Buckling and post-buckling analyses of stiffened composite shells with inter-laminar damages

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Keywords:
Laminated composite, stiffened shell, buckling, post-buckling analysis, delamination, fracture toughness

ABSTRACT

In the present paper buckling and post-buckling response of axially loaded composite stiffened shell with inter-laminar damage regions have been solved using computer code LS-DYNA. Reduced number of layers and reduced stiffness in damaged region has been investigated. In addition skin delamination with contact model has been used for the analysis of the fracture toughness in the damaged regions. Energy release rates are calculated by Technique-B methodology, employing the 2D shell elements. Mode I and mode II fracture properties are obtained in the damaged regions of the carbon/epoxy composite stiffened shell. The influence of different damages regions on the buckling and post-buckling behavior of stiffened shell is investigated.

INTRODUCTION

Lightweight stiffened composite panels and shells are often used in different aircraft structural designs. The buckling and post-buckling behavior under axial load is actual task in the design of such kind of structures. A post-buckling design philosophy can be employed in order to save weight of the shell structure, based on the knowledge that stiffened panels are typically capable of carrying considerable additional load following buckling towards the ultimate failure is reached [1]. Accidental damages can arise from the service events or other unexpected actions therefore causing the fiber brakeage or skin delamination. Due to this reason more actual problem is prediction of the crack growth influence over buckling and post-buckling behavior of the damaged structure, as failure may occur prior to the designed critical load. In this paper has been made analysis of stiffened laminated shell under axial load for evaluation buckling and post-buckling behavior of the structure with damaged zones by computer code ANSYS/LS-DYNA explicit, version 970D [2]. The energy release rate has been calculated in the damaged zones using Virtual Crack Closure Integral method [3].

Experimental Investigations

The panel considered is one sixth of a cylinder with arc length a=680 mm, panel internal radius R=938.5 mm and panel height 720 mm. [4] The skin consists from 8 layers and their stacking sequence is follows $(0/-45/+45/90)_s$. Thickness of each layer is 0.125 mm. The stringers consist from 24 layers with stacking sequence $(-45/+45/0/0/-45/+45/0/0/-45/+45/0/0)_s$.
All layers of the laminate are unidirectional and made from the same material with the following characteristics:

Longitudinal modulus of elasticity	E_{11} = 147.3 GPa
Transverse modulus of elasticity	E_{22} = 11.8 GPa
In-plane shear modulus	G_{12} = 6.0 GPa
Transverse shear modulus	G_{13} = 6.0 GPa
	G_{23} = 4.3 GPa
Poisson's ratio	v_{12} = 0.3
Material density	ρ = 1600 kg/m³

The shell has been modelled with geometric imperfection [5], considering the internal radius and height of ribs and shown in Fig. 1.

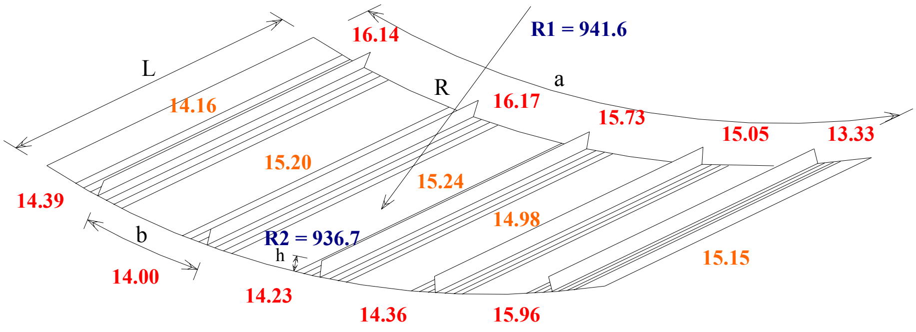

Fig. 1 The geometrical imperfections of the stiffened shell.

The shell finite element has been used for modeling the skin and stiffeners of the structure. The reaction forces at the tip of the cracks have been obtained from inputted link elements. The link element connecting the shell element has been modeled from elastic material with following properties:

Longitudinal modulus of elasticity	E = 1235 GPa
Poisson's ratio	v = 0.3
Material density (virtual)	$\square_{bv}$ $\square$ 1.6e+6 kg/m^3

Material density of the link is multiplied 1000 times comparing with real density in order to decrease the time step for nonlinear solution. Since the volume of the link element is insignificant, virtual density doesn't influence the results of analysis. Selected stiffness for link element is applied ensuring rigidity of the joints between the shell elements in the front of the crack.
The only load case considered is axial compression. The upper and lower edges of the panel are fixed in clamping boxes, boundary conditions are presented in Fig. 2, where T is translation, R is rotation, r, t, a are radial, tangential and axial directions.
For evaluation the influence of damage regions on the buckling and post-buckling behavior of the shell, following types of damages regions have been considered:

1) A delamination of skin in the damage regions, 4 layers of skin are delaminated from outer surface
2) Decreasing the number of layers of skin in the regions with damage
    a. 4 layers of skin are deleted in the damage region
    b. 5 layers of skin are deleted in the damage region
    c. 6 layers of skin are deleted in the damage region

The finite element mesh for case study with decreasing number of layers is presented in Fig. 3. Furthermore a form of the damage regions is shown in Fig. 4. In comparison the finite element mesh with delamination zones in the shell is presented in Fig. 5. To simplify modeling procedure all forms of the regions are idealized Fig. 6.

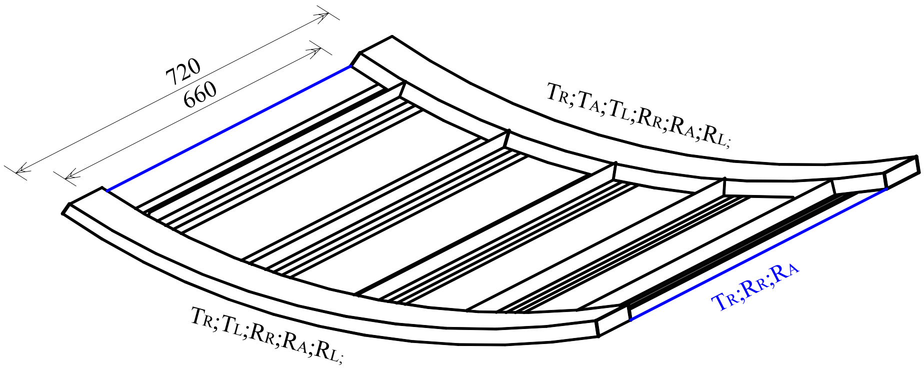

Fig. 2 Boundary conditions of the panel.

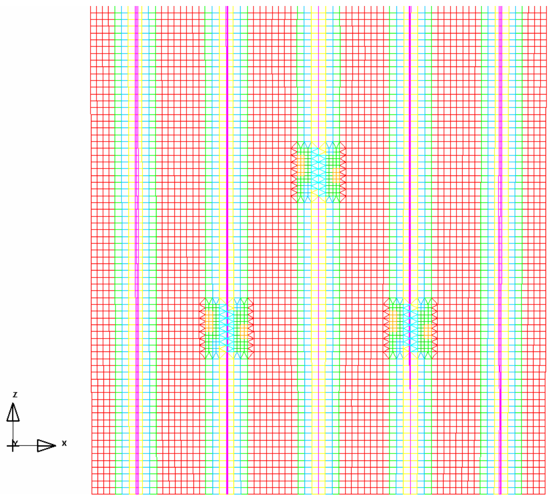

Fig.3 Finite element mesh for model with decreasing number of layers.

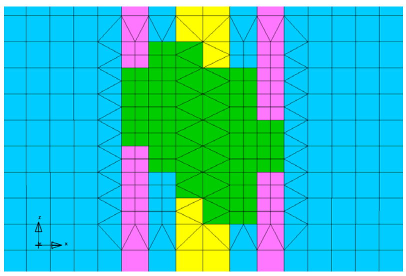

Fig. 4 Damage region with decreasing number of layers.

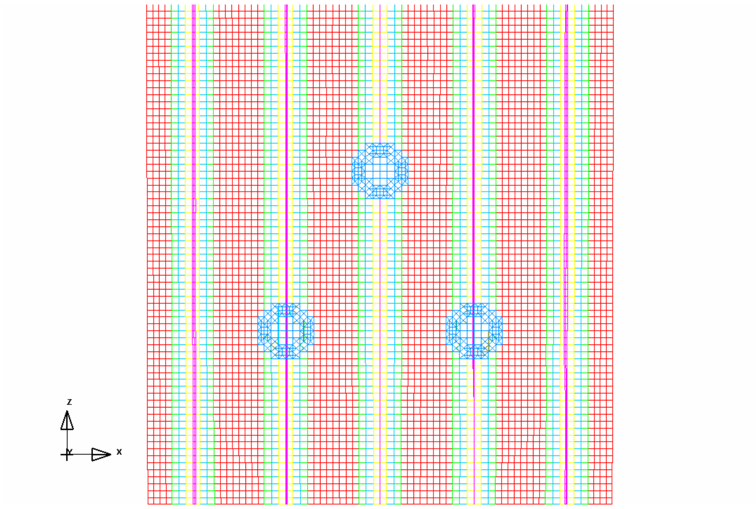

Fig.5 Finite element mesh for model with delamination of skin.

