading case of a 14 m rotor blade, and is representative of flap bending moment fluctuations on a cross-section of the blade, located 2.4 m from the root. The load case definition is for normal operating conditions at a wind speed of 21 m/sec. Time series of this realistic spectrum, henceforth, denoted EPET573, for a maximum applied stress of 240 MPa is presented in Fig. 4.

17 coupons were tested in total using EPET573, partitioned as follows: 8 coupons cut at 0°, and tested at two different maximum stress levels, 6 coupons cut at 30°, tested at three different stress levels and 3 coupons cut at 60°, tested at solely one stress level.

As shown in Figs 3, 4, EPET573 time series that is a realistic one consists of well discriminated load transitions. On the other hand, MWX spectrum seems to be almost a sequel of blocks of loading with the same range and mean values. This comment is made clear if one observes the cumulative spectra of both time series, presented in Fig. 5.

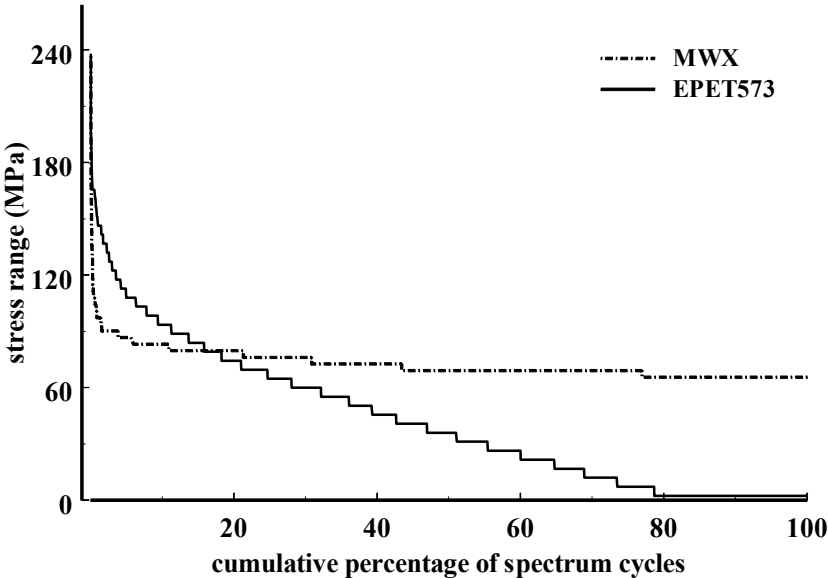
It is evident, that EPET573 is more irregular than MWX, as its cumulative spectrum contains more steps. This is reflected to the 553 bins that were used from the rainflow counting routine

to put the 1946 counted cycles of same range and mean values for EPET573, in contrast to only 114 bins used to accommodate the 12831 counted cycles of the MWX time series.



“Fig. 4. EPET573 time series, maximum value at 240 MPa”

Moreover, in Fig. 4 it is shown that MWX has no cycle with range less than 30% of its maximum range value; while more than 80% of counted cycles of EPET573 have ranges below 30% and more than 60% counted cycles have ranges below 15% of the maximum range value.



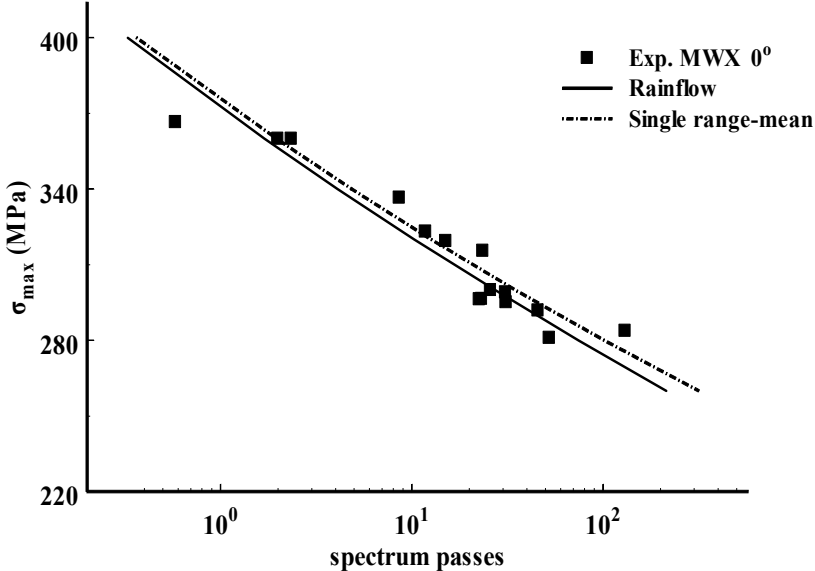
“Fig. 5. Cumulative spectra of MWX and EPET573 time series”

