STRENGTH CRITERIA DEVELOPMENT FOR COMPOSITE STRUCTURES BASING ON SOLUTIONS SUPERPOSITION FOR MODELS OF DIFFERENT LEVELS

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Abstract

The approach to developing strength criteria for composite structures is proposed. It based on superposition of solutions for FE-models of different levels. The first level of FE model is used for analysis of strain state of undamaged composite structure. The parameters of the strain state are considered as base values for estimation of the structure strength taking into account presence of various cracks in matrix.

Strength estimation is carried out basing on a database of typical solutions of specific nonlinear task for different areas of the structure. The analysis concerns buckling, post-buckling behaviour of composite skin, nonlinear deformations of matrix under tension, etc. These tasks are solved on the basis of specialized FE models.

The combination of the solutions for these traditional and specialized models enables to generate simple and reliable criteria for an estimation of strength of thin-walled structures.

Validation of these criteria has been carried out for composite skins with different stacking sequences and with different characteristics of resin on the basis of experimental research of strength. Results of the validation of the strength criteria for orthogonal layers in skin have demonstrated good agreement of numerical results with experimental data.

Strength criteria are shown in the paper as examples for different cases of layup and characteristics of fiber and matrix.

1 Introduction

Applying existent strength criteria for composite laminates under complex loading requires an analysis of stress-strain state in each monolayer of the composite package. A preliminary designing of composite airframe structures comprises analyses of a large number of variants of the structure parameters, so it is very difficult to use conventional strength criteria which require carrying out a large number of calculations. To provide high efficiency of the designing procedure it is necessary to have simple and confident criteria for strength analysis of composite package under complex loading.

This paper contains results of developing a simple strength criterion based on analysis of general strain state of typical elements of airframe consisted of thin skin and ribs (Fig. 1). The skin comprises a set of differently oriented monolayers. It is well known that the main reason of skin failure is delamination resulted in a loss of integrity of the skin package. Compression of the skin package will inevitably lead to failure of the skin. The delamination arises, as a rule, due to cracking between two monolayers.

Current resins are rather fragile and their ultimate strain characteristics for tension are less ($\varepsilon_{utr} \leq 2.3\text{-}2.7\%$) than in the cases of metal structutre. It is well known that tension of a monolayer of the composite package in a direction across fibre leads to the matrix failure at relatively small value of tension strain of the package.

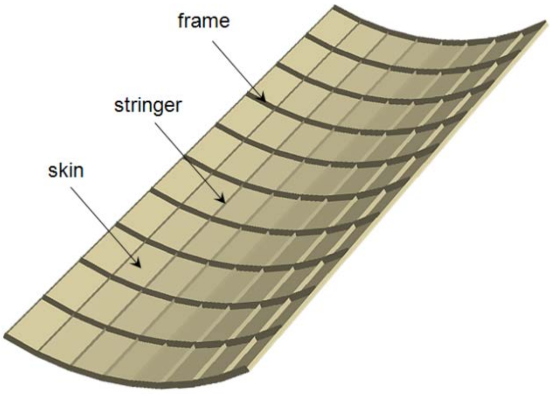

Fig. 1 Composite panel

2 Strength criterion of composite package delamination for matrix failure

A composite structure element is essentially heterogeneous and anisotropic; stiffness and strength characteristics of its components (fibre and matrix) are substantially different. Therefore it is not correct to use for strength analysis of this element criteria based on analysis of general stresses obtained for the homogeneous element.

The composite package consists of fibers and resin. The load-bearing component of the composite element is a stack of fibres which have very high longitudinal stiffness and strength. The resin is intended to transfer loads from one fibre to another providing the element integrity. The notion “stress in a composite package” can be used only as an averaged value for analyzing force flows in a macro-model of structure consisted of homogeneous elements with averaged characteristics.

