A New Progressive Failure Simulation Method Considering In-Situ Property for Multidirectional Laminate Under Tensile Loading

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Abstract

On the basis of the natural rule that the stress transferred by the material can not surpass its strength, the behavior of the material in multidirectional composite laminates was hypothesized to be equivalently elastic-plastic considering the in-situ constraint from the adjacent layers under tensile loading, and a new simulating method based on linear FEA was presented to simulate the progressive failure and predict the strength of the composite laminates. Six kinds of E-glass/epoxy composite laminates specimen with central hole was tested and the results were adopted to verify the method. Comparison results shown that simulation load-displacement curves and predicted strength agreed well with the experimental results. Comparing with the traditional methods, the current method avoided determining the elastic constants' reduction factor of failed material artificially.

1 Introduction

In the past several decades, researchers had made great efforts on strength prediction for multidirectional composite laminate, many failure criteria had been set up, such as those methods based on stress/strain/energy and the popular polynomial criterion and their variations. However, the failure theory of the composite laminate is far to be closed to the ultimate maturity. The most famous "World-Wide Failure Exercise-WWFE" had been carried out for ten years to elucidate the failure phenomenon and theory of the composite laminate, world-wide researchers, professors and engineers were involved in this great event. The initiation, process and consequence of this event can be found in the summarizing book, FAILURE CRITERIA IN FIBRE REINFORCED POLYMER COMPOSITES[1], which will enlighten the following works.

To the opinions in engineering field, engineers would like to use simple criteria with acceptable precision to predict the ultimate strength of the laminate with various layup sequence. The polynomial criterions are popularly applied to simulate the progressive failure process of the composite and its ultimate strength combining with stiffness reduction treatment generally. However, the stiffness reduction is artificial and tricky in some sense, which would affect the simulating results. In the plane stress case, the reduction of the elastic constants can be characterized by the following relation:

$$\left[E_{11}^{*},\ E_{22}^{*},\ \mu_{12}^{*},\ G_{12}^{*}\right] \rightarrow \left[r_1E_{11},\ r_2E_{22},\ r_3\mu_{12},\ r_4G_{12}\right] \tag{1}$$

Where * denotes reduction, and r_i is reduction factor, described by vector $[\boldsymbol{r}]=[r_1, r_2, r_3, r_4]$.

In the table 1, stiffness reduction strategies in the published papers were simply summed up.

Author	Reduction factor's vector
Li[2]	MF: $[\boldsymbol{r}]=[1, 0, 0, 0]$
Dano[3]	Strategy 1: MF: $[\boldsymbol{r}]=[1, 0, 0, 1]$ FF: $[\boldsymbol{r}]=[0, 0, 0, 0]$ strategy2: MF: $[\boldsymbol{r}]=[1, 0, 0, 0]$ FF: $[\boldsymbol{r}]=[0, 1, 0, 1]$
Zhao[4]	MF: $[\boldsymbol{r}]=[1, 0.01, 1, 0.2]$ FF: $[\boldsymbol{r}]=[0.01, 0.01, 1, 0.01]$
Boh[5]	MF: $[\boldsymbol{r}]=[1, 0.05, 1, 0.05]$ FF: $[\boldsymbol{r}]=[0.05, 1, 1, 0.05]$
Tserpes[6]	Strategy 1: MF: $[\boldsymbol{r}]=[1, 0, 0, 1]$ FF: $[\boldsymbol{r}]=[0, 0, 0, 0]$ Strategy 2： MF-T: $[\boldsymbol{r}]=[1, 0.2, 1, 0.2]$ MF-C: $[\boldsymbol{r}]=[1, 0.4, 1, 0.4]$ FF-T: $[\boldsymbol{r}]=[0.07, 1, 1, 1]$ FF-C: $[\boldsymbol{r}]=[0.14, 1, 1, 1]$
Tabici[7]	MF: $[\boldsymbol{r}]=[1, 0.01, 1, 0.2]$ FF: $[\boldsymbol{r}]=[0.01, 0.01, 1, 0.01]$
Akhras[8]	MF: $[\boldsymbol{r}]=[1, 0.05, 0.05, 0.05]$ FF: $[\boldsymbol{r}]=[0.05, 1, 0.05, 0.05]$
Chen[9]	MF: $[\boldsymbol{r}]=[1, 0.56, 1, 0.44]$
Liu[10]	MF: $[\boldsymbol{r}]=[1, 0.175, 0.15, 0.162]$ FF: $[\boldsymbol{r}]=[0.01, 0.01, 0.01, 0.01]$
Puck[11]	MF-T: $[\boldsymbol{r}]=[1, \eta_1, \eta_1, \eta_1]$ MF-C: $[\boldsymbol{r}]=[1, 1, 1, \eta_2]$
Edge[12]	MF: $[\boldsymbol{r}]=[1, r_2, r_3, r_4]$
Rotem[13]	$[\boldsymbol{r}]=[e^{-k\varepsilon}{}_1, 0, 1.0, 0]$
Sun[14]	MF-L: $[\boldsymbol{r}]=[1, 0, 1, 1]$ MF-NL: $[\boldsymbol{r}]=[1, e^{-a\lambda}, 1, 1]$

