VIBRATION-BASED DAMAGE IDENTIFICATION IN LAMINATED COMPOSITE BEAMS

BOJĀJUMU IDENTIFIKĀCIJA SLĀŅAINĀ KOMPOZĪTMATERIĀLA SIJĀS IZMANTOJOT SVĀRSTĪBU PARAMETRUS

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Introduction

Due to their advantages of stiffness and strength over conventional materials, composite materials are finding increasing use in a variety of engineering application such as aircraft, automobiles, sporting goods and electronics. On the other hand, the mechanical properties in composites may degrade severely in the presence of damage which may grow as a combination of such failure modes as matrix cracking, fiber pullout, fiber fracture, fiber-matrix debonding and delamination between plies. Damage in structure may cause failure leading to tragic consequences and therefore structural health monitoring and damage detection in civil, mechanical and aerospace engineering constructions has become one of the most important keys in maintaining the integrity and safety of a structure.
During the last decades vibration-based damage detection methods have attracted most attention due to their simplicity for implementation. These methods are based on the fact that the dynamic characteristics, i.e., the modal frequencies, mode shapes, and modal damping are directly related to the stiffness of the structure. Therefore, a change in natural frequencies or a change in mode shapes will indicate a loss of the stiffness. Valuable reviews of the state of art in the methods for detecting, localizing, and characterizing damage by examining the changes in the measured vibration parameters can be found in [1,2]. Many studies have investigated the effects of damage on mode shapes [3-5] and corresponding mode shape curvatures [6-8]. These papers show that mode shape curvatures are highly sensitive to damage and can be used to localize it. However, the major drawback of those methods is a need for the data of the healthy structure which sometimes could be difficult to obtain or even impossible. To overcome this issue Gapped Smoothing Techniques [9-11] were introduced which allow the damage detection in a structure without prior knowledge on the healthy state. The basic idea of the methods is that the mode shape curvature of the healthy structure has a smooth surface, and it can be approximated by a polynomial. The square of the difference between the measured curvature and the smoothed polynomial is defined as damage index and maximum value indicates the location and size of the damage.
In this paper the method which uses the mode shape curvature squares determined from only the damaged state of the structure for the damage detection in a laminated composite beam is described and compared with other relevant damage detection methods referenced in literature. The experimental modal frequencies and the corresponding mode shapes obtained by using a scanning laser vibrometer with a PZT actuator are used for illustration of the proposed method. In addition damage extent is identified via the modal frequencies by using a mixed numerical-experimental technique.

Damage detection algorithms

By the virtue of the fact that the mode shape curvature squares are derived from mode shapes and also for a better illustration of the proposed method, it was decided to compare the present method with other relevant damage detection methods which employ mode shape information.

Mode shape (MS) damage index

The simplest one is the mode shape damage index. It represents the difference between the mode shapes of the healthy and the damaged structures [3]

$$\Delta v_i = \left| v_i^d - v_i \right| \tag{1}$$

where v^d_i and v_i are mode shapes of the damaged and the healthy state of a structure, respectively, and i denotes the node number or measured point.
The experimentally measured mode shapes are inevitably corrupted by measurement noise. This noise introduces local perturbations to the mode shape which can lead to peaks in the mode shape slope, curvature and curvature square profiles. These peaks could be mistakenly interpreted as damage or they could mask the peaks induced by real damage in a beam and lead to false or missed detection of damage. To overcome this problem, it is proposed to average the sum of damage indices from each mode. To summarize the results for all modes, the index is proposed as

$$MS = \frac{1}{N} \sum_{n=1}^{N} \left(\Delta v_i \right)_n \tag{2}$$

where N is the total number of modes to be considered.