For both test series, experiments were terminated upon coupon ultimate failure. Results are presented customarily with respect to the number of passes of the applied irregular spectrum. To achieve different levels of loading the initial time series was multiplied each time point by point, by a factor. This procedure resulted in time series having different mean, minimum and maximum value.

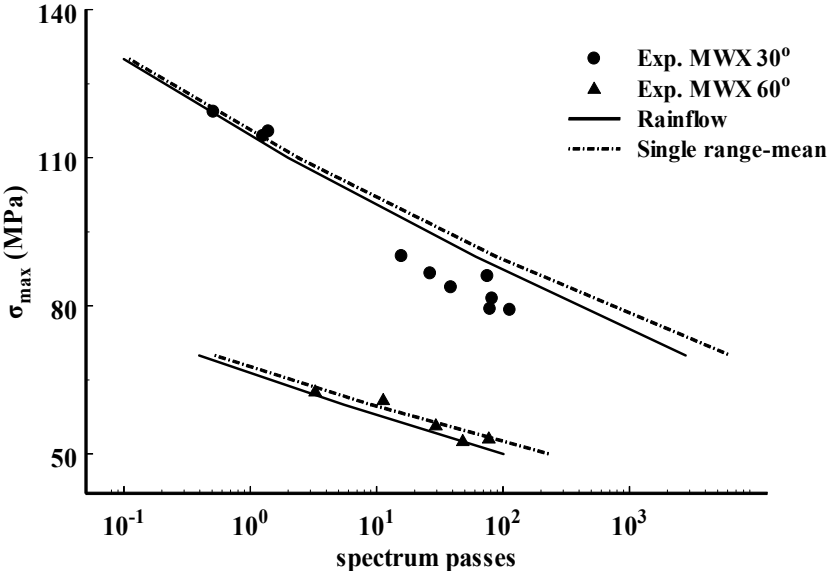
4. RESULTS & DISCUSSION

The standard fatigue life prediction methodology was used to predict life of on-axis and off-axis coupons loaded under the two aforementioned variable amplitude spectra. Lifetime predictions were then compared to corresponding experimental values. For the counting of the load cycles both described methods were used. Comparison graphs are given in Figs 6-9 for all cases studied.

As shown in Figs 6-7 for MWX spectrum, predictions for on-axis and off-axis coupons are corroborated by experimental data, irrespective the used cycle counting routine.



“Fig. 6. Theoretical predictions vs. experimental data, MWX, on-axis coupons”

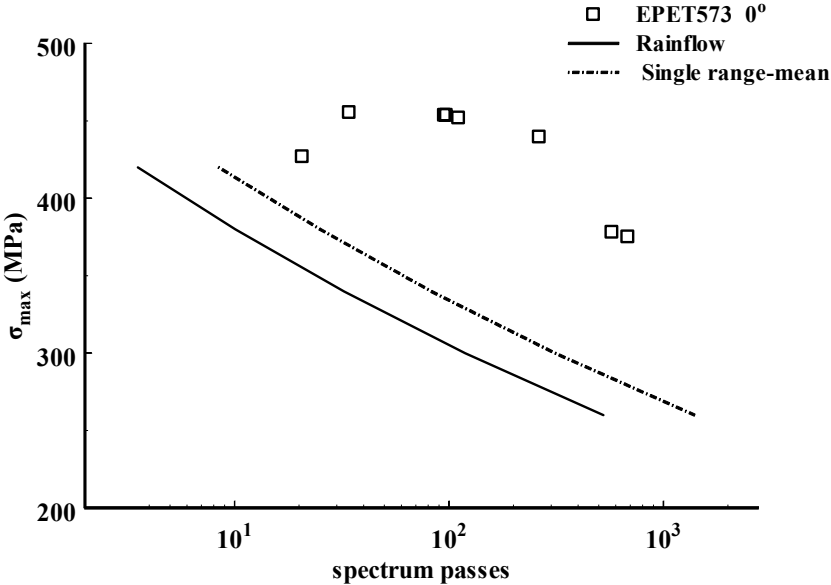


“Fig. 7. Theoretical predictions vs. experimental data, MWX, off-axis coupons”

