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COMPOSITES THEORY AND PRACTICE

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ANALYSIS OF FATIGUE BEHAVIOR OF COMPOSITE STRUCTURES WITH CIRCULAR INTERNAL DELAMINATION

The aim of the paper is to demonstrate and describe the fatigue failure mechanisms of eight-layer glass-epoxy composites with a central circular delamination, numerical description of the delamination problems and a possible optimal design. There are a few variables (tension and compression forces, number of cycles, construction of the tested plates) which can be changed during the experiment that will very likely provide different results. The problem is to find the link among all those variables to fully describe their influence on the physical behavior of the epoxy plate which is the subject of the experiment. The results are illustrated with the use of the numerical analysis method. Thanks to that, it is possible to describe how the number of cycles, tension force and stress variations affect the whole fatigue process.

Keywords: circular delamination, fatigue, glass/epoxy composites

ANALIZA ZMĘCZENIA STRUKTUR KOMPOZYTOWYCH Z WEWNĘTRZNĄ KOŁOWĄ DELAMINACJĄ

Celem pracy jest zademonstrowanie i opisanie mechanizmów uszkodzenia zmęczeniowego ośmiowarstwowych kompozytów szkło/żywica epoksydowa z kołową delaminacją. Opierano się na numerycznym opisie problemów z rozwarstwieniem. Brane są pod uwagę różne zmienne (siły rozciągające i ściskające, liczba cykli), którymi można operować podczas eksperymentu, co wpływa na wyniki. Problem polega na znalezieniu powiązania wszystkich tych zmiennych, aby w pełni opisać ich wpływ na fizyczne właściwości płyty, która jest przedmiotem badania. Wyniki są ilustrowane za pomocą metody analizy numerycznej. Dzięki temu możliwe jest opisanie, jak liczba cykli, siła i zmiany naprężeń wpływają na cały proces zmęczeniowy.

Słowa kluczowe: kołowa delaminacja, zmęczenie, kompozyty szkło/żywica epoksydowa

INTRODUCTION

Delamination in general is one of the most frequent modes of degradation for composite structures. The existence of delamination could lead to the ultimate failure of composite laminates. This form of failure can originate from manufacturing defects [1], imperfections, object impacts, high stress concentrations from geometrical discontinuities or an incorrect fit between different fiber orientations. There are two stages during delamination propagation:

1. related with a slight increase in buckling deformation
2. the second occurs after 90% of the number of cycles to failure.

During the final stage there is rapid development of damage and delamination starts growing outside of the ‘damage zones’. Depending on the type of load, various phenomena can be observed [2]. In compression, delaminations can allow a sublaminate to buckle, which accelerates the growth of delamination. In turn, in tension load cases there will be no increase in delamination or small stiffness degradation to the structure. To avoid uncontrolled delamination growth and premature structural damage, this mechanism must be properly laid out [3-5].

To better describe the mechanism, two approaches for studying delamination growth in composite laminates should be known. The first of those approaches is related to damage mechanics. The interface enclosing the delamination is created from the damaged material. Delamination appears after the damage variable reaches its maximum value. However, a more important and popular approach is related to the methodology of fracture mechanics [6]. In the present work, static and dynamic compression tests were conducted on a unidirectional glass fiber reinforced polymer matrix and on woven roving glass polymer matrix composites at different load rates. The deformation behavior of the structures and failure modes were discussed. It was important for this work to discuss two special cases for the effect of the R ($\sigma_{min}/\sigma_{max}$) ratio. The authors described the tension-compression case when $R < 0$ and the tension-tension case when $0 < R < 1$ to obtain Goodman diagrams. Those cases relate to different R values.

NUMERICAL ANALYSIS

The most commonly accepted approach to delamination failure initiation is based on the concept of the energy release rate [7, 8] and can be written as follows:

$$RB_{del} = \left(\frac{G_{\mathrm{I}}}{G_{\mathrm{I}C}}\right)^a + \left(\frac{G_{\mathrm{II}}}{G_{\mathrm{II}C}}\right)^b + \left(\frac{G_{\mathrm{III}}}{G_{\mathrm{III}C}}\right)^c \qquad (1)$$

where: $G_{\mathrm{I}C}$, $G_{\mathrm{II}C}$ and $G_{\mathrm{III}C}$ are the critical energy release rates for the first, second and third failure forms respectively; a, b and c are the mixed mode fracture parameters determined by matching the experimental test results. If value RB_{del} is greater than 1, delamination failure occurs.

