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COMPOSITES THEORY AND PRACTICE

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ASSESSING THE HAZARD OF DELAMINATION PROPAGATION IN COMPOSITES USING NUMERICAL ANALYSIS

The paper presents a procedure based on numerical analyzes allowing a quick risk assessment of delamination propagation in composite structures during routine inspections. The principle of the procedure is the comparison of size and location of the defect found during maintenance checks with a set of data obtained from series of numerical analyzes in order to determine the potential for growth of the delamination. The decision then can be made regarding the inspected component - whether it can be still used or should be replaced. The data for comparison contains sets of delamination sizes corresponding to critical embedded delamination diameters derived from linear buckling analysis and nonlinear analysis of postbuckling behavior including delamination propagation. The paper shows an example of such a procedure for a structure made of carbon-epoxy laminate. A series of numerical models was created covering all the possible locations of delaminations throughout the laminate thickness. Linear buckling analysis and nonlinear analysis of postbuckling behavior were conducted using the MSC.MARC finite element commercial code. The analysis of delamination propagation is also included based on the Virtual Crack Closure Technique. The critical delamination diameters were determined for each delamination location and the bases for comparison were created.

Keywords: **delamination, buckling, FEM, delamination propagation, VCCT**

OCENA NIEBEZPIECZEŃSTWA ROZWOJU DELAMINACJI W KOMPOZYTACH Z WYKORZYSTANIEM ANALIZY NUMERYCZNEJ

Praca przedstawia schemat postępowania, wykorzystujący analizy numeryczne, który pozwala na szybką ocenę ryzyka propagacji delaminacji w elementach kompozytowych. Z powodu warstwowej struktury oraz różnych kierunków ułożenia zbrojenia laminaty wykazują niską odporność na pękanie międzywarstwowe i powstawanie delaminacji. Wewnętrzne rozwarstwienia, powstałe zwykle na skutek błędów w procesie produkcji lub niskoenergetycznego uderzenia, mogą propagować po lokalnym wyboczeniu, znacząco wpływając na nośność struktury. Procedura zaprezentowana w niniejszym artykule pokazuje proces tworzenia bazy porównawczej, która może być wykorzystywana podczas rutynowych kontroli stanu elementów kompozytowych. Pomaga ona w szybkiej ocenie zagrożenia rozwojem delaminacji i podjęciu decyzji odnośnie do dalszego postępowania z danym elementem. Podstawą opisanego narzędzia są analizy numeryczne metodą elementów skończonych, mające określić zależność stopnia zagrożenia rozwojem delaminacji od rozmiaru defektu oraz jego położenia w strukturze warstwowej. Zaproponowano trzy kryteria oceny ryzyka związane z trzema rodzajami przeprowadzanych analiz numerycznych i pozwalające otrzymać trzy zestawy krytycznych rozmiarów delaminacji. Osiągnięcie przez rozwarstwienie kolejnych wartości krytycznych powinno skutkować zmianą zaleceń eksploatacyjnych, np. zwiększeniem częstotliwości kontroli. W dalszej części pracy zawarto przykład zastosowania opracowanej procedury dla struktury kompozytowej. Przedmiotem analizy był fragment powłoki wykonanej z kompozytu węglowo-epoksydowego o orientacji warstw zbrojenia [0°/90°/0°/90°/0°/0°/45°/-45°/-45°/45°]$_S$, zapewniającej układ symetryczny i zrównoważony, z centralnie zlokalizowaną delaminacją kołową. Rozważano 10 przypadków, obejmujących wszystkie możliwe położenia delaminacji między warstwami laminatu. Do zrealizowania analiz numerycznych metodą elementów skończonych wykorzystano oprogramowanie MSC.MARC. Przeprowadzono liniową analizę wyboczenia dla szeregu średnic delaminacji stopniowanych co 1 mm w celu wyznaczenia krytycznego rozmiaru rozwarstwienia, dla którego nastąpi lokalne wyboczenie przy określonym poziomie odkształceń ściskających. Kolejnym krokiem było przeprowadzenie nieliniowej analizy stanu po wyboczeniu w celu wyznaczenia krytycznej wielkości delaminacji, przy której nastąpi jej propagacja. Do określenia potencjału rozwoju delaminacji wykorzystano algorytm metody VCCT, dostępny w MSC.MARC. Ostatnim etapem było przeprowadzenie szeregu nieliniowych analiz propagacji delaminacji w celu wyznaczenia charakteru i wielkości rozwoju rozwarstwienia. Niewielki i stabilny rozwój delaminacji nie musi dyskwalifikować elementu kompozytowego pod warunkiem monitorowania jego stanu. Przeprowadzone analizy numeryczne pozwoliły na stworzenie trzech zestawów średnic krytycznych, które mogą stanowić bazę porównawczą przy rutynowych kontrolach struktury kompozytowej. Przy stwierdzeniu wady w postaci rozwarstwienia przekraczającego krytyczny rozmiar należy wprowadzić odpowiednie zmiany do zaleceń eksploatacyjnych. W przypadku delaminacji o średnicy grożącej niestabilną propagacją po wyboczeniu element kompozytowy powinien być wymieniony lub naprawiony przed dalszym użytkowaniem.