The main problem of development composite structures of airframe is that there is no industrial technology so far performing strong bonding between fibers, similar to welding of steel reinforcements in reinforced concrete, and consequently, carbon fibers can be bonded in a monolithic structure only by the means of binding (resin). This is the root of many problems of using composite materials in airframe primary structure. One of them is that in frame of quasi-isotropic and other orthogonal packages current resins do not allow carbon fibers to realize fully their high strength characteristics. Due to very small value of ultimate tensile strain a carbon fiber in these packages can be loaded not more than by 25-30% of their ultimate stress. The ultimate relative tensile strain of current resins usually not exceed 2.3-2.7% (on condition that $\sigma_{utr} \geq$ 6-8 kgf/mm^2) Taking into account that this parameter for current carbon fibers is 1.9-2.3%, at first sight it seems that these parameters of resins and fibers are well harmonized, and destruction of fibers will precede the destruction of the resins. However the experience shows that the primary destruction of a composite package, as a rule, occurs in resin. This phenomenon can be easily illustrated in frame of the model task (Fig. 2) when the deformed state of a composite orthogonal package with (0-90^o layers) under an external tensile force coinciding with a direction of a zero layer was investigated.

This research was organized not only to illustrate this well-known phenomenon, but also to find a simple and confident relationship between general deformation of the composite package and a deformed state of a resin in this package. For solving this task parametrical two-level finite element strength model of the orthogonal symmetric composite package consisting of 17 monolayers (thickness of a monolayer was 0.1-0.15 mm) with orientation 0-90^o has been investigated using conventional MSC/NASTRAN code. In frame of this parametrical model two different FE models were automatically generated. First one – “general” FE model with anisotropic membrane 2D elements was created for definition of general stress-strain state of the whole package of layers under external loads. Such FE model is as a rule created for analysis of general deformations of thin-walled structure elements (panel, wall, rib, frame) (see Fig. 2a). The second one – “box” FE model with isotropic 3D elements was created for definition of an internal stress-strain state inside the package (Fig. 2b). This model could be automatically created for each of boxes of the package, but as a rule only two or three boxes with the highest level of general tensile strain were under investigation.

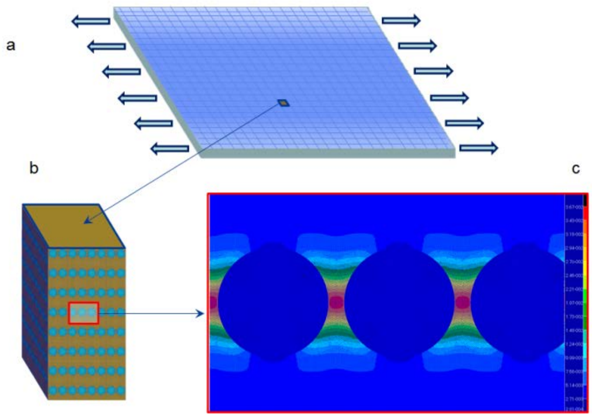

Fig. 2 Distribution of deformation in resin of the 90^o layers of composite package

In frame of "box" model the monolayer (Fig. 1c) was modelled roughly enough by one regular row of fibres and their diameter was determined by the thickness of the package and percentage of fibres in the package.

This two-level parametrical FE model was used to find simple strength criteria for orthogonal composite packages. The percentage of fibres and resin in the packages were varied from 40/60% to 60/40%. All the results presented in the paper correspond to 50/50%. The distribution of strains in the area of monolayer 90^o and in the border of monolayers 0^o and 90^o is shown on Fig. 1c. This picture corresponds to the strain state of non-damaged (without any cracks) 90^o monolayer.

The picture illustrates the following important facts:

1. Significant regular concentrators of relative strains occur in the resin between transversal fibres.
2. The relative strain of resin in the zones close to longitudinal fibers does not exceed the strain of these fibers (which is very close to the strain of the package)

On the basis of this two-level model the investigations for estimation of the initial destruction of the package, first of all, delamination in zone between longitudinal and transverse layers was investigated. The procedure of definition of relationship between the ultimate value of the package tension strain (ε_{utp}) and ultimate strain for resin (ε_{utr}) included two cycles.

