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The role of experiment in the proposal of new approach for the prediction of stiffness reduction of composite structures under fatigue loading

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Abstract. The main goal of this paper is to present the results of the development of methodology for the prediction of stiffness reduction of composite structures under fatigue loading. The main idea of the proposed methodology is to estimate the stiffness reduction of composite structure with complex shape and stress field on the basis of data obtained during unidirectional tensile fatigue tests. To reach this idea it was necessary to find the solution of many problems such as methodology for the measurement of stiffness reduction during unidirectional tests, appropriate stiffness reduction model and the setup for the verification of proposed methodology.

Introduction

Despite a long-term research, the development of methods for the prediction of damage and degradation of mechanical properties of composite structures is still actual and rapidly developing topic. The motivation is based on the requirements of many industrial sectors including aerospace, automotive and others. During last decades many approaches and particular degradation models were developed to predict lifetime and residual mechanical properties of composite structures. Among existing models, it is rather complicated to find model, which can describe damage of structure with general shape and stress state. Almost all proposed models were developed on the basis of tensile experiments with prismatic test specimens. The application of these models in general engineering tasks is questionable.

Basic review of current state of the art

The research in this field lasts for more than 50 years. Developed degradation models are usually divided into three basic categories. The first category of models is usually called phenomenologically based models [1]. These models do not take into account a real damage mechanisms and describe damage on the basis of its outer manifestation, like reduction of stiffness and strength. These models can directly predict residual mechanical properties. A typical phenomenological model was proposed by Paepegem and Degrieck [2]. The second category of models is usually called fatigue life models. These models are based on generally known S-N curves and can be used for the prediction of fatigue life till the final fracture. A typical example is described in [3]. The classification of all existing approaches is beyond the scope of this review. More information can be found in [1].

All of the mentioned approaches are closely linked to experimental testing. Experimental measurement is necessary to obtain data for models identification and further for experimental verification of proposed methodologies. In terms of associated experimental testing, the literature is quite poor and in presented papers a significant improvisation is obvious. The reason of this fact stems from the high requirements to the size of statistical sample. During fatigue testing of composites, higher values of dispersion are reached because of inhomogeneous character of fibre composites and more complicated manufacturing process. Fatigue testing of polymer composites is usually performed with lower frequencies – generally up to 10 Hz. This is necessary because of the lower thermal conductivity and higher inner damping of polymer matrices. For more information see [4].

Description of proposed approach

The motivation of presented work was to propose methodology which can be used for general structures with complex stress state. This proposal consists of several key points including the proposal of methodology for experimental measurement of fatigue characteristics, the proposal of general degradation model, implementation of proposed model to FE code and verification of methodology using appropriately chosen experiments.

Stiffness of each lamina is defined by stiffness matrix C, see Eq. (1).

$$\sigma = C\,\varepsilon \tag{1}$$

Individual components of stiffness matrix C are expressed by five material characteristics including Young's moduli E_1, E_2 and shear modulus G_{12}. There are more material characteristics but only these are key for the description of lamina stiffness. It is expected that the reduction of composite stiffness can be described by the stiffness reduction of individual layers which can be described by the reduction of mentioned moduli E_1, E_2 and G_{12}. The reduction of these moduli can be measured during 1D tensile fatigue tests.

Experimental measurement of moduli E_1 and E_2 reduction

The methodology for measurement of the reduction of Young's moduli E_1 and E_2 is based on standard ASTM D3039/3039M-17 [5] for determination of Young's modulus during tensile static test. Proposed procedure is as follows. The cyclic loading of test specimen is stopped at defined numbers of cycles and static test according to above mentioned standard is performed. Fatigue characteristics are very often affected by the great dispersion. To minimize other inaccuracies which can arise during static tests, this static test is performed three times. Each fatigue test is repeated with four test specimens. Using this procedure, twelve values of residual Young's modulus are obtained for each number of cycles. In Table 1, a part of data for the stress level of 169 MPa is presented. In another step, the normality of data sets for each number of cycles was checked using Shapiro-Wilk's test of normality. The result of this test is statistics W, see Table 1. The normality assumption was met at the significance level of 0.05 in almost all cases. In some cases the normality assumption was not met because of outliers caused by measurement inaccuracy.

During testing of proposed methodology for the measurement of the decrease of Young's modulus, three stress levels were tested. To verify the significance obtained data another statistical testing was performed. In Fig. 1, the results of all three stress levels are presented as the dependence of mean values on the number of cycles.

