Polish Society of Composite Materials
Polskie Towarzystwo Materiałów Kompozytowych

14: 4 (2014) 177-182

COMPOSITES THEORY AND PRACTICE

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Received (Otrzymano) 08.10.2014

MODELING OF DELAMINATION INFLUENCE ON MECHANICAL CHARACTERISTICS OF COMPOSITE CANTILEVER BEAM

The paper deals with the influence of delamination on mechanical characteristics of a composite cantilever beam. The main goal of the performed Finite Element Analysis (FEA) was to recognize the general nature of damage influence on the composite structure' properties by extraction of eigenfrequencies and eigenmodes. The two main geometrical parameters, i.e. the size and location of a delaminated zone were taken into account. In addition, a simple analysis of the friction coefficient on the beam dynamics was performed. The numerical simulations were done in the ABAQUS/CAE commercial software environment. The models contained a single local delamination with appropriate contact definition. The defect length changed from 10 to 100% of the overall beam length. The results obtained for two different sequences of plies show the significant effect of delamination on the composite structure mechanical properties. In particular, the location of the delaminated zone had a non-uniform influence on the decrease in subsequent eigenfrequencies, which in some cases could help to avoid resonance. In the paper, analysis of the numerical results concentrated on the first five eigenmodes and on small and moderate-sized defects. The importance of other factors, e.g. friction coefficient or boundary conditions, as well as prospective experimental verification of the numerical results were also considered. In the performed analyses, glass-epoxy material data were used.

Keywords: damage, delamination, beam dynamics, composite, Finite Element Analysis, ABAQUS

MODELOWANIE WPŁYWU DELAMINACJI NA CHARAKTERYSTYKI MECHANICZNE KOMPOZYTOWEJ BELKI WSPORNIKOWEJ

W pracy omówiono wpływ delaminacji na charakterystyki mechaniczne kompozytowej belki wspornikowej. Głównym celem analizy przeprowadzonej metodą elementów skończonych (MES) było rozpoznanie ogólnej natury wpływu uszkodzenia na właściwości ustroju kompozytowego poprzez wyznaczenie częstości i postaci drgań własnych. Pod uwagę wzięto dwa główne parametry geometryczne, tzn. rozmiar i położenie rozwarstwionego obszaru. Ponadto przeprowadzono uproszczoną analizę wpływu współczynnika tarcia na dynamikę belki kompozytowej. Symulacje wykonano w komercyjnym środowisku obliczeniowym ABAQUS/CAE. Modele zawierały pojedynczą lokalną delaminację ze zdefiniowanymi warunkami kontaktu. Długość defektu zmieniano w zakresie od 10 do 100% całkowitej długości belki. Wyniki otrzymane dla dwu różnych układów warstw wykazały znaczący wpływ delaminacji na właściwości mechaniczne badanego ustroju kompozytowego. W szczególności położenie zdelaminowanego obszaru miało niejednostajny wpływ na zmniejszenie kolejnych częstości drgań własnych, co w niektórych przypadkach może być pomocne w uniknięciu rezonansu. W artykule analiza wyników numerycznych została ograniczona do pierwszych pięciu postaci własnych, przy małych i średnich rozmiarach defektu. Rozważono znaczenie innych parametrów, takich jak wartość współczynnika tarcia, lub wpływ warunków brzegowych, jak również przewidziano weryfikację doświadczalną otrzymanych wyników. W przeprowadzonych analizach używano danych materiałowych dla kompozytu szklano-epoksydowego.

Słowa kluczowe: uszkodzenie, delaminacja, dynamika belek, kompozyt, Metoda Elementów Skończonych, ABAQUS

INTRODUCTION

Composite materials are applied in many branches of contemporary industry, for example in the automotive or naval industry, as well as in aircraft engineering, where high material reliability is essential because of safety reasons. Among the several damage mechanisms typical for laminated composites, delamination is one of the most frequently occurring defects. The risk of inducing such a flaw in a composite structure is relatively high in common maintenance circumstances, for example by dropping a tool on a laminated airplane wing [1]. Thus, both identification and assessment of the delamination influence on the material mechanical characteristics are very important tasks [2]. Many non-destructive test methods (NDT) are available nowadays for the first task (X-ray, thermography etc.). On the other hand, it is crucial to recognize the effect of a defect on the structure dynamics. This task can be solved with numerous techniques based on vibration analysis [3].