In frame of the external cycle the value (ε_{tp}) of the package tension strain was varied from 0 to 1.5% with a small increment. For each value of ε_{tp} on the basis of iteration process the strain state of the "box" model, taking into account appearance and propagation of cracks, was investigated. During this internal cycle stiffness characteristics of the "box" model were being modified. In each subsequent calculation of strain state of the "box" FE model the elements where values of relative tension strain ε_r in resin exceeded ultimate values of relative tension strain ε_{utr} were being excluded from the model. Depending on parameters ε_{tp} and ε_{utr} propagation of cracks around the fibre either stops not reaching other cracks or causes delamination on the border of monolayers 0^o and 90^o.

The procedure of numerical investigation of crack propagation depending on general deformation of the package ε_{tp}=0.5% and ε_{utr}=2.5% is shown on Fig. 3. The subsequent calculation has shown that the value of "delamination" strain of the package was 0.7%.

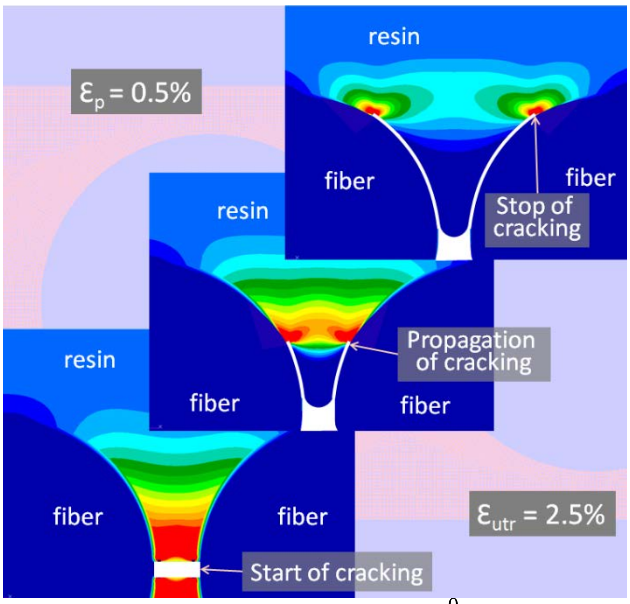

Fig. 3 Propagation of crack in 90^0 monolayer around fibres

The results of numerical calculation on the basis on the two-level model showed that a simple deformational strength criterion for packages comprised by orthogonally oriented layers (0-90^o) could be formulated using the relationship between ε_{tp} and ε_{utr} (see Fig. 5). According to this criterion the ultimate relative tension strain of the package (ε_{utp}) can be found as a function of ultimate tensile strain of resin. This criterion turned out to be very convenient for carrying out fast preliminary analysis of strength of composite package in frame of weight estimation procedure at the initial stage of designing.

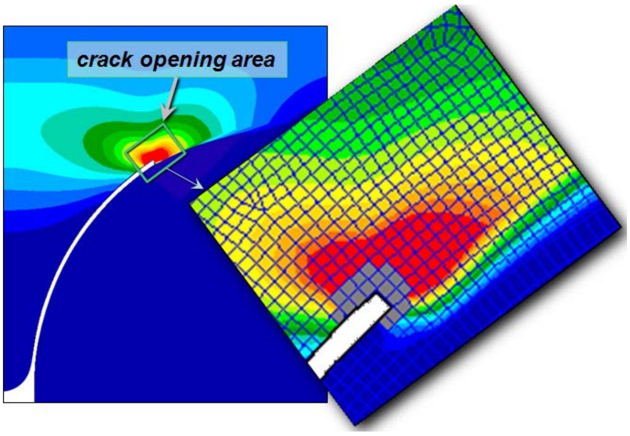

Fig. 4 Strain state in neibourhood of crack

Results presented above concern crack propagation in resin tensed orthogonally to fibre orientation. Similar calculations were carried out for other cases of mutual orientation tension and fibre. Fig. 6 shows typical picture for the crack in the resin for an angle 45° between fibre and direction of tension. The subsequent calculation has shown that in this case the value of “delamination” strain of the package was 1.05%. Results of such investigation were downloaded into special database (see below). Fig. 7 shows an example of dependence of ultimate strain of package on the angle between fibre and direction of tension.