The strain energy release rates G_{I}, G_{II}, G_{III} are calculated numerically using the finite element package NISA II and the method suggested by Rybicki, Kanninen [9].

If the distribution of transverse shear and normal stresses for a delamination having length a is known, then for a longer delamination, $a + \Delta a$, the displacement distribution is computed at the front of the crack (Fig. 1). Symbols + and – correspond to the upper and lower edges of the crack. Ultimately, the strain energy release rates can be written as:

$$G_{\mathrm{I}} = \lim_{\Delta a \to 0} \frac{1}{2\Delta a} \int_0^{\Delta a} \sigma_{zz}(a)\left[U_3^+(a+\Delta a) - U_3^-(a+\Delta a)\right] da \qquad (2)$$

$$G_{\mathrm{II}} = \lim_{\Delta a \to 0} \frac{1}{2\Delta a} \int_0^{\Delta a} \sigma_{xz}(a)\left[U_1^+(a+\Delta a) - U_1^-(a+\Delta a)\right] da \qquad (3)$$

$$G_{\mathrm{III}} = \lim_{\Delta a \to 0} \frac{1}{2\Delta a} \int_0^{\Delta a} \sigma_{yz}(a)\left[U_2^+(a+\Delta a) - U_2^-(a+\Delta a)\right] da \qquad (4)$$

Using relation (2) and the mesh discretization presented in Figure 1, G_{I} may be written in the following way:

$$G_{\mathrm{I}} = \frac{1}{2\Delta a}\left[F_{zb}\left(U_3^{b'} - U_3^{e'}\right) + F_{zc}\left(U_3^{c'} - U_3^{f'}\right)\right] \qquad (5)$$

where F_z - normal forces computed at nodal points b and c; U_3 - normal displacements at nodal points b', c', e' and f', respectively.

It should be noted that the accuracy of the numerically computed values of strain energy release rates G is very dependent on the FE discretization of the area surrounding the crack. Thus, using 3-D FE in the analysis may cause the computational will to be very high.

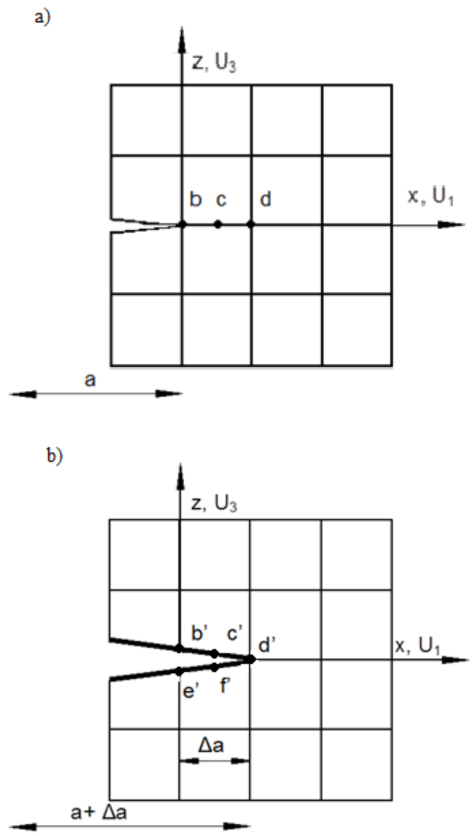

Fig. 1. FE model used in computation of strain energy release rates G: a) delamination having length a, b) delamination having length $a + \Delta a$

Rys. 1. Model FE obrazujący uwalnianie energii podczas odkształcenia płyty z delaminacją: a) dla długości a, b) dla długości $a + \Delta a$

The case of delamination in the compression the process can be considered in two ways:

1. To find the maximal compressive load before initiation of delaminations - which can be written as:

$$\text{Min } RB_{del}(s_i) \qquad (6)$$

2. To find the maximal buckling load by varying the stacking sequences - which can be written as:

$$\text{Max } P_{cr}(s_i) \qquad (7)$$

In Figure 2 the relation between the critical crack length and small crack buckling loads can be observed.