In the following paper, Finite Element Analysis (FEA) of the influence of a defect in the form of delamination on the dynamics of a composite beam structure is presented.

SUBJECT AND GOALS

The paper deals with numerical modeling of the mechanical behavior of a delaminated composite beam, as one of the most common types of damaged structures found in contemporary aircraft [4]. The study presented here is a part of wider theoretical-experimental research work aiming at multilateral description of delamination influence on the mechanical characteristics of composite structures [5]. The particular goal of the current work is to emphasize the complex nature of the location and size of delamination on the dynamic properties of a composite cantilever beam by eigenfrequency extraction and mode shape comparison using available FEA software. The defect size was fixed - no delamination propagation was considered here, as the focus of the study was on the damaged structure dynamics.

BEAM MODEL AND METHODOLOGY

A cantilever beam model was considered, in which a single delaminated zone of variable size was considered. The delamination center was located at X counting from the beam free end. The beam model was L = 250 mm long (Fig. 1) and 10 mm wide. Its height was 4 mm, which resulted from the number of plies and their thickness, as described below. The parameterization of the model was attained by changing size D of the defect from 25 to 250 mm (10 to 100%, respectively) and shifting it along the beam axis, such that parameter X was changed from 12.5 to 237.5 mm, however, for longer delaminations this range was narrower. In such a manner, one can obtain a "map" of eigenfrequency sensitivity to the location and size of the defect.

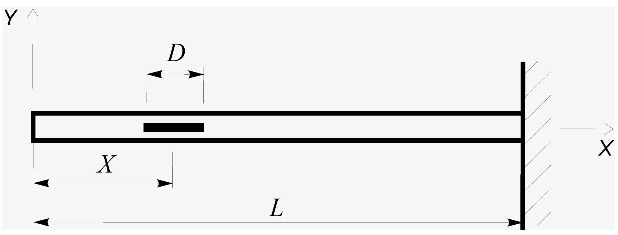

Fig. 1. Delaminated composite cantilever beam model used in numerical simulations

Rys. 1. Model zdelaminowanej belki wspornikowej używany w symulacjach numerycznych

NUMERICAL MODELING AND SIMULATION

The Finite Element method was used to model the delaminated composite beams. A number of composite cantilever beam models were prepared in the ABAQUS/CAE software environment. The eigenvalue problem for different delamination sizes and locations along the beam was solved numerically using the Lanczos algorithm. The layered beams were composed of 16 glass-epoxy plies (0.25 mm thick each) in two different sequences, chosen from a wider set of layups analyzed by the author: S1 = $[0°]_{16}$ and S2 = $[(\pm45°)_2/0°/(45°)_2/-45°]_S$ (Fig. 2). For this purpose, S4 linear four-noded conventional shell elements from the Standard ABAQUS elements library were accepted. The performed mesh convergence study proved that the element size of 5 mm gave sufficient accuracy for the considered scientific problem. In result, each beam model consisted of one hundred finite elements. The layered structure was defined with the *Composite Layup* technique.