Table 1: Example of measured residual Young's modulus data presented in normalized form

	n		0	200	10 000	50 000	100 000	200 000	300 000
	σ_{max} [MPa]	*R* [-]	E_1^n/E_1^0 [-]	E_1^n/E_1^0 [-]	E_1^n/E_1^0 [-]	E_1^n/E_1^0 [-]	E_1^n/E_1^0 [-]	E_1^n/E_1^0 [-]	E_1^n/E_1^0 [-]
Spec. 1	169	0.1	1.000	0.921	0.905	0.894	0.888	0.887	0.889
			1.000	0.915	0.902	0.886	0.885	0.885	0.889
			1.000	0.924	0.906	0.884	0.890	0.885	0.892
Spec. 2	169	0.1	1.000	0.917	0.911	0.899	0.897	0.888	0.876
			1.000	0.932	0.903	0.907	0.901	0.894	0.880
			1.000	0.918	0.894	0.882	0.889	0.882	0.883
Spec. 3	169	0.1	1.000	0.924	0.900	0.887	0.868	0.890	0.877
			1.000	0.932	0.908	0.894	0.886	0.896	0.889
			1.000	0.944	0.909	0.898	0.896	0.902	0.895
Spec. 4	169	0.1	1.000	0.938	0.909	0.896	0.910	0.906	0.902
			1.000	0.932	0.898	0.890	0.896	0.897	0.882
			1.000	0.938	0.911	0.901	0.901	0.908	0.895
Mean [-]			1.000	0.929	0.905	0.893	0.892	0.893	0.887
St. Deviation [-]			-	0.010	0.005	0.008	0.011	0.009	0.008
Var. Coefficient [%]			-	1.035	0.597	0.846	1.186	0.966	0.898
W statistics [-]			-	0.9404	0.9381	0.9711	0.9431	0.9340	0.9583

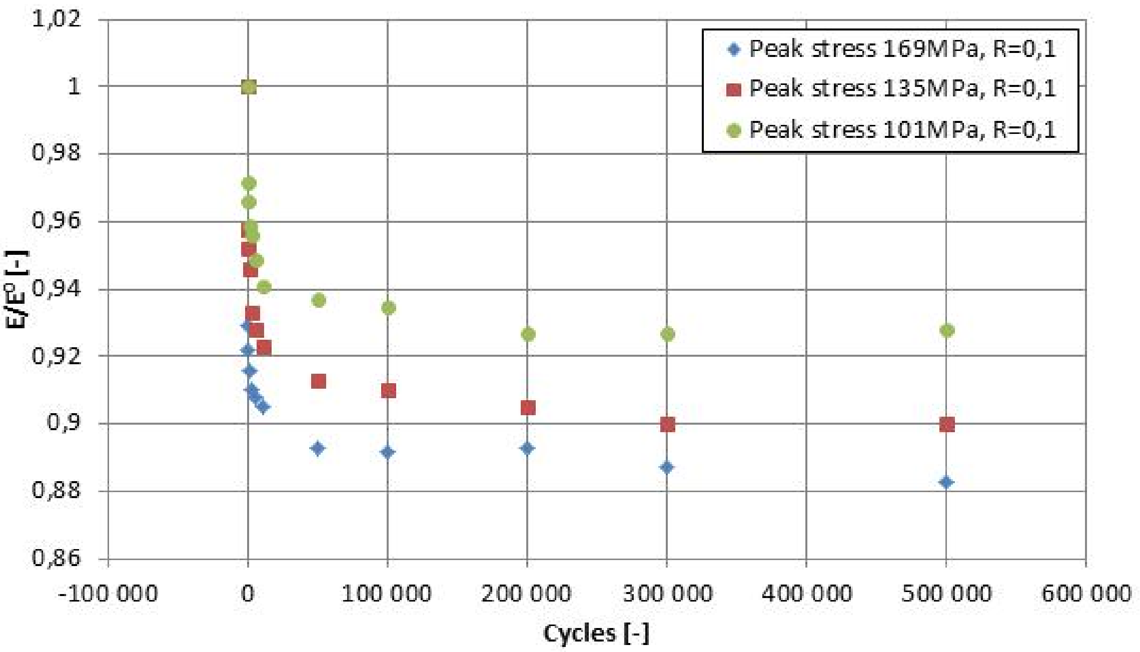

Fig. 1: Residual modulus E_1 on three stress levels with peak stress equal to 101 MPa, 135 MPa and 169 MPa and cycle ratio coefficient equal to 0.1

To compare if there can be find a significant difference between these mean values, t-test was performed. On the significance level of 0.05 the assumption of mean values conformity was not met. Further, the hypothesis of the dispersion conformity was tested using F-test. On the significance level equal to 0.05 the assumption of the dispersion conformity was met in all cases.