Note: MF-Matrix Failure, FF-Fiber Failure, T-Tension, C-Compression

Table 1. Elastic constants reduction strategy summing-up

In table 1, various elastic constants reduction strategies were presented by the researchers, generally the reduction strategies considered the failure model in the composite and the coupled effects among elastic constants. Most of those strategies reduced the corresponding elastic constants to be very small value or 0 in a sudden way, and the reduction factors were determined by subjective/experiential method or those method based on trail and error. Some strategy[11-14] reduced those constants gradually according to the stress/strain level, considering the natural mechanical behavior of the material, these methods predicted more reasonable results, however, the model parameters must be determined by complex experimental procedure.

2 Basic hypothesis

In this paper, each single ply in the laminate was hypothesized to follow the elastic-plastic equivalent mechanical behaviour, which is on the basis that the stress bearing by the material cannot surpass its strength. For composite material, it was difficult to distinguish the elastic-plastic mechanical behaviour in the practical test because of two main factors: 1) the existing method of obtaining basic mechanical properties was based on unidirectional on-axis specimen which would fail in case of crack appearing. 2) the layers in the multidirectional laminate behave in a significantly different way from that of unidirectional lamina due to the adjacent layer's constraint, which is considered to be in-situ property.

For multidirectional composite laminate, the material behaviour was hypothesized to be equivalent elastic-plastic based on the following basic assumptions and gradual failure procedure:

1) The laminas in the laminate are bonded to be monolithic, and their inner stress can be calculated by classic laminate theory under loading.
2) With load increasing, the inner stress in various laminas increases accordingly.
3) When the stress in any layer reaches to its ultimate strength, crack will initiate at the weakest region;
4) When crack appears, it doesn't mean that the corresponding layer loses its capability of bearing loads because of the constrain and support from its adjacent layers, the stress will re-accumulate in the cracked layer by shear effect in the bonding interface, as shown in Figure 1.

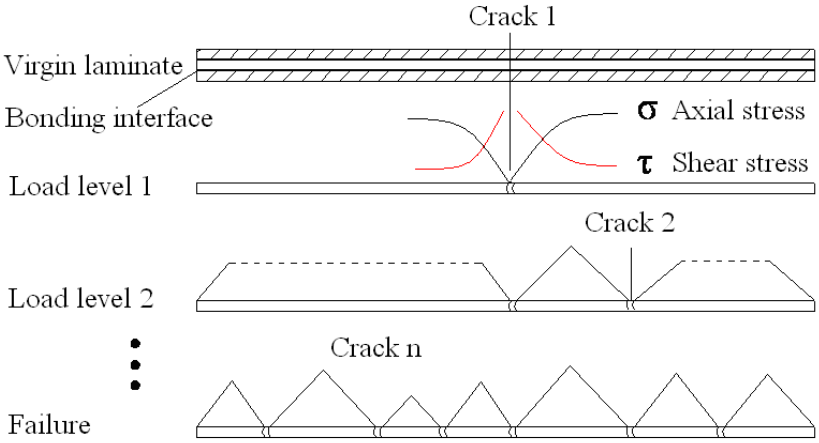

Figure 1. The cracking process in the lamina

In figure 1, the first failure could be assumed at 90° ply (determined by stress and failure criteria). Under a specific load (equals to the strength), first cracking will occurs, however, in this case, the whole 90° ply does not fail completely due to the interface between plies which can transfer shear stress to resume the ability of carrying load. Over a certain distance to the crack, the material can normally participate to carry loading[15,16]. If the external load is continuously increased, so does the inner stress, the cracking continues to occur at condition of local stress equaling local strength till the overall failure of the laminate. The situation in off-axis ply is similar to that of 90° ply. Similar phenomenon occurs in fiber breakage also, but the shear interface is the fiber/matrix interphase. Hence, the material can occur multiple cracks and damages under loading, and the maximum value of stress transferred by the material between two cracks is exactly equivalent to its regional strength, which is the physical foundation of elastic-plastic equivalent behavior assumption.