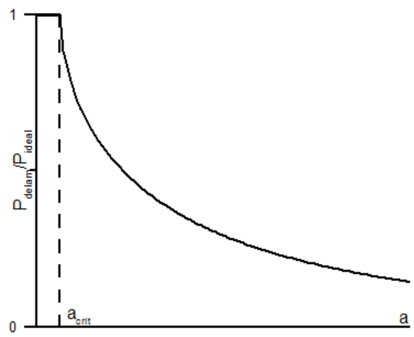

Fig. 2. Buckling loads with crack length a

Rys. 2. Wielkość wyboczenia przy długości pęknięcia a

TENSION-COMPRESSION (R < 0)

When a delaminated structure is subjected to compressive stress, buckling may occur. This phenomenon can be the prevailing failure mode prior to delamination growth and final fatigue damage. Therefore, it is very important to examine the buckling of compressed delaminated plates.

As numerical studies show, buckling loads depend on many factors, but the most important is the thickness of the delaminated segment and the length of the delaminated region. The plate was compressed in the x direction and clamped at edges $x = 0$ and $x = a$. The edges corresponding to $y = 0$ and $y = b$ were free. Figure 3 and Table 1 refer to the results for material 1. A comparison of buckling loads shows the influence of the crack length and delamination location on the buckling loads and modes.

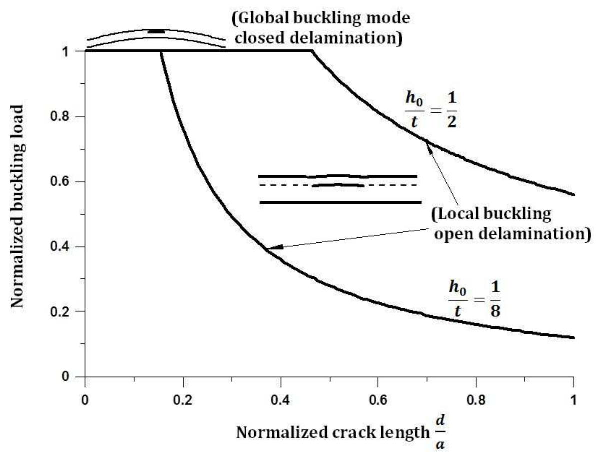

Fig. 3. Effect of delaminations on buckling loads for axially compressed plates

Rys. 3. Wpływ delaminacji na wyboczenie dla osiowo prasowanych płyt

TABLE 1. **Mechanical properties of structures**
TABELA 1. **Właściwości mechaniczne badanych struktur**

Material	E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12}
Unidirectional - glass/epoxy	47.12	14.61	6.84	0.28
Textile	7.8	7.8	3.15	0.24

TENSION-TENSION (0 < R < 1)

The most convenient description of delamination effects can be obtained using Reissner's M mixed variation theorem (RMVT) [10]. It is a special case of the Hellinger-Reissner (HR) principle. The difference between them comes from the chosen master fields. Instead of all the components of stress tensor σ_{ij} (i,j = 1,2,3), the out-of-plane stress components are defined as the master field for RMVT (denoted further as τ_{i3} (i = 1,2,3)) and the transverse strains are evaluated by Hooke's law, i.e.:

$$\Pi_{RMVT}\left[u_k, \tau_{k3}\right] = U_{RMVT} - W_{HR}, U_{RMVT} = = \int_{\Omega}\left(\sigma_{ij}e^{u}_{ij} + \tau_{k3}e^{u}_{k3} - \frac{1}{2}\tau_{k3}e^{\sigma}_{k3}\right), i, j = 1,2, k = 1,2,3$$

$$W_{ext} = \int_{\Omega(I)+\Omega(II)} \sum_{K=I}^{II}\left(\frac{1}{b}P_{x(K)}u_{1(K)} + \frac{1}{a}P_{y(K)}u_{2(K)}\right)dxdy \quad (8)$$

Thus the stresses and strains can be divided into two parts: in-plane and normal (out-of-plane) components.

There are three stages of the fatigue failure process - initiation, crack propagation and crack acceleration. Crack growth can be described by the Paris Erdogan law in many cases:

$$\frac{dd}{dn} = C(\Delta K)^m \quad (9)$$

where d is the crack length (the delamination diameter), ΔK is the stress intensity factor range, n is the number of loading cycles, C and m are constants for the composite material.

Others possible approaches have been presented by Muc, Krawiec [11]. The proposed numerical method in this article was extended by the methodology and conclusions discussed by Turon et al. [12]. In the finite element analysis the variational formulation given by Hooke's law was directly used.

The variation of crack propagation life with an increase in crack length at R = 8/9 is shown in Figure 4.