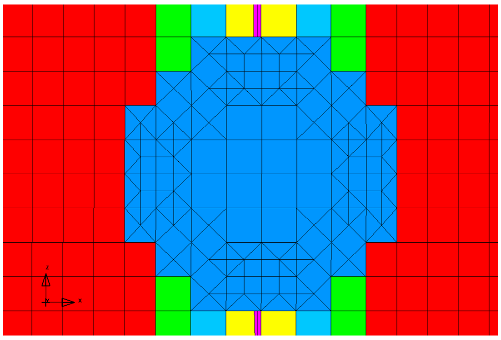

Fig. 6 Damage region with decreasing number of layers.

The four-node shell element was employed for composite shell modeling. One integration point along the thickness for each layer is considered. The beam two-node element has been used for monitoring the reaction forces between layers of the shell at the front of crack propagation. The cross section of link element is 0.5 x 0.5 mm. Contact task has been realized for modeling delamination in damaged region.

The so-called Technique-B has been used for calculation the energy release rate in the region with delaminating. The modeling was performed in way that the size of all elements ahead and behind of the debonding front are equal to *a*. Details of the model near the debonding front is shown in Fig. 7. The energy release rates have been calculated by following expressions:

For mode I component For mode II component For mode III component

$$G_{1c} = \frac{F_{z_j} w_m}{2ea}, \quad (1) \qquad G_{IIc} = \frac{F_{x_j} u_m}{2ea}, \quad (2) \qquad G_{IIIc} = \frac{F_{y_j} v_m}{2ea}, \quad (3)$$

Total energy release rate $\boldsymbol{G_T}$: $\boldsymbol{G_T = G_I + G_{II} + G_{III}}$

The loading speed of the shell with reducing numbers of layers in damaged zones was 0.5 mm/sec based on convergence of solution under different loading speeds. The maximal displacement of upper part of shell reached 4 mm.

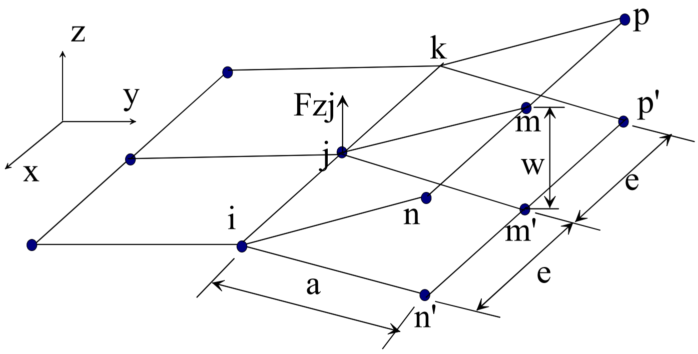

Fig. 7 Model with 4-noded shell element near debonding front.

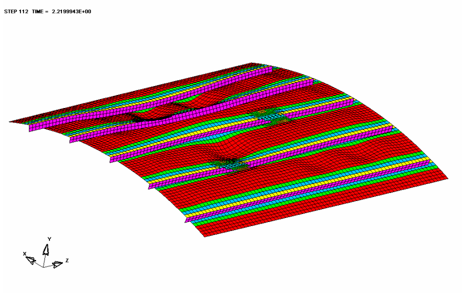

Fig. 8a Deformation under axial comp- ression 66.8 kN, shortening 0.61 mm

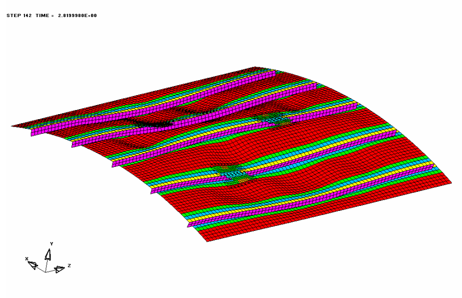

Fig.8b Deformation under axial comp- ression 100.4 kN, shortening 1.04 mm

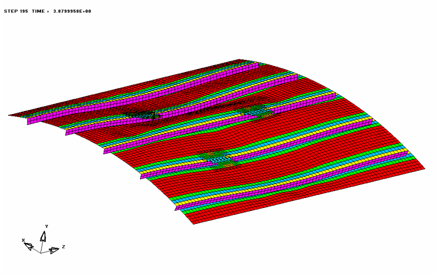

Fig.8c Deformation under axial compression 128.9 kN, shortening 2.54 mm

The buckled mode of the shell with reduced 4 layers in the damaged regions is shown inn Fig. 8 a-c. Besides summarized load-shortening curves for undamaged and damaged shells with reduced layers in damaged regions are presented in Fig. 9.

