NONLINEAR PROGRESSIVE DELAMINATION OF COMPOSITE PLATES UNDER CYCLIC LOADINGS

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SUMMARY: The paper deals with the numerical computations of pre – and post – buckling behaviour and with the prediction of a single delamination progression in a compressively loaded composite plates. The aim of the work is to propose the numerical method of fatigue stiffness degradation of a laminated composite structures by the analysis of one possible damage mode only i.e. delaminations. The composite structure is modelled with the use of 3-D finite elements and geometrical nonlinearities (large strains) are taken into account. The analysis includes also the possible contact (with or without friction) between the separated plies in the laminate. The load-displacement curves are used to estimate the overall laminate stiffness degradation. Applying the proposed numerical methodology the computations can be conducted from the initiation of the delamination process up to the prescribed end.

KEYWORDS: Delaminations, local instabilities, numerical modelling, plates, fatigue problems, contact analysis, nonlinear postbuckling behaviour.

INTRODUCTION

Delamination is one of possible damage mode in composite laminated structures. It is well-known that the delamination failure can lead to the significant degradation of the overall laminate stiffness and strength. In addition, the delamination is commonly associated with the local instability of a weaker sublaminate. Once the delamination has been initiated then catastastrophic failure may take place as a result of delamination buckling at greately reduced loads . Adjacent laminae actually buckle away from one another leading to local, global or mixed mode buckling.

The complexity of the problem as well as the increasing use of composite materials in industry have caused that the behaviour of delaminated structures has received a considerable attention in recent years. Chai et al. [1] may have been the first investigators to study this problem. Then, several authors have examined various aspects of delamination damage both under static and fatigue loading conditions. In general, research studies in this area have dealt with the following subjects:

- the initiation of delamination damage both in a pure numerical way (FE modelling – see e.g. Davila and Johnson [2]) and via the formulation of appropriate strength criteria – see e.g. Brewer and Lagace [3] or Kim and Soni [4],

- buckling analysis – the length and the form of the delaminated region is prescribed in advance and then the carrying capacity of structures (mainly plates) , understood in the sense of local buckling, is studied; both single (e.g. Sallam and Smitses [5]) and multiple (e.g. Lee et al. [6]) delaminations are considered,
- contact problems – during the loading (or unloading process) the initially opened region of delamination can both grew and shrink, however, in the latter case the strict and concise contact analysis is required – see e.g. Cochelin and Potier-Ferry [7] – 2-D analysis and Whitcomb [8] – 3-D analysis,
- theoretical bacground of the problem – there is need for an analytical theoretical formulation that can be applied to the analysis of multilayered composite structures – Barbero and Reddy [9] adopted layer-wise plate theory , whereas Ochoa et al. [10] proposed 3-D FE formulations for large deformation analysis,
- fatigue problems – the fracture of laminated composites is induced by several distinctly different failure modes where delaminations are one of them; Bergmann and Prinz [11] suggested a mechanistic model for fatigue life estimations.

SCOPE OF INVESTIGATIONS

A short review of investigations conducted in this area demonstrates evidently that there is a lack of a general approch to the delamination problem, connected particularly with the modelling of the problem from the initiation of the process up to the end. In the present study we intend to model the delamination crack development including both geometrical nonlinearities and contact growth and possible closure. Since for cyclic loads the fatigue life predictions are the most interesting problem we propose the method of numerical modelling of loading and unloading process. Then, we consider their influence on the delamination progression.
The numerical analysis is conducted with the use of the commercial FE package NISA II [12]. The problem discussed herein deals with the compression of a multilayered rectangular plate (b/a =2, t/a=0.1) made of unidirectional fibre reinforced plastics. The external compressive forces act on the opposite, longer edges of the plate. In the thickness direction each ply of the composite plate is approximated by two layers made of 3-D wedges (NKTP = 4) having six nodes, each of them posseses three degrees of freedom - displacements. It is assumed that the plate has a single delamination only, however its localization and dimensions are not known in advance. They are determined and verified at each incremental step of the loading process in order to establish the propagation of the delaminated zone. At each step of loading large strain and updated Lagrangian formulation options are switched on. The classical linear approach cannot address properly the complexity that arises when the delamination is present. In addition, at this stagethe laminate may become unsymmetric and the bending – stretching coupling which enhancesthe possiblity of large deformation response is important.
In general, the analysis is divided into the following steps:

- at each nodes of the adjacent plies of the laminate the strength criterion given in Ref. [3] is applied in order to detect the initiation of the delaminated regions; if one delaminated region has been detected we assume that the delamination progression is posible between those plies in the laminate only,
- if the delamination is possible the initial FE model is supplemented by additional 2-D gap (contact) FE that connect the initially separated plies; the gap elements may be frictionless or not,
- the loading process is conducted according to the assumed time amplitude curve (cyclic loads) where the assumed maximal value of the compressive force is prescribed to be

higher than the loads corresponding to the delamination initiation and bifurcation buckling.