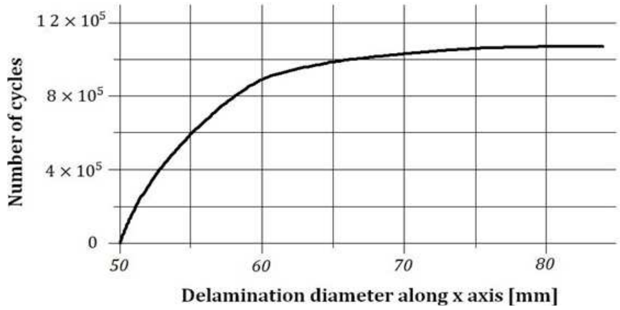

Fig. 4. Dependence of crack propagation life on crack length

Rys. 4. Zależność liczby cykli od wielkości delaminacji

MATERIALS AND METHODS

The specimens used in this study were 8-layer glass/epoxy composite plates with circular internal delamination. Plates of dimensions 200 mm long by 200 mm wide by 2.4 mm thick were used in the investigation. The fiber orientations of those plates were [45°, −45°, 45°, −45°]s. They also have an internal circular 50 mm diameter delamination sheet between the layers. The mechanical properties of the considered structures are given in Table 1.

The nominal geometry of the investigated space of the samples and composite plate before tests is shown in Figure 5.

a) b)

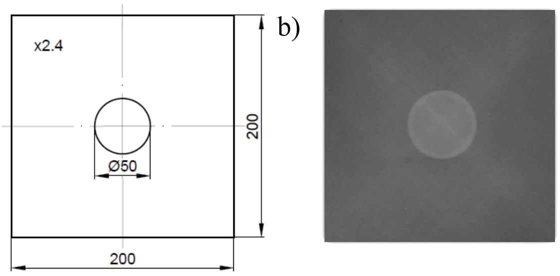

Fig. 5 a) Geometry of plates with delaminations (without grips), b) Composite plate with delamination before fatigue test

Rys. 5 a) Geometria płyty z delaminacją (bez uchwytów), b) Płyta kompozytowa z delaminacją przed badaniem zmęczeniowym

The plates were placed between the bottom and top base and tested with the use of a universal testing machine MTS 793 (Fig. 6).

Fig. 6. Experimental testing stand for composite structures with delamination

Rys. 6. Stanowisko do badań struktur kompozytowych z delaminacją

RESULTS AND DISCUSSION

The samples were subjected to static compression (material 1) and fatigue tests (material 2). The fatigue tests were conducted when the frequency was equal to 20 Hz, for the maximum value of the force - 3.5 kN and subjected to tension at R = 8/9. The main effect of the fatigue tests which can be observed after the tests was the form of deformation. The shape of delamination was changed into an ellipse from a circle. There were also forms of destruction spreading from the location of the delamination sheet to the apex of the plate. The width of these forms was comparable to the diameter of the delamination (Fig. 7). The compressed plate (woven roving) was subjected to static compression tests. Buckling occurred when the force reached the value of 4.15 kN. The damages occurred near the delamination location and also near the grips. They can be observed as bright points (Fig. 7).

a) b)

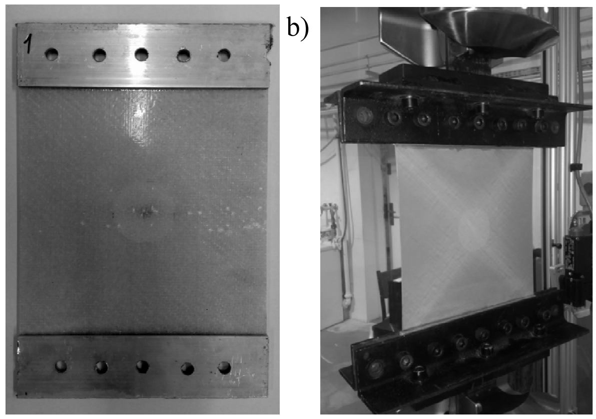

Fig. 7. Composite plates after static compression (material 1) (a) and fatigue tests (material 2) (b)

Rys. 7. Płyty kompozytowe po statycznej próbie ściskania (materiał 1) (a) i po badaniu zmęczeniowym (materiał 2) (b)

CONCLUSIONS

The aim of the study was to investigate composite materials with delaminations. Samples were subjected to fatigue tests and static compression tests. There are some forms of destruction of the composites for both experiments. In the case of compression, only buckling in the delamination area occurred. Analyzing the results of fatigue tests, some forms of material destruction can be observed. Their distribution may be conditioned by the fiber orientation.

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