Experimental measurement of the shear modulus G_{12} reduction

The methodology for the measurement of the reduction of shear modulus G_{12} is based on standard ASTM D3518/3518M-13 [6] for the determination of shear modulus during static tensile test, see Fig. 2. Methodology was modified and biaxial extensometer was used instead of strain gauges because of cyclic strain.

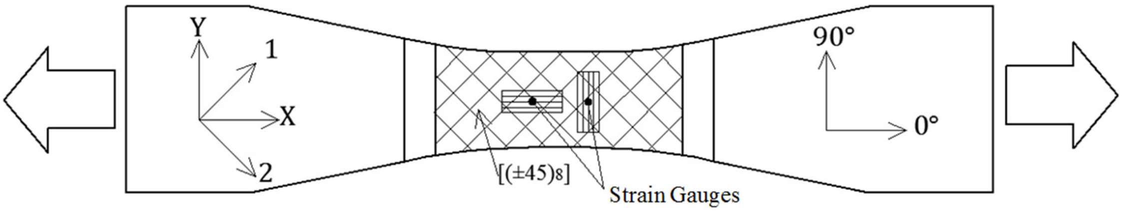

Fig. 2: Modified test specimen according to ASTM D3518 used for the determination of shear modulus in the plane of lamina

Shear modulus can be calculated using Eq. 2. Used coordinates systems are defined in Fig. 2.

$$G_{12} = \frac{\tau_{12}}{\gamma_{12}} = \frac{\sigma_x}{2(\varepsilon_x - \varepsilon_y)} \tag{2}$$

The methodology for the determination of reduction of shear modulus is similar to methodology used for Young's modulus. During research, it was shown, that modelling of the shear modulus G_{12} is not necessary on achievable load levels. The increase of shear modulus occurred instead of decrease, see Fig. 3. This is caused by the significant increase of matrix stiffness. More detailed study of this phenomenon is presented in [7].

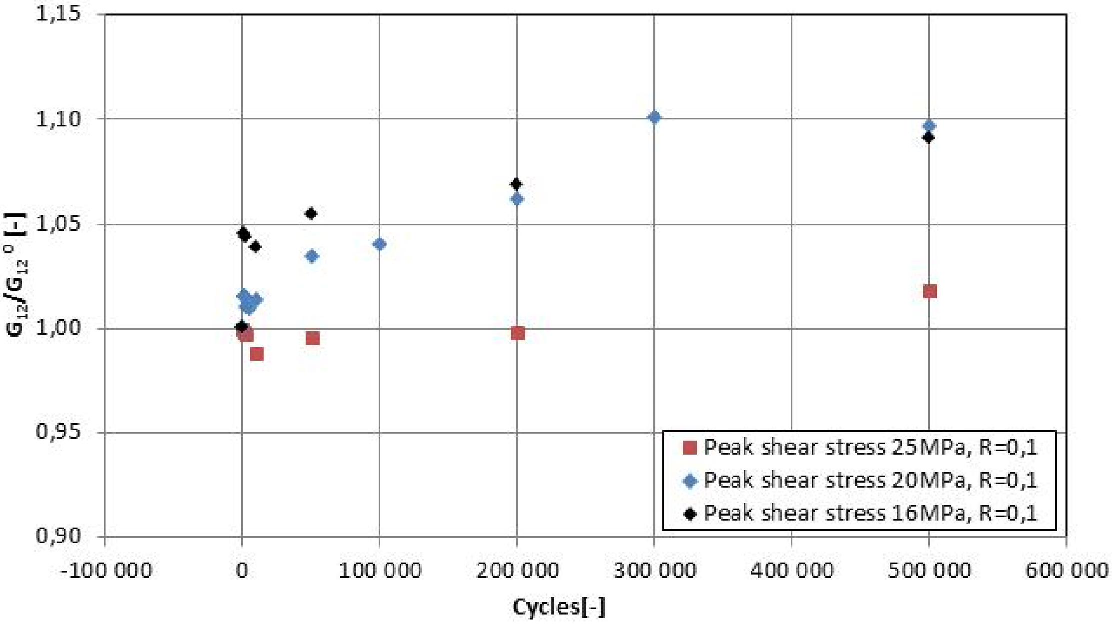

Fig. 3: Residual modulus G_{12} on three load levels with peak shear stress equal to 16 MPa, 20 MPa and 25 MPa