For validation of the results of numerical analysis a number of experimental investigations of strength of composite specimens (with monolayers 0-90^{o}) were carried out using acoustic emission method (Fig. 7,8). By the means of this method strength characteristics of specimens were investigated. The non-destructive method of acoustic emission allows to identify the beginning of destruction inside the composite package on the basis of significant increase of acoustic emission level during the experimental investigation.

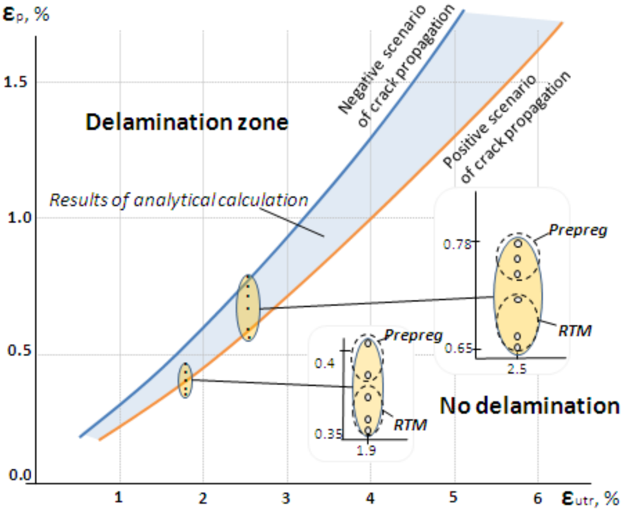

Fig. 5 Relationship between relative strain of the orthogonal package and ultimate relative tensile strain of resin

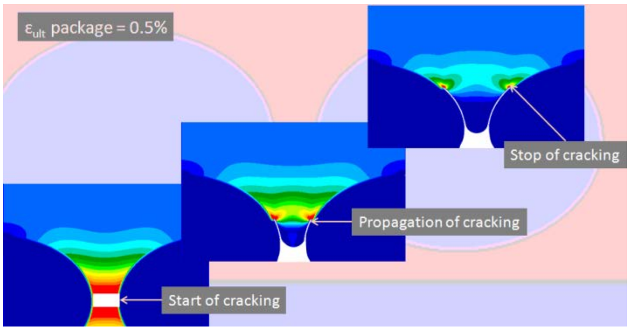

Fig. 6 Strain state in neibourhood of crack opening; case 45° between fibre and direction of tension

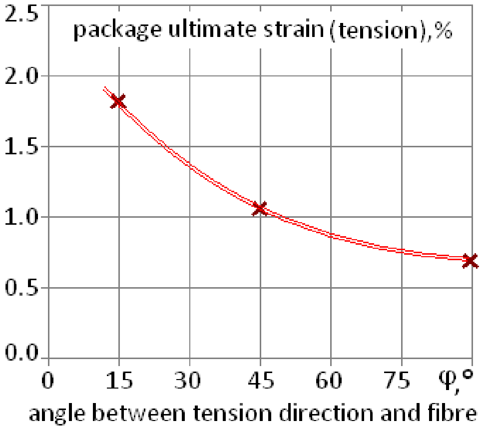

Fig. 7 Example of dependence of package ultimate strain on the angle between fibre and direction of tension