However, this is not the case for EPET373 spectrum. For this spectrum, predictions for 30° off-axis coupons are corroborated well by relevant test data, while this is not true for on-axis, and 60° off-axis coupons, as presented in Figs 8-9. Thus, it would rather be said that predictive efficiency of the methodology, in the present framework, is not affected by fibre lay-ups, but it seems that accuracy is dependent on spectrum type itself. For the more “irregular” EPET573 spectrum, results are less accurate, while for the smoother MWX spectrum that is almost a sequence of block loading patterns, relatively accurate predictions can be produced irrespective the used cycle counting method. For the comparison of the two

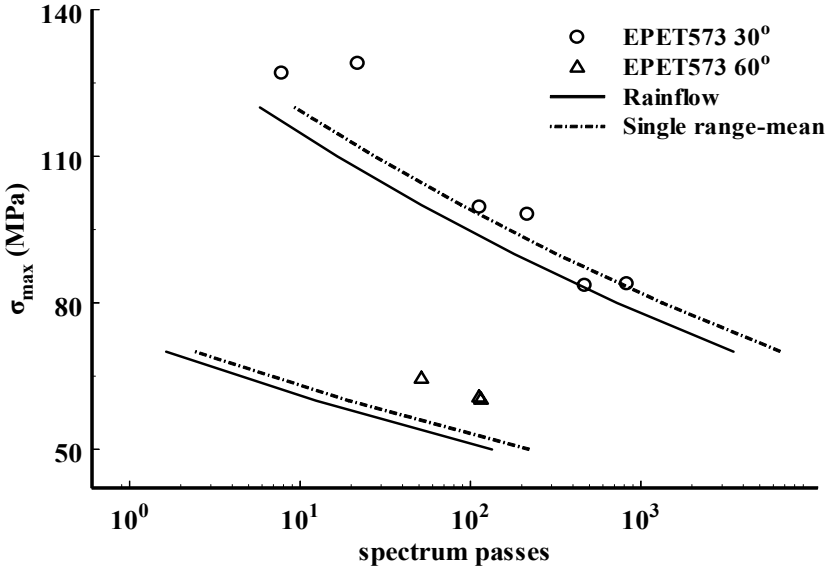
different cycle counting routines, it is shown that use of single range-mean counting method improves the predictions of the procedure for EPET573 spectrum and predictions are almost unaffected for MWX spectrum.

A reason for this fact could be the extreme and frequent load transitions of EPET573 time series and the attribute of rainflow counting method to “produce” cycles that not really exist, as it conjugates parts from all over the time series having no relation to each other. Thus, when the time series consists of extreme and frequent load transitions, like EPET573, the phenomenon is more intense and differences in counted cycles between rainflow and single range-mean methods are more evident. Though, for the smoother MWX time series, this is not the case, as a considerable number of counted cycles, by rainflow method, are formed from adjacent load reversals.



“Fig. 8. Theoretical predictions vs. experimental data, EPET573, on-axis coupons”

In general, it is demonstrated that both cycle counting methods are competent to be a part of the entire life prediction methodology. It should be noticed, however, that these comments have to be validated by more comparisons between predictions and other experimental data, considering for different loading spectra and/or different material systems.



“Fig. 9. Theoretical predictions vs. experimental data, EPET573, off-axis coupons”

5. CONCLUSIONS

Comparisons between experimental data and theoretical predictions demonstrated that two, different in the basis, methods for cycle counting can be used in the frames of a life prediction methodology to produce reliable results. Single range-mean counting method, which is really simple and easy to use, seems to produce more accurate results than rainflow counting routine. Moreover, it has another advantage as it counts cycles at the time they appear and thus, it can be used in combination with non-linear damage summation rules.

Both methods were accommodated in a software framework that is currently designed. This modular computer code contains basic routines for all the necessary tasks that have to be accomplished to fulfil requirements of a complete life prediction methodology. However, any new routine that would be proposed, for any simple task, could be easily incorporated. The framework should be enriched with other modules for each task. To this end, easily accessed libraries containing routines to solve each one of the tasks of the software framework are under preparation. The proposed software framework can be used for benchmarking purposes between partners that need to validate their routines.

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