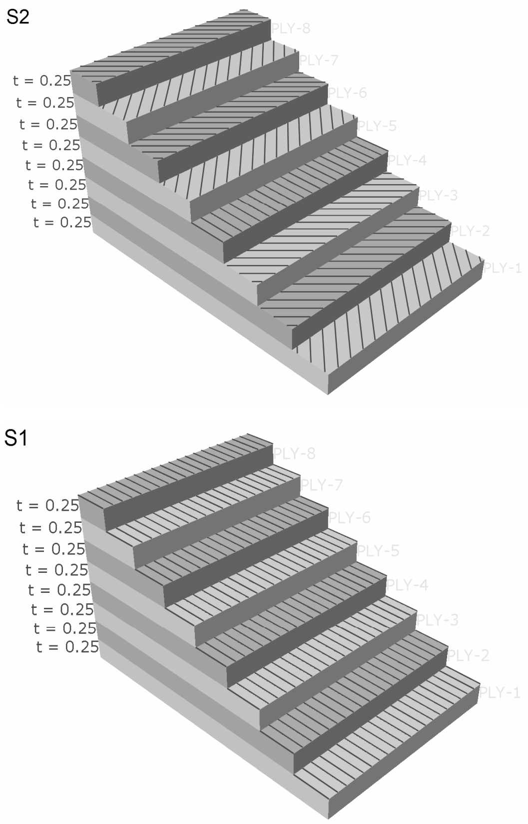

Fig. 2. Ply sequences S1 and S2 of considered FE beam models

Rys. 2. Układy warstw laminatu S1 i S2 w analizowanych modelach MES belek

In the case of the intact beam model, the layered structure was just one package of 16 plies. The damaged beam model needed in contrast two separate 8-ply beams stuck together by joining the nodes with the *Tie Constraint* technique [6] and appropriate contact modelling. Such an approach allowed the author to include, among others, friction in the model. The defect (delamination) was located in the beam mid-plane.

The glass-epoxy material data found in available literature [7] are collected in Table 1.

TABLE 1. **Material data of glass-epoxy composite**
TABELA 1. **Dane materiałowe kompozytu szklano-epoksydowego**

E_1 [GPa]	E_2 [GPa]	ν_{12} [–]	$G_{12} = G_{13} = G_{23}$ [GPa]
46.43	14.92	0.27	5.23

RESULTS AND DISCUSSION

Up to 5 eigenmodes were analyzed and the delamination location influence on the eigenfrequencies was modelled every $0.1L$. The analysis of the obtained results shows the complexity of the observed phenomena of the defect size and location influence on the beam dynamics. Due to the amount of data, the eigenfrequencies given below are only for a chosen size of delamination $D = 0.5$ in the form of tables. Table 2 contains the results of ABAQUS calculations obtained for the unidirectional (S1) composite beam model, whereas in Table 3 similar results are given for the S2 sequence beam. For the purpose of comparison, the second row in the two tables contains the eigenfrequency values for an intact beam.

TABLE 2. **Eigenfrequencies of delaminated S1 beam for $D = 0.5$**
TABELA 2. **Częstości własne zdelaminowanej belki S1 przy $D = 0.5$**

Location (X/L)	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]	f_5 [Hz]
Intact	49.34	308.45	860.48	1677.60	2755.50
0.25	45.88	207.06	617.12	1127.20	1930.10
0.35	46.94	278.29	635.96	1131.00	1889.10
0.45	46.12	294.41	544.53	1124.60	1959.60
0.55	45.44	272.95	571.55	1159.30	1978.00
0.65	44.90	233.15	645.30	1232.00	1958.90
0.75	44.52	199.23	630.79	1154.30	1938.50

TABLE 3. **Eigenfrequencies of delaminated S2 beam for $D = 0.5$**
TABELA 3. **Częstości własne zdelaminowanej belki S2 przy $D = 0.5$**

Location (X/L)	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]	f_5 [Hz]
Intact	31.24	195.65	547.58	1072.70	1772.90
0.25	28.76	126.57	380.68	696.68	1193.70
0.35	29.53	174.54	391.61	700.35	1178.60
0.45	28.96	185.73	332.85	693.81	1222.50
0.55	28.48	170.48	352.62	717.79	1233.40
0.65	28.11	144.03	399.56	767.84	1224.40
0.75	27.90	122.39	391.06	716.84	1206.30

The results are visibly different for the two considered sequences of plies and in both cases the highest numbers characterize the beams without delamination (the intact one). However, the defect location had a significant effect on the intensity of the eigenfrequency decrease. This effect was particularly strong for f_2 and f_3 for both the considered sequences of plies, as shown in Figure 3. For any other size of delamination, the nature of the location-induced eigenfrequency variety phenomenon was similar but still different for the subsequent eigenmodes.

