FINITE ELEMENT ANALYSIS OF A LAYERED COMPOSITE CYLINDER USING THE CONNECTION BETWEEN THE MACRO- AND MICROSTRUCTURE

A. Szekrényes
Research Assistant, Department of Applied Mechanics, Budapest University of Technology and Economics, H-1111. Budapest, Muegyetem rkp. 5. Hungary, Tel: (1) 463 1170, e-mail: szeki@mm.bme.hu

Summary

This paper presents a finite element study about a layered composite cylinder. Macro- and micromodels were constructed using the finite element code COSMOS/M. Different criterions were used to identify the macroscale failure of the composite cylinder. Varying the stacking sequence, results indicate matrix cracking and fibre-breakage as initial damage modes. Micro-stresses were investigated by three-dimensional finite element micromodels considering the periodicity and the offaxis of the fibres.

1 INTRODUCTION

Considering the composites in literature three types of FE analyses, namely micro-, meso- and macro-analysis can be found. The heterogeneous structure and the different fibre orientation of the composite materials require the usage of 3D FE models. In the micro/meso analyses, most of the cases 3D micromodels were used, because of the contacting layers with different fibre orientations. XIA et al. investigated a glass/epoxy laminate using RVE, as a meso-model [5]. SOLID elements were utilized to represent the micromodel. The model was a simplified unit cell and was not periodic in all directions. One surface of the model was loaded with uniformly distributed normal displacement. The damage was investigated using linear and nonlinear material models for the matrix. ISMAR and co-workers carried out a similar finite element study about metal matrix composites (MMCs) using different type of fibres [3]. These papers occupy only with 0° and 90° fibre orientations. The construction of 3D composite micromodels with various offaxis angle is an interest challenge, and no attention was focused to this problem. On the other hand in macroscale the composite structures are considered as linear orthotropic continuum, the damage occurrence can be identified using criterions related to the homogenized strength properties of the composites [2,4].

2 THE PROBLEM

In this study we identify the damage in a laterally loaded cylinder [4] and establish the connection between the macro- and microstructure. The stacking sequence was $[\theta/-\theta]_{sym}$, θ was varied from 0 to 90° in 5° increments. The geometry of the cylinder is shown in Fig.1. The experimentally measured elastic properties of the carbon-fibre (E_{11}=230 GPa, E_{22}=E_{33}=19.1 GPa, G_{12}=G_{31}=24 GPa, G_{23}=7.2 GPa, ν_{12}=ν_{13}=0.02, ν_{23}=0.28), epoxy resin (E=2.5 GPa, ν=0.35 and σ_{Yield}=55 MPa) and the composite (E_{11}=139 GPa, E_{22}=E_{33}=9.4 MPa, G_{12}=G_{31}=4.5 MPa, G_{23}=2.98 MPa, ν_{12}=ν_{13}=0.0209, ν_{23}=0.33 and V_f=0.57) were found in the literature [1,2]. The cylinder was modeled in two-scale step. In the first macroscopic step the cylinder was meshed with SOLIDL layered composite elements. An uniformly meshed model was used to study the failure mode and the location of initial failure varying the stacking sequence. After the FE analysis the failure indices were determined for every layer according to criterions. Then in the second macroscopic step in the vicinity of the nodes, where the failure index reached the critical value a locally refined mesh was constructed on the model. The mesh size was chosen to obtain the same size of the previously constructed periodical micromodels. The refined mesh was constructed to obtain the nodal displacement components (u, v and w) from the macro-analysis. The aforementioned displacement field was used as boundary condition in the micromodels (microscale step). Bilinear interpolation was utilized to prescribe the nodal macro displacements to the surfaces of the micromodel.