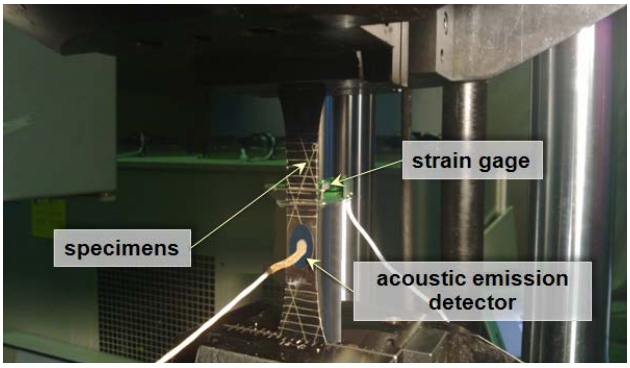

Fig. 7 Experimental investigation of composite specimen under tensile loading

Fig. 8 Specimes for experimental investigation

For validation of the results described above 12 composite specimens consisting of 17 monolayers with thicknesses $0.1 \geq t \geq 0.15$ mm were manufactured for testing. Six of these specimens were manufactured using the resin with ε_{utr}=1.85%, other 6 specimens had ε_{utr}=2.5%. The ultimate relative stresses of these specimens were equal σ_{utr}=6.5 kgf/mm^2 and 6.0 kg/mm^2 respectively.

Results of experimental testing for definition of beginning of delamination of monolayers (0/90^o) have shown good coincidence (author didn't expect such a good coincidence) with numerical investigation (which had been carried out before testing) both for brittle and more viscous resins. Typical results of these experiments are shown on Fig. 9.

Experimental and numerical results have shown that for preliminary estimation of strength of orthogonal packages the following parameters of the package should be defined:

- relative tensile strain of the package (in all points of the composite skin);
- ultimate tensile strain of the resin ε_{utr};
- percentage of fibers and resin in the package.

For the orthogonal package where the percentage of resin and fibers 50/50% the ultimate tensile strain of the package can be defined as: $\varepsilon_{utp} \approx 0.25\, \varepsilon_{utr}$.

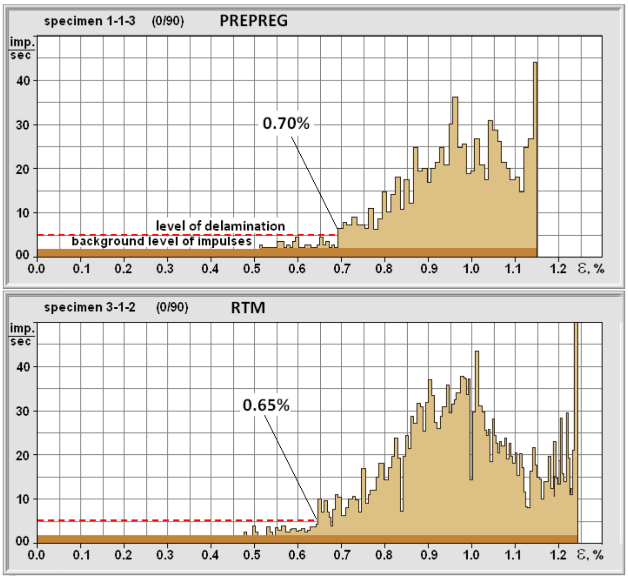

Fig. 9 Typical results of experimental investigation of composite specimens for prepreg- and RTM-technologies

Such numerical-experimental investigations for quasi-isotropic, ±45^o and also for some other stacking sequences were carried out. It was shown that the delamination of 90^o layers occurred approximately at the same level of relative tensile strain of the package both for orthogonal and quasi-isotropic packages.