Degradation model

The main contribution of proposed model VZLU FDC Model stems from the possibility of damage prediction on arbitrary stress levels. Models proposed in the past did not have predictive capability and worked well only on stress levels closed to level used for the identification of the model. VZLU FDC Model can be expressed by the Eq. (3)

$$\frac{dD_i}{dn} = \frac{(\gamma_i \cdot \sigma_{imax} + \kappa_i)^{B_i} \cdot A_i \cdot (\sigma_{imax})^{C_i}}{B_i \cdot (D_i)^{B_i - 1}}, \quad D_i = 1 - \frac{E_i^n}{E_i^0}, \quad i = 1,2, \tag{3}$$

where D is damage parameter, σ_{max} is peak stress of the cycle, n is the number of cycles and the other variables are model coefficients. Using this model it is possible to predict stiffness reduction of elasticity moduli E_1 and E_2 of orthotropic layer. To identify model coefficients, it is necessary to measure the dependence of residual modulus on the number of cycles on minimally two stress levels.

Regression of experimental data using proposed model is shown in Fig. 4. Data on stress level 101 MPa and 169 MPa were used for the identification of model coefficients and stress level 135 MPa was used for the verification of predictive capability of the model. Predictive capability of the model can be rated as very good.

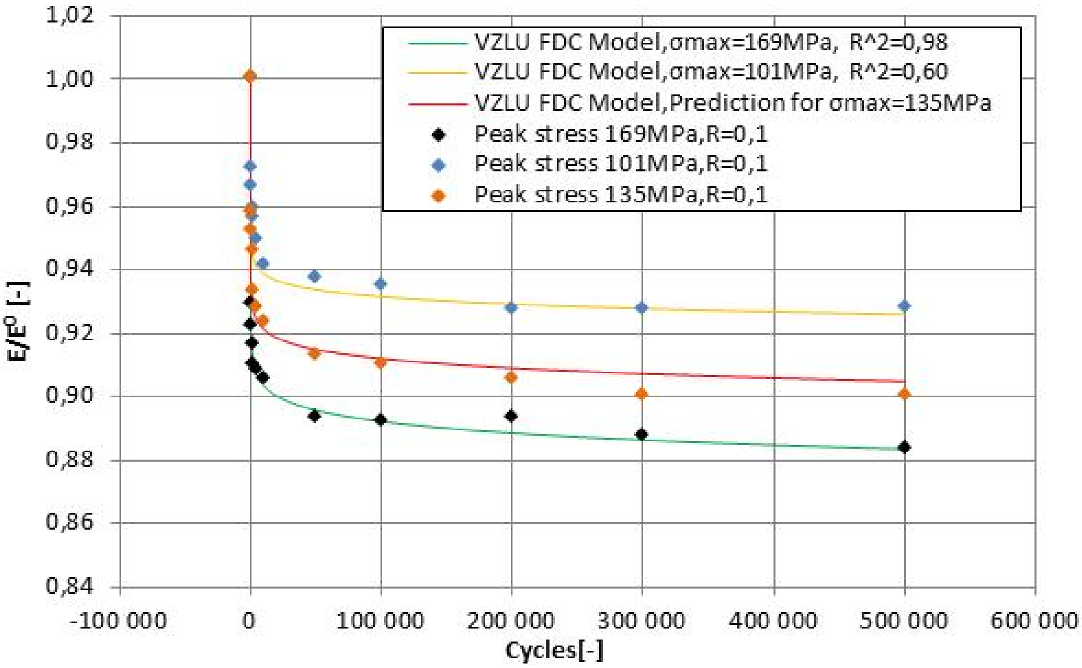

Fig. 4: Regression of experimental data using VZLU FDC Model on stress levels with peak stress equal to 101MPa and 169 MPa. Verification of predictive capability on stress level with peak stress equal to 135 MPa

Verification examples

Verification of the prediction accuracy was performed by the comparison of predicted and measured stiffness reduction. Proposed methodology allows the prediction of distribution of residual moduli in each layer. But it is impossible to verify these results because it is impossible to measure stiffness of individual layers of composite.

Verification was performed using model examples with increasing complexity of the test specimen shape and stress field. The first task was the tension of specimen with more complex stacking sequence [(0/90/ ±45/ 0/90/ ±45)s]. Testing was performed on two stress levels with peak stress of the cycle equal to 102 MPa and 127 MPa. Accuracy was determined as the fraction of predicted and experimental value. Obtained values of accuracy after 200 000 cycles are 0.95 for stress level 102 MPa and 0.82 for stress level 127 MPa. In Fig. 5 there are shown test specimen and the example of predicted residual modulus E_1 in layer 1 after 300 000 cycles.