Based on the assumption and analysis above, cracked material's residual modulus is determined by the natural rule that the residual bearing stress between two adjacent cracks equals its strength, not a small value defined artificially. In this case, the typical stress-strain curve in the whole process is shown in figure 2, similar to those rules from the works of Rotem[13] or Sun[14]

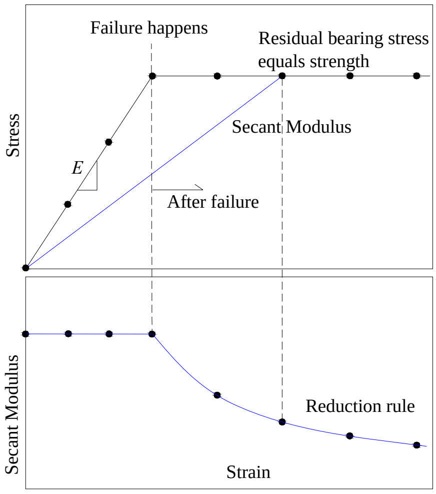

Figure 2. Constitutive relationship for failed material

3 Simulation procedure and treatment

The simulation procedure for strength prediction based on FEA is shown in Fig. 3. Commercial software MSC.Patran/Nastran was adapted for modelling and stress analysis, some C codes developed in house was applied to deal with the preprocessing, post treatment or results picking-up.

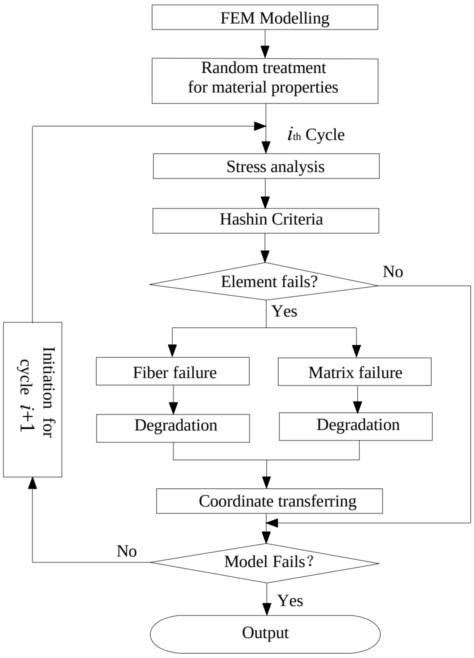

Figure 3. Flow chart of simulation

3.1 Failure criteria

The amendatory Hashin failure criteria, shown as formula 2, was applied to determine the failure state of each ply in the elements, Hashin criteria is simple in calculation and can identify failure modes.

$$\text{Fiber failure} \quad \left(\frac{\sigma_{11}}{X}\right)^2 = 1 \tag{2a}$$

$$\text{Matrix failure} \quad \left(\frac{\sigma_{22}}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 = 1 \tag{2b}$$

Where X, Y, S denotes the material on-axis strength in longitudinal, transverse and in-plane shear direction, σ_{11}、σ_{22}、τ_{12} denotes corresponding on-axis stress components.

3.2 Treatment of nonlinear

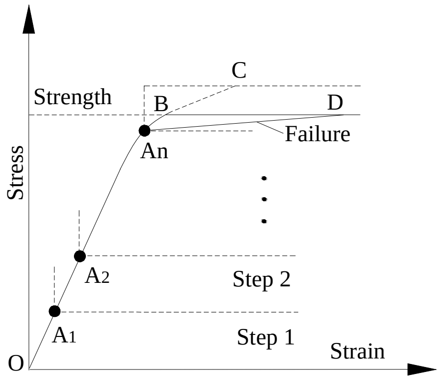

Figure 4. Nonlinear treatment by coordinate transferring

Current simulation carried out linear FEM analysis, however, the response of in-plane shear and failure material with hypothetic equivalently elastic-plastic behavior are typically nonlinear. In order to solve this problem in an easy way, the authors adopted a method of coordinate transferring shown in Fig 3. A specific load step is applied to the model and inner stress was calculated, shown as A_1 point. Before failure, the on-axis strength of the material in each direction minuses the on-axis stress caused by the load step, which is the equivalent of transferring the origin point of the coordinate in the direction of ultimate strength. When material fails (the origin point of coordinate transferred to A_n point), corresponding elastic constants were degraded in sudden way according to the reduction rule. In the whole range, the constitutive law of the material followed curve of O-A_n-D. If load step is sufficiently small, the equivalent plastic behavior can be distinctly simulated. The load step was set to be approximate 2% of ultimate strength for each laminate.