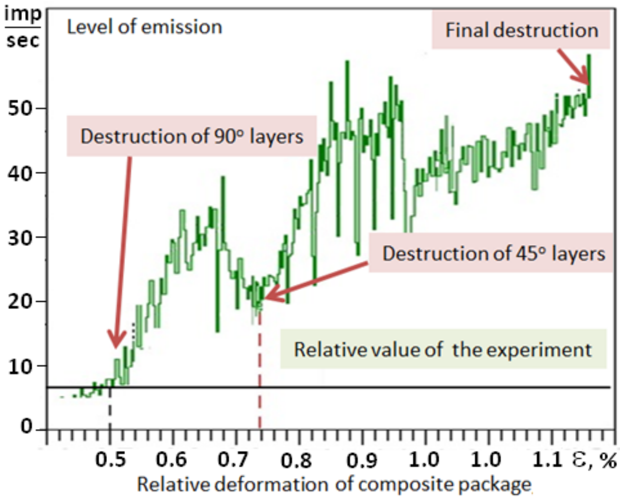

Fig. 10 The relationship between level of acoustic emission and relative tensile strain of quasi-isotropic package

The dependence of acoustic emission on deformation for quasi-isotropic package with the ultimate tensile strain of resin ε_{utr}=1.85% is shown on Fig. 10.

On the basis on these investigations the database on deformation criteria for strength of composite skin have been created [1]. Using this database for analysis of strength of skin under tension allowed to reduce significantly time needed to estimate the composite structure weight on the basis of general (manufacturing) FE model [2].

3 Strength analysis of skin at post-buckling state

To save weight of metal structure of thin-walled stiffened panel designers usually allow local buckling of skin at relatively low level of external loads (0.35-0,5·λ_{ult} for lower panel of fuselage and 0.5-0.67·λ_{ult} for upper panels of wing; λ_{ult} – ultimate level of loading). To realize advantages of composite material in airframe designers have to allow the composite skin buckling (usually at 0.67·λ_{ult} in fuselage). It means that composite skin should not failure at post-buckling stage up to 1.5 of buckling loads.

To bear the tensile loads the skin should buckle without failure. Post-buckling behaviour of a structure was studied well enough for the metal panels. Numerous results of the investigations showed that as a rule, at external loads $P>P_{cr}$, where P_{cr} is buckling load for skin, the panel was not being destroyed because a redistribution of internal loads between the skin and stiffeners allowed keeping the load-carrying capability of the structure at a sufficient level with some degradation of structure's rigidity [3,4].

As for composite panels this paper illustrates that the real weight saving by means of using this effect in frame of conventional fuselage panel is rather small (Fig. 11) because of premature failure of composite skin in post-buckling state.

Fig. 12 shows the deformation of the composite skin in post-buckling state for a level of external loads on the panel $\lambda=P/P_{ult}$ =0.9. Critical load of the skin buckling was λ_{cr} =0.67 λ_{ult}. Lower part of the figure demonstrates that the matrix of layers 0° destroyed because of high value of tension strain across the layer fibres.