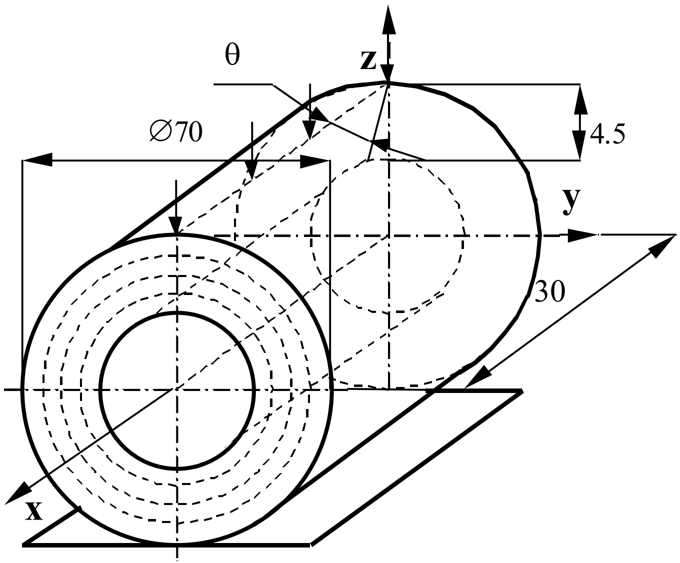

Fig.1. The cylinder geometry

3 FAILURE CRITERIONS AND STRENGTH PROPERTIES

The failure of the composite material was identified according to the Chang-Chang and the Tsai-Hill criterion. The Chang-Chang criterion considers three different failure modes, according to the contribution of stresses, while in the Tsai-Hill criterion the composite material is considered as homogenous orthotropic material and general failure occurs when the failure index reaches the value of '1'. The Chang-Chang criterion according to [2]:

Fibre failure (tension):
$$\mathbf{e_f} = \left(\frac{\sigma_{11}}{\mathbf{X_T}}\right)^2 + \left(\frac{\sigma_{12}^2 + \sigma_{13}^2}{\mathbf{S_f^2}}\right) \geq \mathbf{1},\ \text{if } \sigma_{11} > \mathbf{0} \tag{1}$$

Fibre failure (compression):
$$\mathbf{e_f} = \left(\frac{\sigma_{11}}{\mathbf{X_C}}\right)^2 + \left(\frac{\sigma_{12}^2 + \sigma_{13}^2}{\mathbf{S_f^2}}\right) \geq \mathbf{1},\ \text{if } \sigma_{11} < \mathbf{0} \tag{2}$$

Transverse matrix cracking:
$$\mathbf{e_{m1}} = \left(\frac{\sigma_{22}}{\mathbf{Y_T}}\right)^2 + \left(\frac{\sigma_{12}^2}{\mathbf{S_{12}}}\right) + \left(\frac{\sigma_{23}^2}{\mathbf{S_{m23}}}\right) \geq \mathbf{1},\ \text{if } \sigma_{22} \geq \mathbf{0} \tag{3}$$

Matrix crushing:
$$\mathbf{e_{m2}} = \frac{\mathbf{1}}{\mathbf{4}}\left(\frac{-\sigma_{22}}{\mathbf{S_{12}}}\right)^2 + \frac{\mathbf{Y_C}\sigma_{22}}{\mathbf{4S_{12}^2}} - \left(\frac{\sigma_{22}}{\mathbf{Y_C}}\right) + \left(\frac{\sigma_{12}^2}{\mathbf{S_{12}}}\right) \geq \mathbf{1},\ \text{if}\sigma_{22} < \mathbf{0} \tag{4}$$

Delamination:
$$\mathbf{e_d} = \left(\frac{\sigma_{33}}{\mathbf{Z_T}}\right)^2 + \left(\frac{\sigma_{23}^2}{\mathbf{S_{123}}}\right) + \left(\frac{\sigma_{31}^2}{\mathbf{S_{31}}}\right) \geq \mathbf{1},\ \text{if } \sigma_{33} \geq \mathbf{0} \tag{5}$$

The macro-stresses were calculated in the local element (X'-Y'-Z') coordinate system, according to Fig.2. Due to the offaxis (θ) of the fibre orientation, these stress components were transformed into the material coordinate system using the well-known stress transformation equations. The strength properties of the composite were also found in literature, the following values were used [2]: X_T=2070 MPa, X_C=1000 MPa, Y_T=74 MPa, Y_C=237 MPa, Z_T=74 MPa, Z_C=237 MPa, S_{12}=64 MPa, S_{m23}=64 MPa, S_{13}=86 MPa, S_f=120 MPa.