In another step, fatigue tests in bending were performed. Experimental results were very affected by changes in stiffness of matrix and the comparison of experiment and prediction was impossible. More detailed discussion of this issue is performed in [8]. In Fig. 6 there is shown the setup of experimental measurement and numerical simulation.

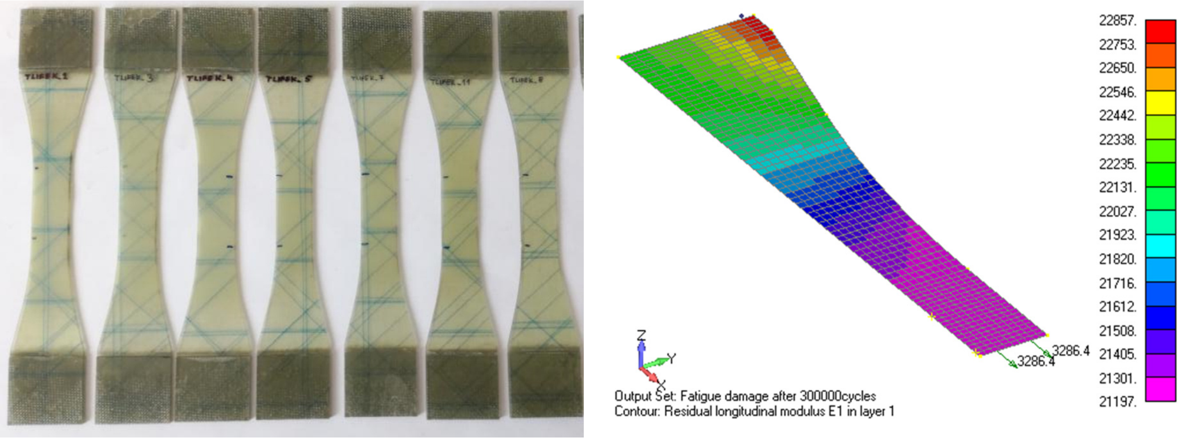

Fig. 5: Test specimens with stacking sequence [(0/90/ ±45/ 0/90/ ±45)s] used for experimental verification (left) and the distribution of residual modulus obtained by numerical simulation (right)

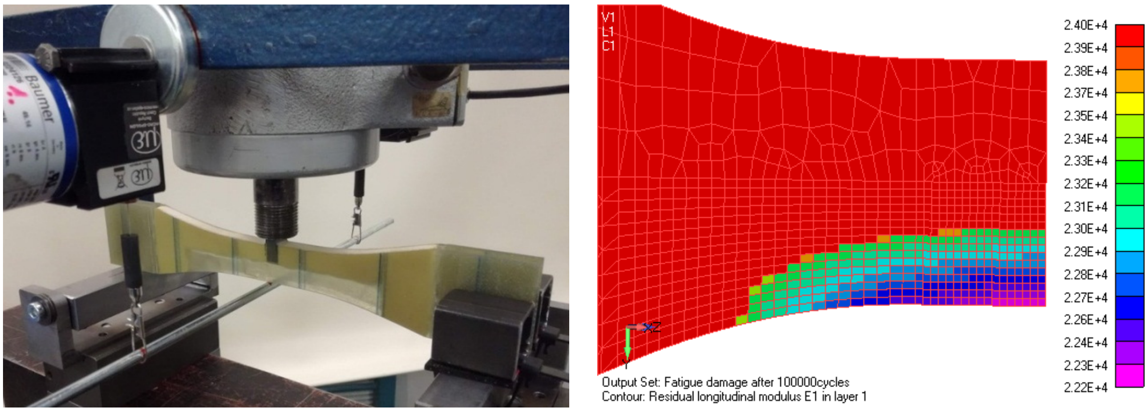

Fig. 6: Cyclic three - point bending test of composite specimen and corresponding numerical simulation using VZLU FDC Model

Conclusions

Proposed methodology shown to be an effective tool for the sizing of structures made of composite materials based on continuous glass fibres embedded in epoxy resin. During experimental measurement it was determined that cyclic loading can cause significant changes of mechanical properties of epoxy matrix affecting global response of composite structures. This newly discovered phenomenon will be the aim of following research. Obtained results show a great complexity of damage in composites modelling. This complexity is probably caused by a heterogeneous character of fiber composites and also by a great dispersion in quality and repeatability of manufacturing process.

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