3.3 Degradation rule

If material in the elements fails, its properties must be reduced to simulate the progressive failure procedure. When fiber fails, based on experimental study, the fiber bundle fully spreads as brush-like, which makes material lose load bearing capability in all directions. When matrix cracks, matrix can not transfer load in transverse and in-plane shear direction. Therefore, the reduction rules were applied as following:

$$\text{Fiber failure} \quad E_{11}^{*} = cE_{11}^{0}, E_{22}^{*} = cE_{22}^{0}, G_{12}^{*} = cG_{12}^{0} \tag{3a}$$

$$\text{Matrix failure} \quad E_{22}^{*} = cE_{22}^{0}, G_{12}^{*} = cG_{12}^{0} \tag{3b}$$

Based on the coordinate transferring method, equivalent modulus of the failed material in the last step can be reduced to a very small value, so take c=0.01 here. In addition, authors found that the reduction of Poisson's ratio v_{12} has little effect on the simulated results, therefore, the Poisson's ratio was set to be constant to avoid numerical difficulties in FEA. From simulation result, the curve of displacement-loading has a turning point which can be defined as the catastrophic failure of the model.

Additionally, traditional progressive failure simulation based on loading step by step was also carried out and compared with current method, which can be found in part 4.

4 Experiments and verification

Six kinds of E-glass/epoxy laminates with central hole were carried out tensile test at clamp speed of 1mm/Min. The stacking sequences of these laminates is as following: $[0]_8$，[90], $[0/90]_{2S}$，$[\pm 45]_{2S}$, $[45/0/0/-45]_S$，$[45/90/-45/0]_S$. The dimensions of specimens are shown in Fig 4. The volume fraction of fiber is 50% in the specimen. The elastic constants of material are given in table 2.

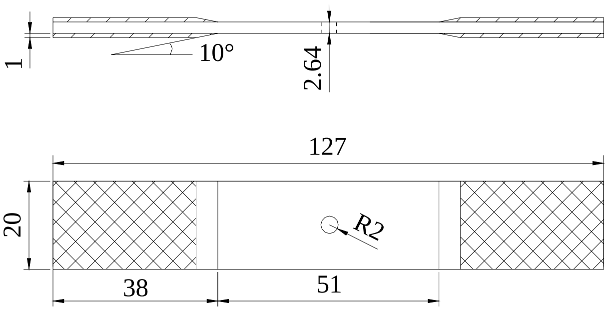

Figure 5. Geometry and size of the specimen

Properties	Mean value	V_X
E_{11}	42.0 GPa	0.036
E_{22}	11.3 GPa	0.055
v_{12}	0.3	0.014
G_{12}	4.5 GPa	0.042
X_T	908 MPa	0.056
X_C	908 MPa	0.050
Y_T	36 MPa	0.068
Y_C	140 MPa	0.050
S	60 MPa	0.079

Note: T-Tension，C-Compression，G_{12}-Initial shear modulus

Table 2. Material's properties and CV

The nonlinear in-plane shear behavior was taken into account in linear FEA, so tangent modulus should be applied in the calculation with coordinate transferring. In traditional progressive failure simulation, the secant modulus was required to consider nonlinear behavior. The tangent shear modulus and secant shear modulus were obtained from test as following:

$$G_{12}^{\mathrm{T}} = -595928\varepsilon^3 + 35545\varepsilon^2 - 716.24\varepsilon + 5.16 \tag{4a}$$

$$G_{12}^{\mathrm{S}} = -216962\varepsilon^3 + 14925\varepsilon^2 - 390.64\varepsilon + 4.88 \tag{4b}$$

Where G_{12}^{T} denotes tangent shear modulus, G_{12}^{S} denotes secant shear modulus, ε means strain.