The plate with one stacking sequence have been considered only - 90/0/0/90. The ply mechanical properties used in computations was typical for carbon / epoxy resin and are given below:

$$E_1 = 134 \text{ GPa}, E_2 = E_3 = 10.2 \text{ Gpa}, G_{12} = G_{13} = 5.52 \text{ GPa} , G_{23} = 3.43 \text{ GPa},$$

$$\nu_{12} = \nu_{13} = 0.3, \nu_{23} = 0.49$$

LOAD – DISPLACEMENT CURVES

Buckling, postbuckling and contact analysis

The classical pattern of the load – displacement curves is shown in Fig.1. The lateral displacement w measured at the plate center (the maximal displacements of the delaminated zone) is plotted against the load parameter denoted also further as time. The plot consists of two parts , the first where the trivial fundamental path exists and the second corresponding to bifurcation buckling – both for frictionless or with friction contact problem analysis in the delaminated region.

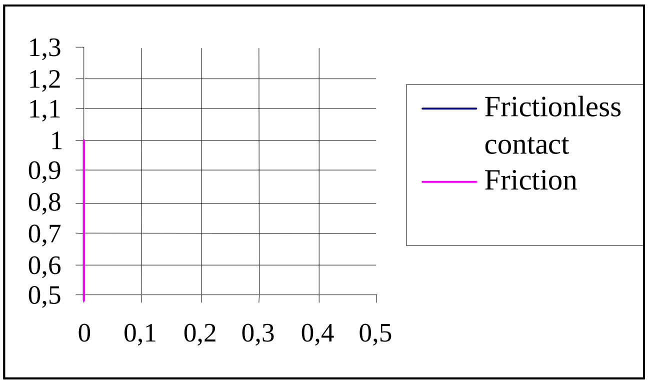

Fig.1: The load-displacement curves for an axially compressed rectangular plate.

It is worth to mention that the delamination progression starts at the first part of the curves (see Fig.2a) and then as the bifurcation buckling occurs the contact domain is reduced and the existing gap between the adjacent plies is negligibly small – Fig.2b. Let us note that the friction changes the character of the postbuckling deformations due to the energy dissipation in the contact area. Whitcomb [8] demonstrated that a large percentage of the initially delaminated front was closed. It imposes evidently the necessity of using friction contact condition in the contact analysis. However, as it is presented in Fig.1 friction may change also the post-buckling behaviour of structures but it is not known in advance what type of the friction constitutive law can be applied in the analysis.

a)

b)

Fig.2: Deformations of the plate cross – section (not to scale) at the pre-buckling (a) and post-buckling (b) states.

It should be emphasized that the partial closing of the delaminated zone at the post-buckling states is one of possible modes of deformations. Others associated with openning of the delaminated regions are discussed e.g. in Refs. [6,7].
The initial delaminated region at the pre-buckling state is of the elliptical form, however as the plate buckles about 65 % of the delaminated zone is closed .