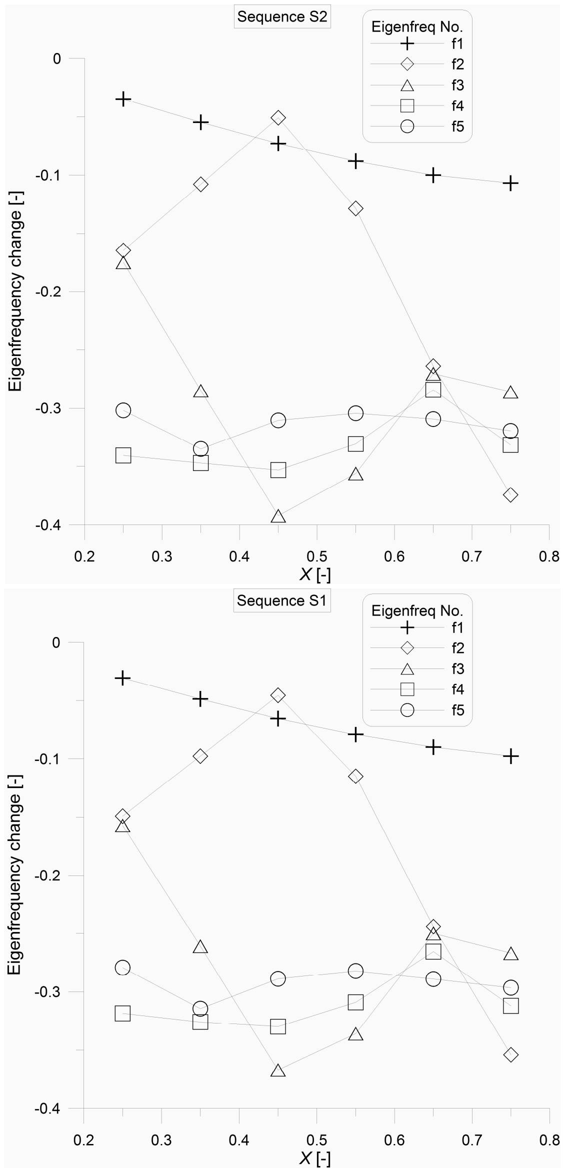

Fig. 3. Influence of half-length delamination on eigenfrequencies of composite cantilever beam

Rys. 3. Wpływ 50% delaminacji na częstości własne kompozytowej belki wspornikowej

Another way of comparing eigenfrequencies which seems to be clearer is to present relative changes (with respect to the intact beam characteristics) in the form of graphs for subsequent frequencies. First of all, the first eigenfrequency (f_1) was analyzed towards being affected by the defect size and location - Figure 4. The graph shows that the relative decrease of the first eigenfrequency grows as the defect size grows; the f_1 frequency drop is noticeable for $D \geq 0.3$. Of course this tendency is not surprising to an engineer. One would also expect for the assumed boundary conditions that the biggest effect of the flaw is when it is located closer to the clamp, such that the frequency drop changes from –0.0030 to –0.0244 at D = 0.3 and from –0.0648 to -0.1483 at D = 0.6, when the S1 sequence is considered. For the S2 composite layup, the respective numbers are as follows: from –0.0033 to –0.0255 at D = 0.3 and from –0.073 to –0.1624 at D = 0.6. This shows the significance of the ply sequence, which of course is non-negligible even for the first eigenmode and without taking into account the friction between the delaminated surfaces.