4 FINITE ELEMENT AND MATERIAL MODELS

To investigate the damage process, a series of macro- and micromodels were constructed with the finite element code COSMOS/M 2.0. The homogeneous macromodels consist of SOLIDL layered composite elements with different fibre orientations. In the macroscale the composite was modeled as a linear elastic, orthotropic material. First of all the whole cylinder was modeled to observe the stress field and the distribution of failure indices along the half of the circumference. A refined FE mesh was generated according to the location of the initial damage. The FE models and boundary conditions are depicted in Fig.2. After the macro-analysis was completed, observing the stress distribution several macro elements were selected and the nodal displacements were used as boundary conditions for the separated heterogeneous micromodels. The micromodels were constructed using simple SOLID elements, assuming the followings:

- the variation of the width along the thickness was neglected
- similar neglections were made for the displacement components
- periodicity in all three direction were assumed considering one layer
- the fibres are uniformly distributed in the matrix and behave as a linear elastic, orthotropic material
- the matrix is a nonlinear polymer and behaves similarly under compression and tension
- the interface between fibre and matrix is assumed to be perfect, and no debonding occurs.

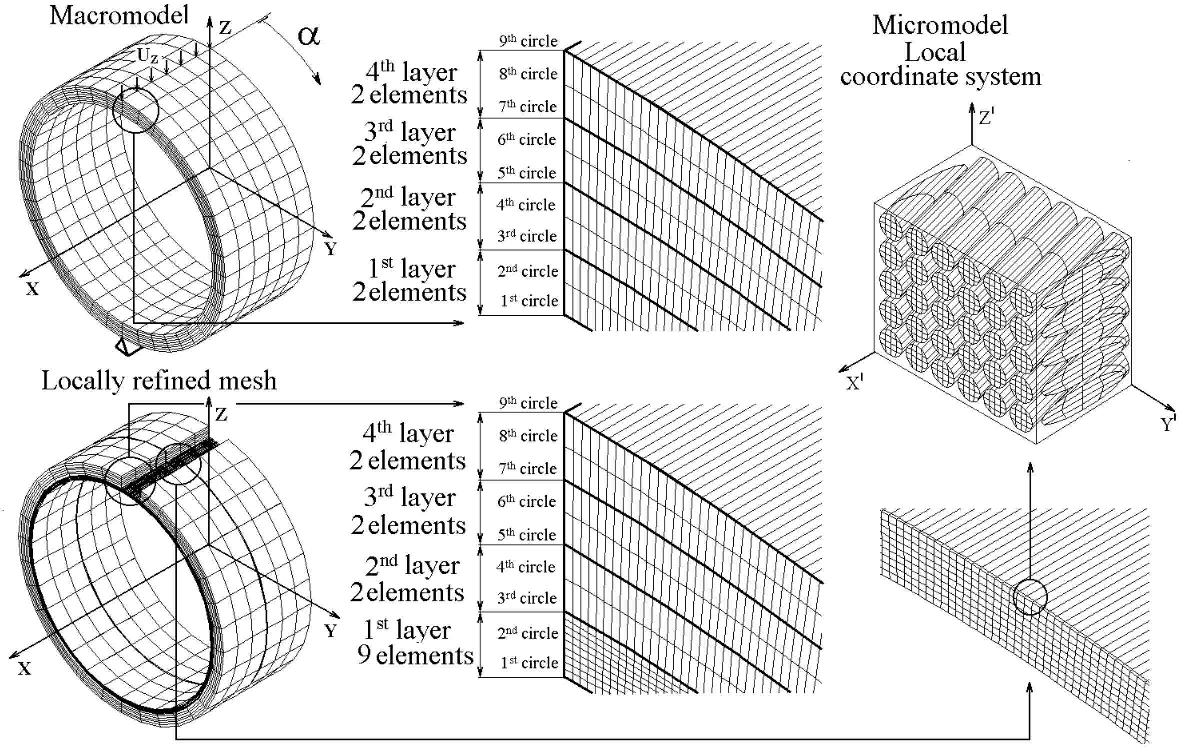

Fig.2. Finite element models

The nodal displacements from the macromodel were used for the linear interpolation. A computer program, written in Visual Basic 6 achieved the interpolation. The former program is suitable to make a proper input file (session file), that can be loaded into COSMOS/M. The micromodels were constrained in the X' direction. Prescribing the displacements for the micromodel another analysis was run. Both linear and nonlinear behaviors were investigated. In the right of Fig.2 a micromodel with only fibres (θ=15°) are depicted due to the simplicity and perspicuity. Every 3D FE micromodel contains five fibres along the thickness. The thickness of the models is 0.125 mm (125 μm), the width and the length was varied according to the offaxis angle and the periodicity criterion.