Słowa kluczowe: **delaminacje, wyboczenie, MES, propagacja delaminacji, VCCT**

INTRODUCTION

Problem statement

The typical structure of a composite shell consists of several layers of reinforcement impregnated with resin. Due to variation in the reinforcement orientation and stratified structure, laminates display relatively low resistance against interlaminar fracture and the formation of delaminations. They are areas inside the laminated structure where separation between two layers occurred. Two of the most common delamination types in regard to their origin are: discontinuity resulting from a faulty manufacturing process or from a low energy impact. Delaminations being manufacturing defects are mostly embedded ones and can propagate when buckling. Such defects can significantly influence the load capacity of the structure and they should be looked for during routine inspections of the components. After finding delaminations in the composite structure, the decision must be made whether the defected structural element should be scrapped or can be repaired, or perhaps, it can be left as is with a shorter time between subsequent inspections. To make the right decision several factors should be considered, the most important being the potential for growth of the delamination. This paper presents a procedure based on numerical analyzes that should help with quicker assessment of the level of risk connected with delamination growth during inspections of composite structures. A series of numerical analyzes, including linear buckling analysis, nonlinear analysis of postbuckling behavior and delamination growth with the use of the Virtual Crack Closure Technique (VCCT), allows for creating guidelines that can be helpful in planning maintenance and routine checks of composite structures. In the second part of the paper an example of such a procedure is shown.

Literature review

The buckling of delaminations has been an object of attention for at least the last three decades. Early models by Chai et al. [1] or Kachanov [2] represented through-the-width delaminations in plates of an infinite width, and due to this they were of limited practical application. However, the buckling of plates with multiple delaminations was investigated by Suemasu [3], who noticed a significant decrease in compressive buckling load in the presence of delaminations. More realistic 3D models of embedded delaminations were presented by Chai [4], Jane & Yin [5], Yin & Jane [6], however, application of the corresponding analytical expressions for the analysis of delamination growth was difficult. More useful were numerical models obtained with the use of FEM. The buckling and postbuckling behavior of embedded delaminations was studied by Kim & Hong [7]. The usefulness of numerical methods in investigating the buckling of circular delaminations was confirmed by Arman et al. [8]. They were used to analyze the onset of delamination propagation - the VCCT was used to determine the Strain Energy Release Rate (SERR) along the delamination front, Whitcomb [9]. Moreover, these FE models enabled proper consideration of contact between the delaminated layers that resulted from buckling, Whitcomb [10] and Riccio et al. [11], and the consecutive local loss and recovery of such contact occurring due to variation in the loading level. The simulation of delamination growth, however, has been studied only in more recent papers. An extensive description of the VCCT used for this purpose was given in Krueger [12]. Nevertheless, those papers mainly focused on delaminations that grow in a self-similar manner e.g. Turon et al. [13], Liu et al. [14] and Orifici & Krueger [15]. Papers on embedded delaminations or delaminations with curved fronts were presented by Pitropaoli & Riccio [16, 17] and Aoki et al. [18]. The postbuckling propagation in composite plates with multiple delaminations was investigated by Suemasu [19].

Course of conduct

The purpose of the analysis is to create a tool which will help in quick assessment of the degree of risk of delamination growth during maintenance checks in order to undertake adequate measures. The potential of growth under specified loading conditions, which can be allowable stresses and strains in the component, depends on the location and size of the delamination, both measured during inspection. They can be then compared with a set of critical values to decide about subsequent actions regarding the inspected component depending on the potential of growth of the delamination. The author proposes three sets of sizes and locations based on three types of numerical analyzes and reflecting three degrees of risk of delamination growth. Finding a delamination exceeding any of the critical sizes should entail some maintenance action: increasing the frequency of inspections or replacing the defected component.

Local buckling. The occurrence of a delamination diminishes the load capacity properties of the structure, however, there is no risk of growth if there is no local buckling of the separated area. Defects with sizes and locations not causing buckling under a specified load can be considered safe. The component does not need to be scrapped - the delamination should just be monitored.