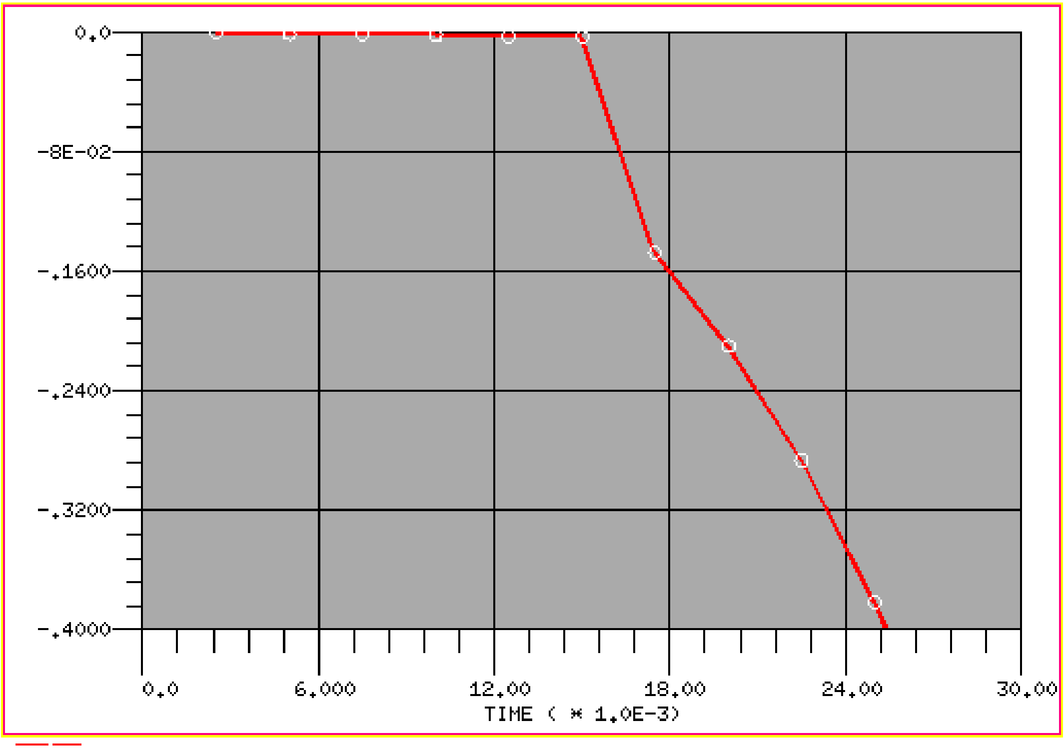

Fig.3: Variations of the axial displacements with the load parameter (time).

The plot presented in Fig.1 is not very convenient during the analysis of the stiffness degradation what is the most significant effect in the fatigue analysis. Therefore, another load-displacement plot have been studied that demonstrates the stiffness variations. For our purposes the plot showing the axial displacements variations u versus the load parameter – Fig.3. As it may been seen the slope of the curve corresponds directly to the overall stiffness of the laminate. The drastic change of the overall stiffness is observed in the post-buckling region.

Loading – unloading process

The similar plot to that shown in Fig.3 have been constructed to analyse one cycle (loading – unloading) of the fatigue process. The results are drawn in Fig.4.

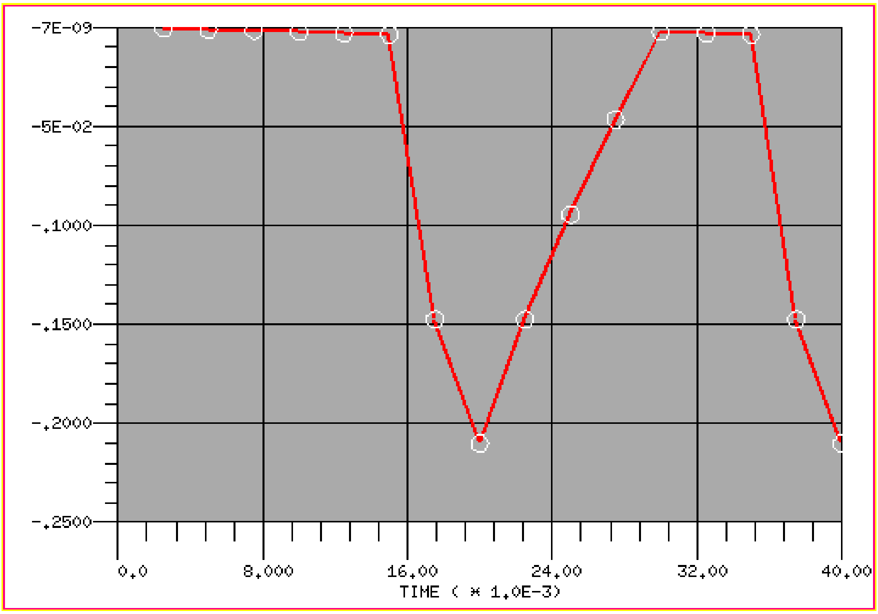

Fig.4: The load –displacement curve for one cycle of loading – axial displacements u.

As it may be noticed the slopes and the final displacements for the curves are almost identical. In addition, the unloading portion of the curve is associated with the openining of the delaminated zone – its form is presented in Fig.5.

Fig.5: Deformations of the plate cross-section during unloading (the plot corresponds to the minimal value of the external forcein one cycle of fatigue load).

It should be emphasized that the above results obtained with the use of the numerical model are in a very good agreement with the experimental ones. It has been observed that during fatigue loading the overall stiffness degradation caused by the delamination damage mode only is almost independent on the number of loading cycles. This is obvious from the results plotted in Fig.4.

CONCLUDING REMARKS

The present work demonstrates a numerical model applied to the description of delamination failure mode influence on the stiffness degradation for composite laminated structures subjected to buckling loading conditions. The following conclusions can be reached as the result of the study:

- the importance of the concise contact analysis during the deformation process both in the pre-buckling and post-buckling range,
- the necessity of taking into account of friction effects in post – buckling analysis,
- the post-buckling analysis allows us to determine the overall stiffness degradation during fatigue loadings,
- the proposed model does not explain the possibility of the final fatigue failure of structures caused by the fibre breakage – we may expect only that repeated openning of delaminations associated with the large deformations can lead to the matrix cracking and further damage of constructions,
- it is necessary to include in considerations the initial matrix cracking of structures connected with the initial fatigue damage.

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