In order to compare different damage zone influence the load shortening curves for undamaged shell and shell with delamination in damaged zones are presented in Fig. 10.

The investigation of crack opening in the damaged zones showed the dependence this one from a rate of load. For investigation of this influence the shell has been analyzed using varying speed of loading, 0.67 mm/sec, 0.5 mm/sec and 0.25 mm/sec. The crack openings in the central points of damaged regions in depending of shortening are shown in Fig. 11a,b,c. The results of calculation of the energy release rates at the crack tip in some points of damaged region are presented in Table 1 for Mode I and in the Table 2 for Mode II.

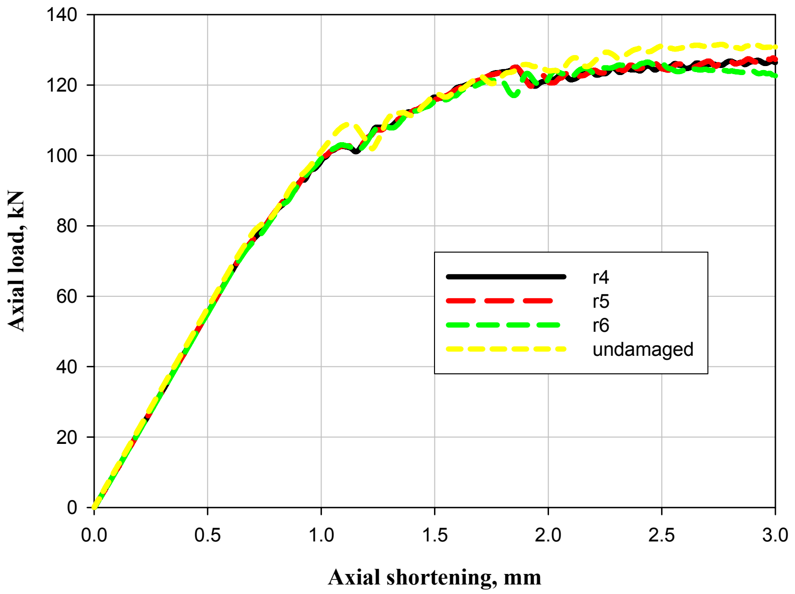

Fig. 9 The summarized load-shortening curve for undamaged and damaged shells with reducing number layers in damaged regions.

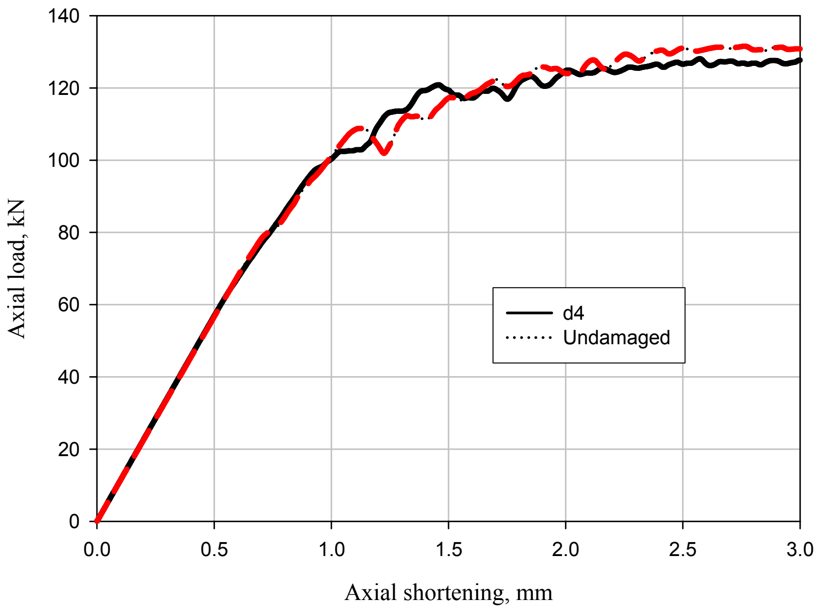

Fig. 10 Comparison of load shortening for undamaged panel and panel with delamination of 4 layers in damaged regions.