Onset of delamination growth. Once the defect is large enough to buckle under a specified load, the potential for growth of the delamination must be considered - the Virtual Crack Closure Technique was used for such a purpose in the paper. The strain energy release rates (SERR) values were calculated for the given delamination front which determines the possibility of crack propagation. If they do not reach critical values, the composite structure will work without delamination growth. The component can still be considered safe, however, more frequent inspections of the defected area are required.

Characteristic of delamination growth. After reaching critical SEER values the delamination will propagate. Stable growth of the delamination may be allowed, provided very frequent checks are carried out. If the numerical analysis, however, suggests unstable delamination growth, the component should be repaired or scrapped. The characteristic of delamination propagation is also dependent on its size and can be assessed with the VTTC method.

NUMERICAL MODEL

This part presents the numerical analysis procedure of establishing sets of data that can be used for comparison during inspections of composite components. A structure made of carbon-epoxy laminate was used as an example.

Modelled structure

What was analyzed was a fragment of a carbon-epoxy shell in the form of a rectangular plate with dimensions 150 mm x 100 mm x 2.86 mm with a circular delamination located in its center. Each location of the delamination through the plate thickness was analyzed and the delamination diameter was to be established throughout the analysis.

The laminate consisted of 20 layers with an 0.143 mm thickness stacked so as to achieve a symmetrical and balanced structure. The mechanical properties of the layers forming the plate were based on the experimental data provided by the manufacturer of a unidirectional carbon-epoxy prepreg MTM46/HTS5631(12 K) and are shown in Table 1. The reinforcement configuration was [0°/90°/0°/90°/0°/0°/45°/-45°/-45°/45°]$_S$.

TABLE 1. **Mechanical properties of a single layer**
TABELA 1. **Właściwości mechaniczne pojedynczej warstwy**

Composite properties	
E_{11} [MPa]	128 290
$E_{22} = E_{33}$ [MPa]	8 760
$G_{12} = G_{13}$ [MPa]	4 270
G_{23} [MPa]	3 000
ν_{12}	0.288
$\nu_{23} = \nu_{13}$	0.320
Energy Release Rates	
G_{Ic} [N/m]	120
G_{IIc} [N/m]	630
G_{IIIc} [N/m]	630

Analyzed cases

The purpose of the analyses was to establish the maximum diameter of an embedded defect that will not propagate under assumed loading specified in the form of a deformation of 0.9%. All the possible locations of delamination throughout the plate thickness were analyzed differing by the number of laminae in the delaminating layer. The cases analyzed in the paper are schematically presented in Figure 1.

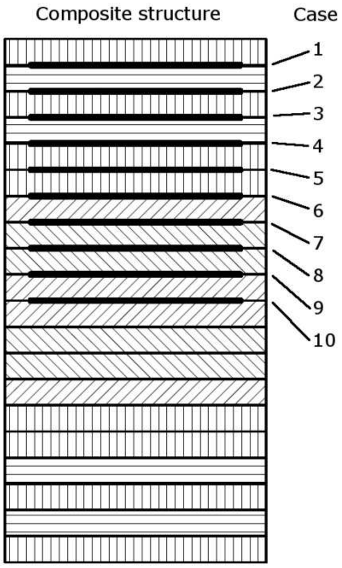

Fig. 1. Analyzed cases

Rys. 1. Analizowane przypadki

FE models

For each case, a series of models was created with delamination diameters augmenting by 1 mm. The mesh was composed of solid elements (denoted in MSC.MARC nomenclature as Type 185 solid shell elements which give good results in modelling layered structures) and shaped so as to reflect the circular shape of the delamination (Fig. 2). The element edge length in the delamination front varied from 0.2 to 0.4 mm which ensured good representation of the delamination front. To prevent possible interpenetration of disbonded layers in the post buckling and propagation stages, contact conditions were introduced in the respective plane. In the case of small delamination diameters, only a central portion of the plate was modelled.

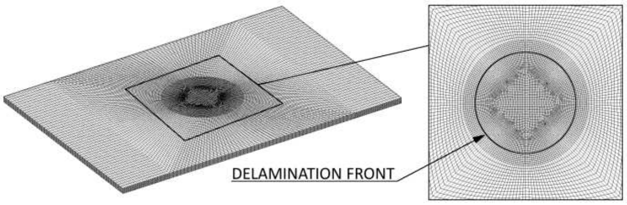

Fig. 2. Finite element mesh

Rys. 2. Siatka elementów skończonych

Boundary conditions

The analyzed plates were subjected to compression in the y direction (Fig. 3), while movement in other directions was prevented on the edges according to Figure 3.