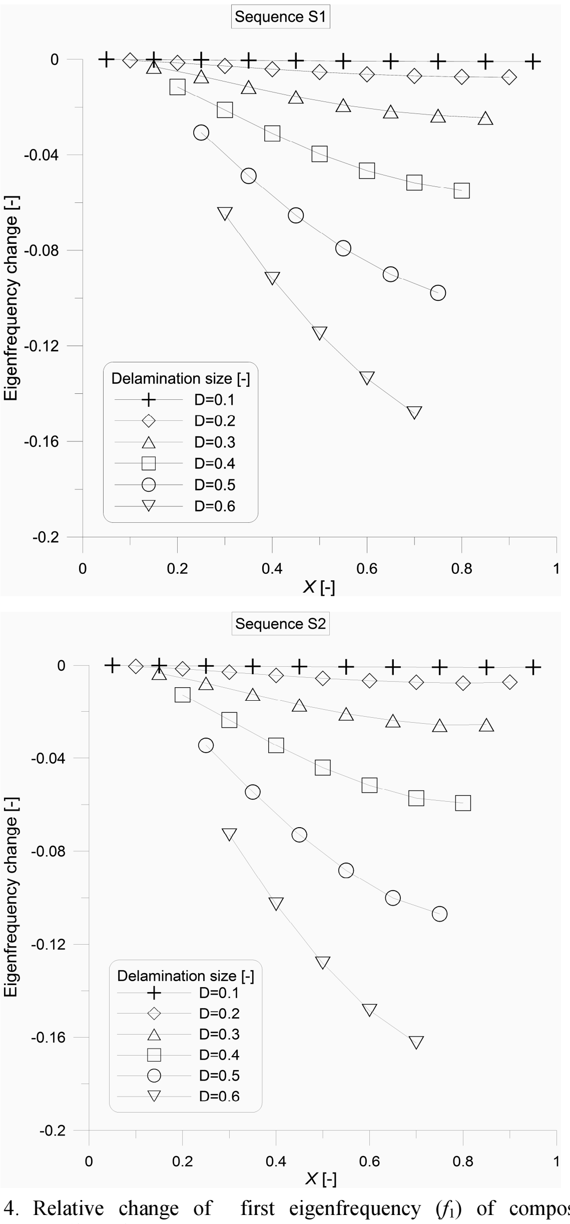

Fig. 4. Relative change of first eigenfrequency (f_1) of composite cantilever beam

Rys. 4. Względna zmiana pierwszej częstości własnej (f_1) kompozytowej belki wspornikowej

When considering the subsequent modes, one can observe the non-monotonic courses of the curves representing relative eigenfrequency changes in function of the defect location. In the case of the second mode (f_2), there is a maximum representing the slightest drop in frequencies of free vibrations for the location parameter (X) from ca. 0.42 to 0.48 for the two considered sequences of the composite beam (Fig. 5). This means that there is a special defect location (delamination) where its influence on f_2 is very limited, practically for any reasonable size of flaw: $D \in$ <0.2,0.6>. It is worth emphasizing the difference between the eigenfrequency drop when the defect is located at the free end of the cantilever beam and the minimum value can reach 7%, as the respective values for D = 0.6 in the S2 composite sequence are –0.1808 and –0.1144. (cf. Fig. 3). Nevertheless, the difference between the beam free end and the clamp in the sense of the defect location influence on f_2 for D = 0.6 is even bigger - more than 21% for both the considered sequences. Moreover, for smaller defect sizes ($D \leq 0.3$), the local extreme practically reaches zero which means that at the respective special delamination location, its influence on the second eigenfrequency is naught.