The simulating results from current method and traditional stiffness direct reduction method are shown in Fig 5, where CM means Current simulation Method, TM means Traditional progressive failure analysis Method(reduction factor was set to be 0.01), L means Linear, NL means Non-Linear.

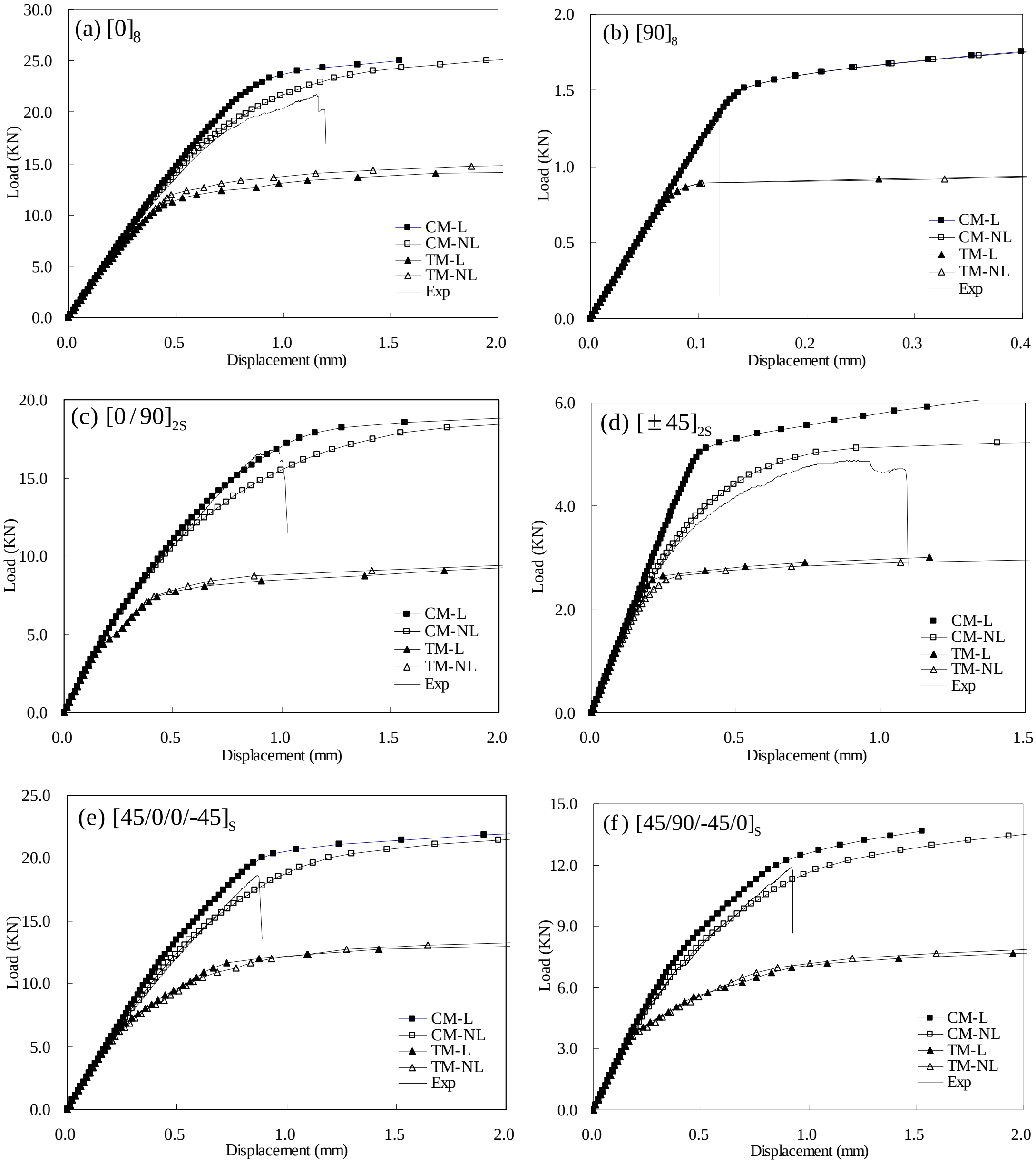

Figure 6. Simulation results for six kinds of laminate

From Figure 6, it can be seen that two simulation methods obtain four load-displacement curves, which all agree well with experimental results in the initial segment but differ from each other after failed elements appearing. The typical character of TM's results based on direct stiffness reduction shows obvious folding line for the load-displacement curve, however, CM's results show out a gradual failure process, which agrees much better with experimental results in the whole range. Comparing two cases whether considering nonlinear shear behavior or not, it can be found that the predicted ultimate strengths are closed, but under the same loading, the displacement is larger considering nonlinear behavior, and the load-displacement curve is much closer to experimental results in this case.