5 RESULTS AND DISCUSSION

Fig.3 shows a typical distribution of the failure indices along the half of the circumference in the macromodel. The matrix cracking and matrix crushing were denoted as

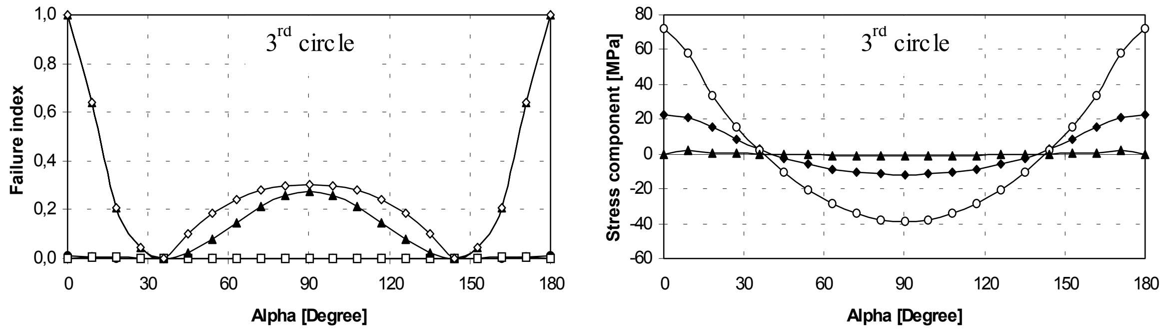

Fig.3. Failure indices and stresses along the circumference; θ=30°, u_z=-1.69; fibre failure [⎛], matrix damage [◊], delamination [□], Tsai-Hill [ʃ], σ_{11}[♦], σ_{22}[O], σ_{33}[ʃ]

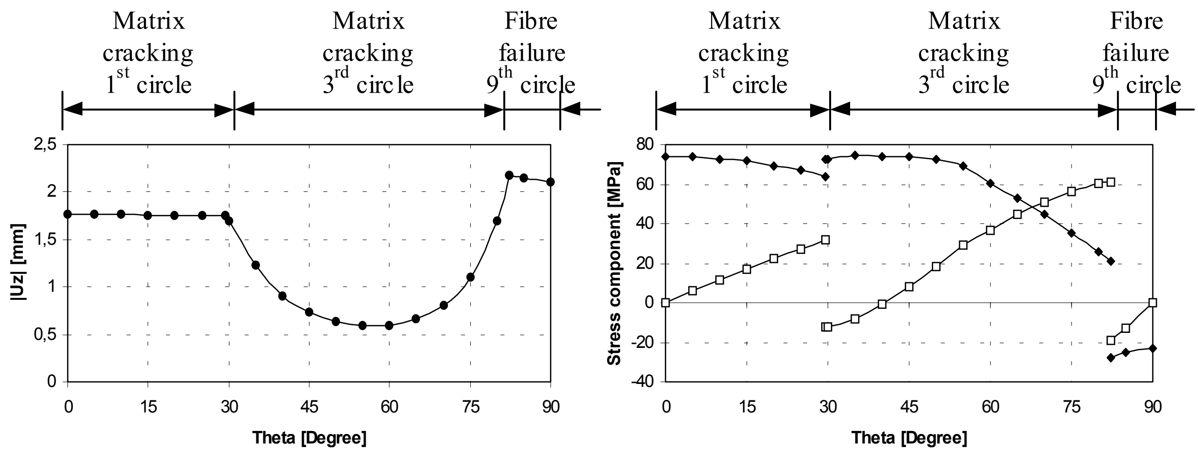

Fig.4. Critical absolute displacement, $|u_z|$ [⎛] and σ_{22} [♦], τ_{12} [□] against θ

matrix damage, according to the direction of σ_{22}. According to Fig.3 the critical points are in α=0 and 180°. The Tsai-Hill criterion produces the similar distribution as the criterion for matrix damage. Fig.4 shows the variation of the critical absolute lateral displacements against θ, and σ_{22}, τ_{12} against θ. Results indicate the damage always occurs in the layers of positive θ. It can be seen that three distinct regions exist according to Fig.4. In region I (0°≤θ≤29.5°) the failure modes is matrix cracking in the 1st circle, due to mainly σ_{22}. In region II (29.5°≤θ≤82.25°) the matrix cracking arises in the 3rd circle. Fig.4 shows τ_{12} significantly contributes to the matrix damage increasing the θ. Considering region III (82.25°≤θ≤90°) there is fibre failure in the 9th circle due to compressive stresses. Further observations show that the extension of damage shows two distinct regions. The first region (0°≤θ≤65°) the damage extends along the full width, but in the second region, if θ>65° the damage concentrates around the middle of the width. If θ=90° the damage again arises along the full width. These results correspond well with the experiments, presented by NISHIWAKI et al. [4]. The stress distribution in the microstructure was investigated using the micromodels.