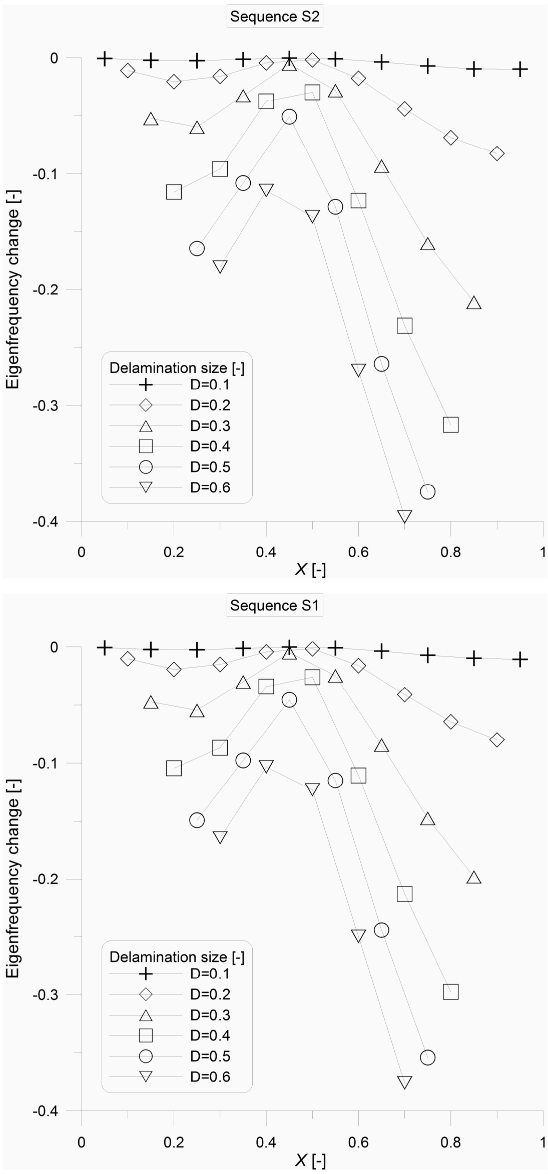

Fig. 5. Relative drop of second eigenfrequency (f_2) of composite cantilever beam

Rys. 5. Względna zmiana drugiej częstości własnej (f_2) kompozytowej belki wspornikowej

The analysis of the subsequent (higher) modes of cantilever beam vibration reveals the growing complexity of the defect location (X) and its size (D) influence on eigenfrequencies (Fig. 6). More local extremes appear and the maximum frequency drop can exceed 40% for the S2 sequence composite. Analysis of the graphs given in Figure 6 yields in particular that location of the defect in the middle of the beam will give a bigger frequency drop than at the free end. This is different in comparison to the results obtained for f_2.

Moreover, for moderate defect sizes $D > 0.3$, the decrease in eigenfrequency for the middle location is bigger than that for the defect placed right at the clamp. This is in contrast to any engineering intuition and demands further research. On the other hand, even for smaller defects ($D < 0.2$) the "fluctuation" of the frequency drop is noticeable.

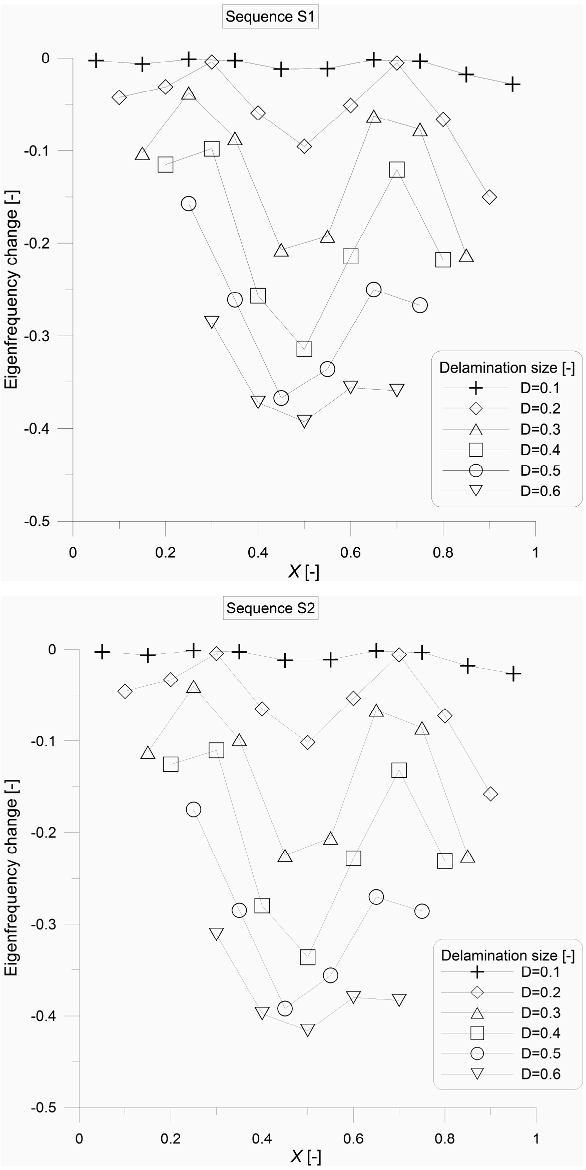

Fig. 6. Relative drop of third eigenfrequency (f_3) of composite cantilever beam

Rys. 6. Względna zmiana trzeciej częstości własnej (f_3) kompozytowej belki wspornikowej