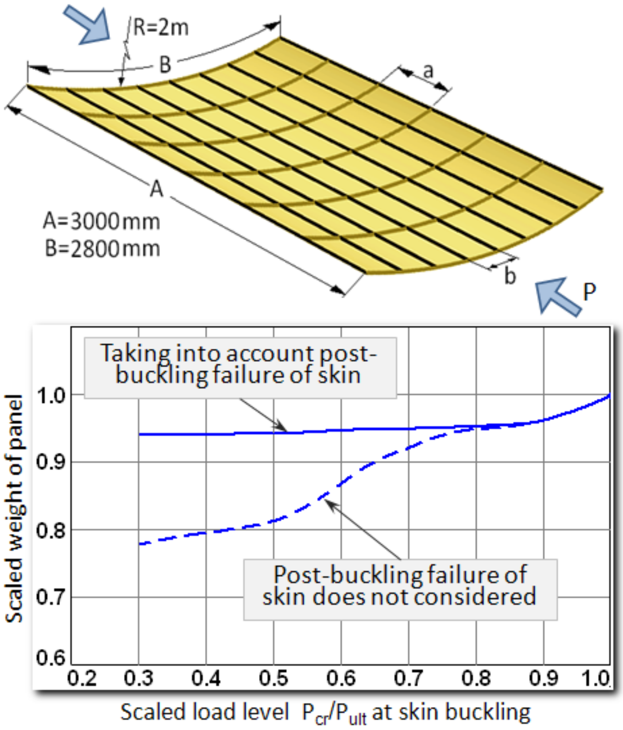

Fig. 11 Dependence of panel weight on load level with allowed buckling of skin

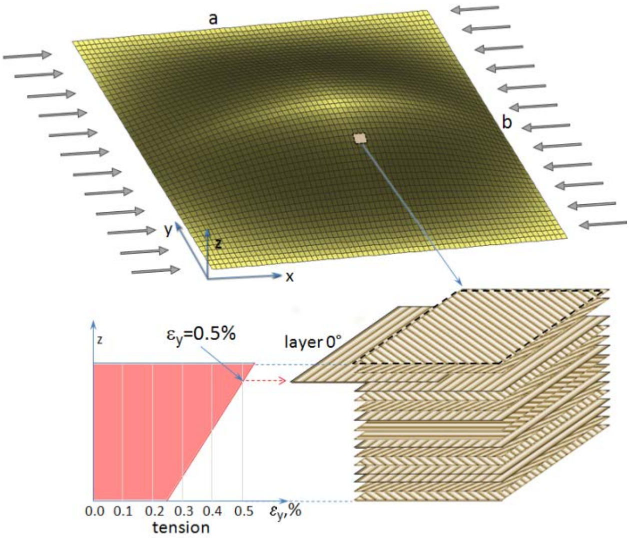

Fig. 12 Post-buckling deformation of composite skin (strain in layer 0°)

Figure 13 illustrates one of the main reasons of this failure. The skin after buckling was in tensile strain in a direction across the main loads P_x (in spite of presence of ribs on the skin edges), and the general deformation of the skin composite package in the *y*-direction was $\varepsilon_{py}\approx$0.2%. But real tension strain across the 0°

monolayer was more than 0.5% because of bent state of buckled skin.

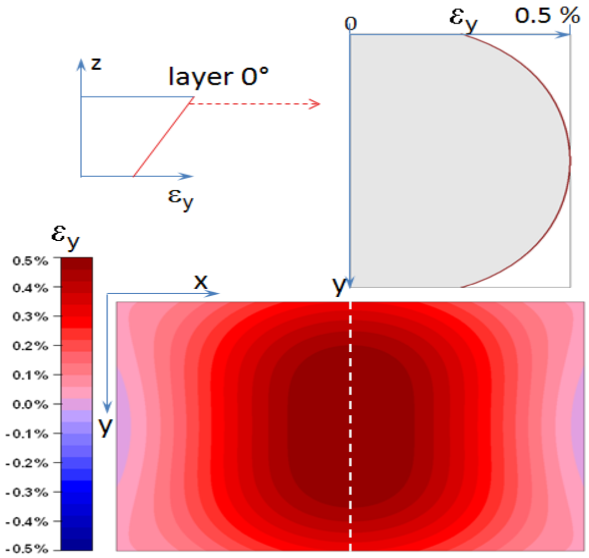

Fig. 13 Strains across fibres in the layer 0° of buckled skin composite package

Taking into account the investigation described in Chapter 2, we may conclude that internal strain state of the skin monolayer is close to failure (delamination). For this reason allowing post-buckling behaviour of skin is not effective in designing of conventional composite panels.

It should be noted that described above phenomenon of premature failure of buckled skin cannot be revealed by means of linear FEM techniques. The results showed in this paper were obtained by using of two levels of the structure model. Non-linear analysis was carried out only for skin cells. A superposition of linear (FEM) and non-linear (semi analytical) solutions provides use of the strength criterion described in Chapter 2 for analysis of the composite structure after buckling of its skin.

Summary

The strength analysis of the composite package on the basis of parametrical two-level FE model allowed formulating a simple deformation criterion of strength for the composite skin with orthogonal and quasi-isotropic stacking sequences.

Recommendations for analysis of composite panel in post-buckling state were formulated. The necessity of analysis of post-buckling failure of composite skin even at a preliminary designing was substantiated.

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