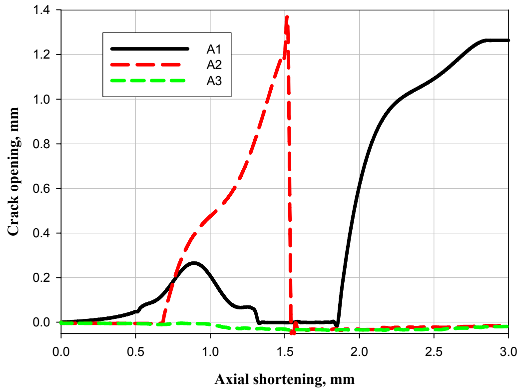

Fig. 11 a Approximation of the crack openings in the central points of damaged regions in depending of shortening, loading rate 0.67 mm/sec.

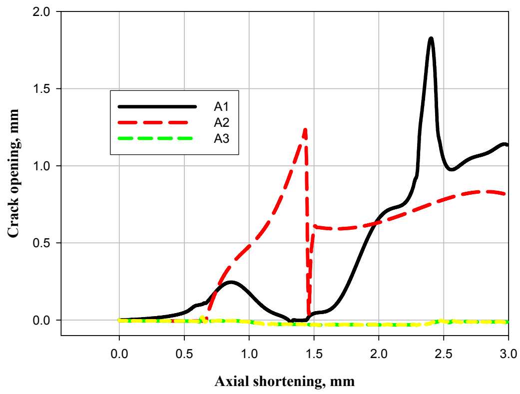

Fig. 11 b Approximation of the crack openings in the central points of damaged regions in depending of shortening, loading rate 0.5 mm/sec.

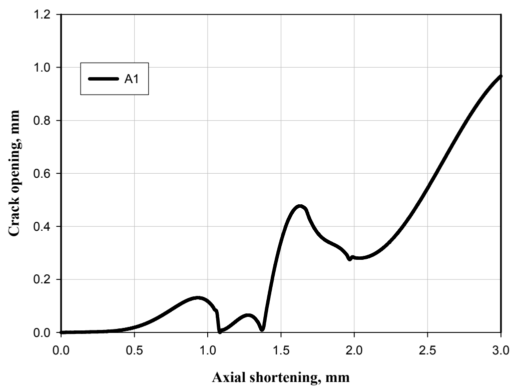

Fig. 11 c Approximation of the crack openings in the central points of damaged regions in depending of shortening, loading rate 0.25 mm/sec.

Table 1. Results of calculation of energy release rate in Mode I

Stroke (mm)	***E1*** (J/m^2)	***E2***(J/m^2)	***E3***(J/m^2)	***F1*** (J/m^2)	***F2*** (J/m^2)	***F3*** (J/m^2)
0.6	0.0	0.2	0.0	0.1	0.0	0.0
1.2	0.0	2.6	2.5	1.2	0.0	0.0
1.8	37.5	3.7	1.0	0.0	1.2	0.0
2.4	37.5	3.7	1.0	12.3	14.4	20.2
3.0	0.0	7.1	0.0	26.5	58.6	0.0

Table 2. Results of calculation of energy release rate in Mode II

Stroke (mm)	***E1*** (J/m^2)	***E2***(J/m^2)	***E3***(J/m^2)	***F1*** (J/m^2)	***F2*** (J/m^2)	***F3*** (J/m^2)
0.6	0.2	0.1	1.0	0.1	2.2	3.6
1.2	0.2	0.0	36.2	8.0	8.4	281.8
1.8	38.2	12.9	28.8	2.4	739.4	621.6
2.4	38.2	12.9	28.8	79.1	1116.7	952.6
3.0	101.6	35.6	51.5	251.1	1449.0	1080.3

The critical energy release rate, obtained from unidirectional material DCB and ENF tests are following: G_I^C = 269 J/m^2 and G_{II}^C = 687 J/m^2. Assuming that the crack should begin to grow in point F2 when axial shortening will reach the limit of 1.6 mm and for point F3 when axial shortening will reach the limit of 1.9 mm due to Mode II loading conditions.

Summary and Conclusions

The buckling and post-buckling behavior of stiffened composite shell with damaged regions has been investigated under axial load using computer code LS-DYNA. Dependences between axial load and shortening have been obtained for different kind of damages in stiffened composite shell. Contact task has been realized for modeling of delamination. Energy release rates have been calculated in the damages regions for prediction of crack growing. Crack opening in the damaged zones is depending from rate of loading in numerical simulation. The numerical results should be compared with experimental results for prediction of crack growing.

"This work was partly supported by the European Commission, Priority Aeronautics and Space, Contract AST3-CT-2003-502723. The information in this abstract is provided as is and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof uses the information at its sole risk and liability."

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