Description of delaminations in composite multilayered structures – comparison of numerical and experimental results for compressed plates

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Abstract. The buckling loads and the post-buckling behavior of the perfect and imperfect delaminated plate are investigated in the paper. For this purpose the concise formulations enabling to derive pre- and post-buckling behaviour of plates with embedded delaminations is presented. The computations are made using FE package NISA II and Mathematica package. Obtained results for buckling loads and the post-buckling behaviour are compared with the experimental results. The Digital Image Correlation (DIC) technique is employed to verify the uniformity and homogeneity of deformations.

1. Introduction

The influence of delaminations on the deformations, failure modes and loads have been studied by the author for many years. The analysis started in 1995 when the buckling loads of doubly-curved shells with delaminations were considered [1]. Then, various problems connected with the behaviour of composite structures with delaminations were discussed by the author with coworkers in Refs [2-12]. The discussed problems dealt with the analysis of composite plates and panels with elliptic and circular delaminations and subjected to static and cyclic (fatigue) loads. The considerations were not only theoretical (numerical – FE studies) but also experimental with the use of the SHM and thermography. The cited above references give the review of the literature in this area. The supplemented information from the existing literature is also given in Ref [13]. The aim of the present paper is following:

- to present the results of experimental investigations by the analysis of the deformation process characterized by the force-displacement curves and with the use of the digital image correlation (DIC) technique – see Ref. [14];
- to compare the experimental results with the finite element (FE) computations.

2. Experimental Studies

The composite laminated plates were made of eight layers of glass/epoxy prepreg (TVR 380M12/26%R). The symmetric laminates were studied and each of the layers were oriented at ±45° referring to the axis of loading. Seven rectangular plates were tested:

- two plates without delaminations (Lx=200, Ly=300);
- two plates (Lx=200, Ly=300) with a central circular delamination (Ddel=142.5) located between fourth and fifth layer (see Fig. 1a);
three plates with a central rectangular delamination located between first and second layers (see Fig. 2a).

All plates had the following mechanical properties: $E_L=47.12$ [GPa], $E_T=14.61$ [GPa], $\nu_{LT}=0.09$, $\nu_{TL}=0.28$, $G_{LT}=16.03$ [GPa]. The assumed total average thickness of the plates was equal to 2.1 mm. The artificial delamination was made of Teflon tape of thickness 0.15 mm.

**Figure 1.** The form of the delamination and the corresponding load-displacement curves.

The presented diagrams in Figures 1 and 2 show that no damage/fracture occurs before buckling. After buckling the appearance of internal cracks can be observed in the form of irregularities in the curves force-displacement (the specimen S3 in Fig.1 and specimens S2 and S3 in Figure 2). In Figure 2 the significant differences in the values of the maximal loads are observed for specimens S1 and S3 due to the development of delaminations in the specimen S3 before the loss of stability.

**Figure 2.** The form of the delamination and the corresponding load-displacement curves.
3. Digital Image Correlation

The progressive failure analysis of composite structures depends on crack generation, crack propagation and, which can’t be analyzed and this can’t be identified by a human eye, due to damages may occur at micro scale and nano scale. Chu et al 1985 developed a measurement technique by combining deformation theory and Digital Image Correlation and by applying interpolation theory to expand its applications.

The Digital Image Correlation technique was applied during the compression tests in order to obtain the stress-strain curves and to identify the fracture location at the early stages of the tests. Figures 3-5 present the distributions of the normal to the plate deflections w for the tested specimens. As it may be observed in Figures 3, 4 the distributions of displacements corresponds directly to the buckling form/mode of the compressed plates and the maximal displacement occurs at the middle of the plate. The situation is changed for plates with rectangular delamination demonstrated in Figure 2. The final plate deformation (Figure 5) has no symmetry. The opening of the delamination starts at the opposite edges of the delamination and then is developed in the direction of the plate center. This phenomena is mainly connected with the free edge delamination process and in general it has a random character as it may be noticed by the comparison of the results for three specimens plotted in Figure 2.

Figure 3. The normal w displacement distribution for plate with no delamination (specimen S2).

Figure 4. The normal w displacement distribution for plate with circular delamination (specimen S3).
discrepancy is mainly due to random scatter of buckling loads. However, the experimental values of buckling loads are lower than theoretical. The figures 1 and 2.

Table 1.

5. Discussion of Results and Concluding Remarks

circular delamination, b) rectangular delamination, c) form of the imperfection.

4. Numerical (Finite Element) Modelling

Then, with the aid of the numerical FE package NISA II the buckling loads and the post-buckling behaviour (the Riks method) were computed. The example of the mesh is shown in Figures 6 a, b. The analysis was carried out with the use of 3D FE layered orthotropic elements. In the thickness direction the plate was divided into four layers – the thickness of the first layer is equal to the thickness of the first sublaminate. The results were compared with the results presented by Ricci [15] for perfect delaminated plates. Reducing the delamination ratio (δ→0) one can obtain the results for perfect plates (Figure 6 c).

Figure 5. The normal w deflection distribution for plate with rectangular delamination (specimen S1).

Figure 6. Example of the mesh used for the discretization of the delaminated plates (low density) a) circular delamination, b) rectangular delamination, c) form of the imperfection.

5. Discussion of Results and Concluding Remarks

The experimental (average for the identical type of specimens) and numerical results are compared in Table 1. Let us note that the difference of dimensions between the tested plates is observed (see Figures 1 and 2). As it may be observed in Figure 7 the prescribed imperfection reduces the values of buckling loads. However, the experimental values of buckling loads are lower than theoretical. The discrepancy is mainly due to random scatter of geometrical parameters characterizing the tested plates.
As it is shown in Ref [16] the non-homogeneity of plate geometry can affect significantly the load distribution along plate edges. In addition it is well known that the residual thermal stresses (heating and cooling process) may increase or reduce significantly buckling loads and post-buckling behaviour. It should be emphasized that new experiments in this area are planned.

![Figure 7. The comparison of the results for buckling loads and the post-buckling behaviour.](image)

### Table 1. Comparison of buckling loads

|                     | Without delamination | Circular delamination | Rectangular delamination |
|---------------------|----------------------|-----------------------|--------------------------|
| Experimental (average) | 3.35 [kN]           | 2.75 [kN]             | 3.55 [kN]                |
| Numerical (perfect plates) | 5.5 [kN]           | 3.2 [kN]             | 4.25 [kN]                |

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