5 Conclusion and Discussion

On the basis of the natural rule that the stress transferred by the material cannot surpass its strength， new equivalently elastic-plastic behavior were hypothesized for the in-situ ply considering the constraint from adjacent layers. When the stress in the layer is lower than its strength, it obeys its original constitutive law. When inner stress reaches the material strength, cracking mechanism can prevent stress increasing continuously. Therefore, the in-situ failed material keeps to sustain the stress as same as its local strength. A simulation method based on linear FEA combining with new nonlinear treatment was presented to predict the strength and progressive failure process of multidirectional laminate. The current method avoided determining the reduction factor of failed material in artificial way or fully experimental dependence. Test results of six kinds of laminates with a central hole was adopted to verify the simulation method and treatment strategy, comparing results shown that current method is valid and can provide better results than traditional method.

References

[1] Hinton M.J., Kaddour A.S., Soden P.D. Failure Criteria in Fibre Reinforced PolymerComposites: The World-Wide Failure Exercise. ELSEVIER(2004).

[2] Li S., Reid S.R., Zou Z. Modelling damage of multiple delaminations and transverse matirx cracking in laminated composites due to low velocity lateral impact. Composites Science and Technology, 66, pp. 827-836 (2006).

[3] Dano M.L., Gendron G., Picard A. Stress and failure analysis of mechanically fastened joints in composite laminates. Composite Structures, 50, pp. 287-296 (2000).

[4] Zhao L. G., Warrior N. A., Long A. C. Finite element modelling of damage progression in non-crimp fabric reinfored composites. Composites Science and Technology, 66, pp. 36-50 (2006)

[5] Boh J.W., Louca L.A., Choo Y.S. Damage modelling of SCRIMP Woven roving laminated beams subjected to transverse shear. Composites: Part B, 36, pp. 427-438 (2005).

[6] Tserpes K.I., Labeas G., Papanikos P. Strength prediction of bolted joints in graphite/epoxy composite laminates. Composites: Part B, 33, pp. 521-529 (2002).

[7] Tabici A., Ivanov I. Materially and geometrically non-linear woven composite micro-mechanical model with failure for finite element simulations. International Journal of Non-linear Mechanics, 39, pp. 175-188 (2004).

[8] Akhras G., Li W.C. Progressive failure analysis of thick composite plates using the spline finite strip method. Composite Structures, 79(1), pp. 34-43 (2007).

[9] Chen H.R., Hong M., Liu Y.D. Dynamic behavior of delaminated plates considering progressive failure process. Composite Structures, 66, pp. 459-466 (2004)

[10] Liu K.S., Tsai S.W. A progressive quadratic failure criterion for a laminate. Composites Science and Technology, 58, pp. 1023–1032 (1998).

[11] Puck A., Schurmann H. Failure analysis of FRP Laminates by means of Physically based phenomenological modes. Composites Science and Technology, 58, pp. 1045-1067 (1998).

[12] Edge E.C. Stress-based Grant-Sanders method for predicting failure of composite laminates. Composites Science and Technology, 58, pp. 1033-1041 (1998).

[13] Rotem A. Prediction of laminate failure with the Rotem failure criterion. Composites Science and Technology, 58, pp. 1083-1094 (1998).

[14] Sun C.T., Tao J.X. Prediction of failure envelopes and stress/strain behaviour of composite laminates. Composites Science and Technology, 58, pp. 1125-1136 (1998).

[15] Rotem A, Nelson H.G. Failure of a laminated composite under tension-compression fatigue loading[J]. Composite science and technology, 36, pp. 45-62 (1989).

[16] Petitpas E., Renault M., Valentin D. Fatigue behavior of cross-ply CFRP laminates made of T300 or T400 fibres[J]. International Journal of Fatigue, 12(4), pp. 245-251 (1990).

[17] Waterbury M. C., Drzal L.T. On the determination of fiber strength by in-situ fiber strength testing[J]. Journal of composites Technology & Research, 13(1), pp. 22-28 (1991).