Fig.5 shows the distribution of σ_{22} and τ_{12} in the case of θ=15° and 30°. Imagining the averaged stresses the nonlinear model gives more realistic results than the linear one. In comparison with the results of Fig.4 it is concluded that averaging the nonlinear micro-stresses in Fig.5 σ_{22} results in 150 MPa if θ=15° and 80 MPa if θ=30°. In Fig.4 these corresponding macro-stress values are 72 and 71 MPa. Considering the full interval (θ=0 to

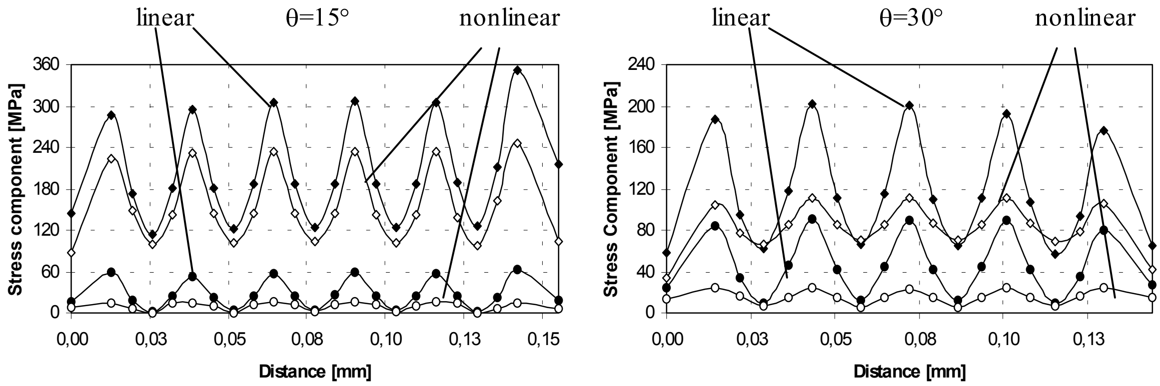

Fig.5. Stress distribution in the microstructure. σ_{22} [♦,◊], τ_{12} [(,O]

90°) the averaged micro-stresses show three different regions. In the interval of 0°≤θ<30° the micromodels overpredict the values of σ_{22} but underpredict the values of τ_{12}. Considering the 30°≤θ<60° interval both stress components are in good agreement with the macro-stresses. In the 60°≤θ≤90° region the agreement was found to be poor again.

6 CONCLUSIONS

The Chang-Chang and Tsai-Hill criterions were used to investigate the initial failure in the layered composite cylinder. The Tsai-Hill criterion predicts the general failure, while the Chang-Chang criterion separates the failure modes according to the contribution of stresses. The Chang-Chang criterion is suitable to predict three types of failure. Matrix cracking and fibre failure due to compression can be assessed as initial failure modes. The location and the mode of the failure depend on the stacking sequence. Results of the microanalysis show, that in the microscale the matrix yielding contributes to the accuracy of the prediction of stresses.

REFERENCES

1. Fiedler B., Hojo M., Ochiai S., Schulte K., Ochi M. (2001), "Finite-element modelling of initial matrix failure in CFRP under static transverse tensile load", *Composites Science and Technology*, Vol.61, 95-105
2. Hou J.P., Petrinic N., Ruiz C., Hallett S.R. (2000), "Prediction of impact damage in composite plates", *Composites Science and Technology* Vol.60, 273-281.
3. Ismar H., Schröter F., Streicher F. (2000), "Inelastic behavior of metal-matrix composites reinforced with fibres of silicon carbide, alumina or carbon: a finite element analysis", *Composites Science and Technology* Vol.60, 2129-2136.
4. Nishiwaki T. Yokoyama A., Maekawa Z., Hamada H., Mori S. (1995), "Quasi-three-dimensional analysis for composite cylinder under lateral compressive loading", *Composites for the Pressure Vessel Industry. PVP*-Vol. 302.
5. Xia Z., Chen Y., Ellyin F. (2000), "A meso/micro-mechanical model for damage progression in glass-fiber/epoxy cross ply laminates by finite-element analysis", *Composites Science and Technology* Vol. 60, 1171-1179.