Mode shape slope (MSS) damage index

This algorithm uses the change in the mode shape slope

$$\Delta v_i' = \left| v_i'^d - v_i' \right| \tag{3}$$

The central difference approximation is used to derive the mode shape slope from the mode shape

$$v_i' = \frac{\left(v_{i+1} - v_{i-1} \right)}{2h} \tag{4}$$

where h is the distance between two successive nodes or measured points.
If more than one mode is used, the index is given by

$$MSS = \frac{1}{N} \sum_{n=1}^{N} \left(\Delta v_i' \right)_n \tag{5}$$

Mode shape curvature (MSC) damage index

In this algorithm the location of damage is assessed by the difference in the mode shape curvature between the healthy and the damaged case [6]

$$\Delta v_i'' = \left| v_i''^d - v_i'' \right| \tag{6}$$

The mode shape curvatures is computed from experimentally measured or numerically calculated mode shapes using the central difference approximation

$$v_i^{''} = \frac{\left(v_{i+1} - 2v_i + v_{i-1}\right)}{h^2} \tag{7}$$

The average sum of the damage indexes from each mode is defined by

$$MSC = \frac{1}{N}\sum_{n=1}^{N}\left(\Delta v_i^{''}\right)_n \tag{8}$$

Mode shape curvature square (MSCS) damage index

This damage index is defined by [3]

$$\Delta v_i^{''2} = \left| v_i^{''d2} - v_i^{''2} \right| \tag{9}$$

For more than one mode used, the index is

$$MSCS = \frac{1}{N}\sum_{n=1}^{N}\left(\Delta v_i^{''2}\right)_n \tag{10}$$

All the aforementioned methods assess the location of the damage by the largest computed absolute difference between the mode shape function of the damaged and the healthy state of a structure. However, the major drawback of those methods is a need for the data of the healthy structure which sometimes could be difficult to obtain or even impossible. To overcome this issue it was proposed to use the mode shape curvature squares from only the damaged state of the beam as a damage index.

Mode shape curvature square magnitude (MSCSM) damage index

The vibration strain energy (U_i) associated with the particular mode shape at a point is given by

$$U_i = \frac{1}{2}\int_x EI\left(v_i^{''}\right)^2 dx \tag{11}$$

where $v_i^{''}$ is the mode shape curvature and EI is the flexural stiffness of the structure. The idea of the proposed method is based on the relationship between the mode shape curvature square and the flexural stiffness of a structure. Damage induced reduction of the flexural stiffness of the structure subsequently causes an increase in the magnitude of the mode shape curvature square. The increase of the magnitude of the curvature square is local in nature, thus the mode shape curvature square may be considered as an indicator for the damage location. The location of the damage is assessed by the largest magnitude of the mode shape curvature square. The summarized damage index for all modes is proposed as

$$MSCSM = \frac{1}{N}\sum_{n=1}^{N}\left(v_i^{''d2}\right)_n \tag{12}$$

Laminated composite beams

Two laminated composite beams considered in this study are cut out from a carbon/epoxy composite plate (Fig.1.). The laminate lay-up for the plate is $(0/90/+45/-45)_s$. The ply thickness t = 0.3 mm, thus thickness of the plate is 2.4 mm. Experimentally determined material properties of the plate are as follows:

$$E_x = 54.5\text{GPa}; \quad E_y = 31.04\text{GPa}; \quad G_{xy} = 7.09\text{GPa};$$
$$G_{yz} = 6.5\text{GPa}; \quad \upsilon_{xy} = 0.3; \quad \rho = 1364.9\text{kg/m}^3$$

Dimensions of the beams are as follows: *Beam 1* - length L = 550 mm, width B = 35 mm and thickness H = 2.4 mm; *Beam 2* - L = 350, B = 35 mm, H = 2.4 mm.