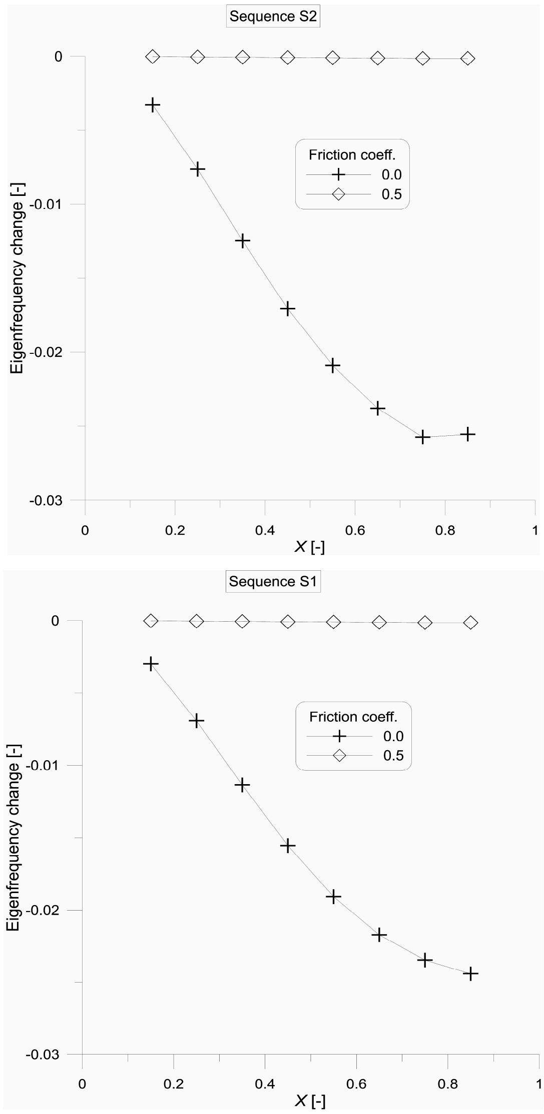

Fig. 7. Relative drop of first eigenfrequency (f_1) of composite cantilever beam when friction is taken into account

Rys. 7. Względna zmiana pierwszej częstości własnej (f_1) kompozytowej belki wspornikowej przy uwzględniu tarcia

The performed analyses also show that increasing the friction in the delaminated zone could restrain the eigenfrequency drop, providing that the surfaces were in contact. For this purpose, the *Hard Contact* option was used in ABAQUS/CAE together with the *Penalty* friction formulation. As there is a limited number of papers concerning the friction coefficient of glass-epoxy composites [8], it was accepted to be $\mu = 0.5$ with isotropic directionality. Nevertheless, a separate experimental study seems to be necessary.

As an example, the effect of friction on the first eigenfrequency (f_1) at delamination length $D = 0.3$ is presented above. Figure 7 proves that friction must be taken into account in the model in order to simulate the real composite beam dynamic behavior properly. In the case of the directional ply sequence (S2), the effect of friction can in general be limited by only partial contact of the delaminated surfaces due to the warping of the separated parts of the beam.

SUMMARY

The diversity of the results obtained for the same defect size at different locations along the beam shows the complexity of the problem of delamination influence on composite cantilever beam dynamics. One of the most revealing aspects of this work is the observation that changing the size or location of the delamination in a structure can in some cases completely change the mechanical characteristics of a composite beam. The advantage of this observation is that in some cases the resonance phenomenon could be avoided. On the other hand, it is not simple to guess whether the location of the defect at its particular size is safe for the structure. Besides the two above defined main parameters, i.e. the delamination size and the location, also other factors must be considered, for example the friction coefficient, the ply sequence in the case of laminated composites and of course the boundary conditions. The Finite Element Method implemented in the commercial ABAQUS/CAE software turned out to be a powerful tool for simulating the dynamics of damaged structures. Experimental verification of the numerical results is necessary.

Acknowledgements

Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project "Modern material technologies in aerospace industry", Nr POIG.01.01.02-00-015/08-00 is gratefully acknowledged.

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