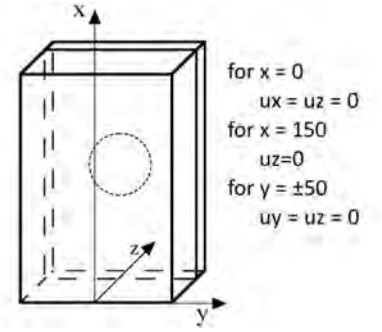

Fig. 3. Boundary conditions

Rys. 3 Warunki podparcia

Types of analyzes performed

Three types of analyzes were performed in order to establish the safety of the delaminations - linear buckling analysis using the Lanczos method for calculating eigenvalues, nonlinear postbuckling analysis of the delamination growth potential, and nonlinear postbuckling analysis of delamination propagation. In the last two types of analyzes, the Virtual Crack Closure Technique was used for crack analysis. In this method, the simulation of delamination growth is based on evaluation of the energy release rates corresponding to three crack propagation modes. If the specified separation criterion is fulfilled, meaning failure index FI equals 1, the connection between the node of the delaminated layer and the node of the base composite is released and the delamination propagates. The separation (delamination) criteria are phenomenological ones. The criterion applied in the analyses is one of the simplest and most often referred to in literature [17-20]:

$$\frac{G_I}{G_{Ic}} + \frac{G_{II}}{G_{IIc}} + \frac{G_{III}}{G_{IIIc}} = FI \tag{1}$$

where G_I, G_{II}, and G_{III} are energy release rates for the first, second and third crack propagation modes, respectively, and G_{Ic}, G_{IIc}, and G_{IIIc} are corresponding critical values.

For assessing the onset of crack propagation, the criterion above was checked for all the nodes on the delamination front for the maximum load analyzed. In the delamination propagation analysis, the MSC MARC algorithm allowed for automatic checking of the criterion for each node and performing the delamination growth.

RESULTS

The purpose of the analyzes was to establish sets of data containing delamination sizes and locations that can be used for assessing delamination safety during inspections. Each set of data should be accompanied by specific instructions concerning further maintenance of the composite component: more frequent checks, repair or replacement.

Local buckling

The mode shape for the first critical loading is similarly independent of the delamination diameter; an example is presented in Figure 4. The delamination was considered safe if there was no local buckling for the maximum load of 0.9% deformation of the plate. The results obtained are presented in Table 2.

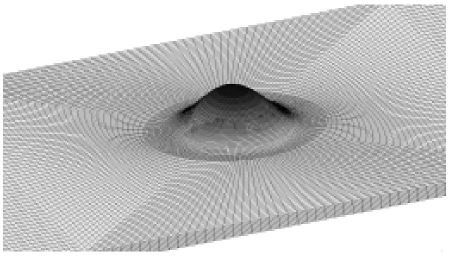

Fig. 4. First buckling mode shape

Rys. 4. Kształt pierwszej postaci wyboczenia

TABLE 2. **Critical delamination diameters for local buckling**

TABELA 2. **Krytyczne średnice delaminacji przy lokalnym wyboczeniu**

Case number	Safe diameter of delamination
1	2
2	4
3	6
4	12
5	13
6	15
7	18
8	23
9	26
10	29

Onset of delamination growth

At this safety level, the failure index, Equation (1), was analyzed for each node on the delamination front. The delamination was considered safe if the maximum value of the failure index was lower than 1 for the maximum load of 0.9% deformation of the plate. The results obtained are presented in Table 3.

TABLE 3. **Critical delamination diameters for delamination growth onset**

TABELA 3. **Krytyczne średnice delaminacji przy rozwoju delaminacji**

Case number	Safe diameter of delamination
1	2
2	4
3	7
4	13
5	14
6	16
7	19
8	23
9	26
10	30

Characteristic of delamination growth

For each case investigated, the delamination growth analysis was also performed to establish whether the delamination growth is stable and stops after reaching the maximum load or is unstable and causes fast progress of the area of separation, thus being very dangerous. The delamination diameters considered were 1 mm larger than in the analysis of the propagation onset. However, in each case the delamination propagation was unstable. The delamination area covered the full width of the analyzed plate just after reaching the critical value of the failure index. Therefore delaminations with diameters larger than presented in Table 3 must be considered dangerous and the components should be replaced with new ones.

CONCLUSIONS

The degree of risk of delamination propagation depends strongly on the location and size of the defects and on the material structure of the laminate. Numerical methods can be helpful in the maintenance of composite components by determining the potential of growth of delaminations found during routine inspections. The paper presents an example of a maintenance tool for assessing the safety of embedded delaminations. Three sets of data containing critical values of delamination sizes are paired with the guidelines describing the appropriate course of action that should be undertaken after defects have been found. The procedure, however, should be verified experimentally to confirm its usefulness.

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