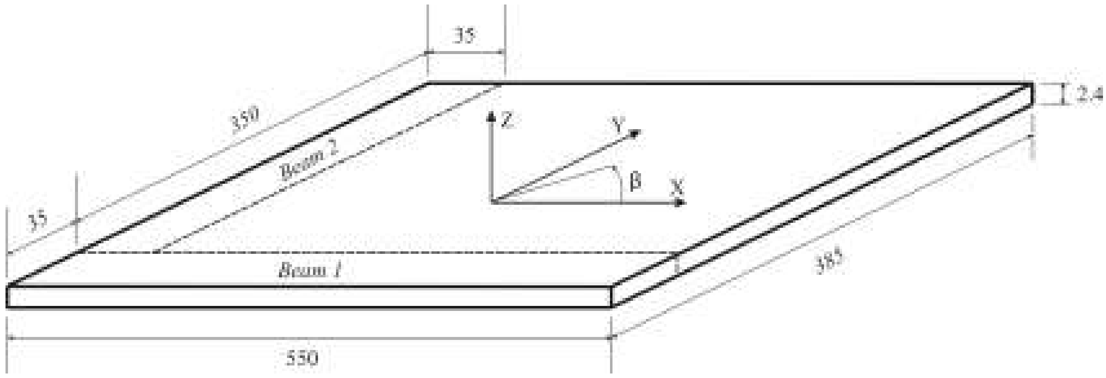


Fig.1. Geometry and dimensions of the test beams

Low-velocity impact testing

Impact tests were performed on INSTRON Dynatup 9250 HV drop tower. By varying the drop height, different impact energies and velocities were obtained. The beams were fixed by using pneumatic clamps. The impactor had a hemispherical nose of 20 mm in diameter. Re-strike of the crosshead was prevented by pneumatic rebound brakes. For the Beam 1 the impact energy of 15 J were selected, location of impact is set at the distance L_i = 345 mm. For the Beam 2 – 10 J at the distance L_i = 175 mm (Fig. 2.).

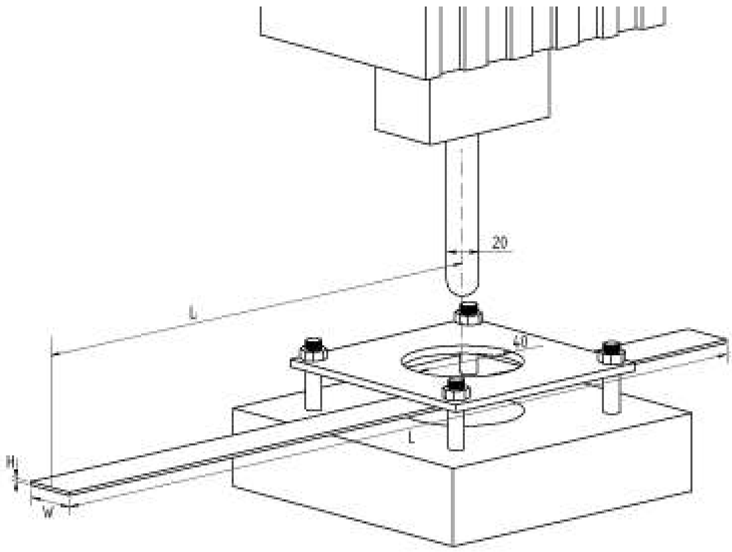


Fig.2. Low-velocity impact testing

Numerical analysis

To validate the effectiveness of the damage algorithms introduced above, the numerical modal analysis based on the finite element (FE) method was performed. The numerical analysis was carried out by using the commercial FE software ANSYS 11.0. Finite element models for the laminated composite beams consist of two dimensional beam elements. Each node has three degrees of freedom, namely translations along the X and Y axes and rotation along the Z axis. Finite element length of 10 mm is considered, thus the *Beam 1* is constructed by means of 55 equal length elements (i=56 nodes) and the *Beam 2* -35 elements (i=36 nodes). For the healthy beam, a constant stiffness EI is assumed for all elements, while the damaged beam is modelled by reducing stiffness of the selected elements. Reduction of stiffness is achieved by decreasing the elastic modulus of elements in the damaged region of the beam. The modal frequencies and corresponding mode shapes for the first 15 flexural modes of both the healthy and the damaged beams were calculated.

Vibration experiment set-up

Modal frequencies of the test beams were measured by employing the POLYTEC PSV-400-B scanning laser vibrometer (SLV). General experiment set-up consists of the PSV-I-400 LR optical scanning head equipped with the highly sensitivity vibrometer sensor (OFV-505), OFV-5000 controller, PSV-E-400 junction box, the amplifier Bruel&Kjaer type 2732, and the computer system with data acquisition board and PSV Software (Figure 2). The system requires defining geometry of the object and set up scanning grid. To match the finite element model 56 equally spaced scanning points have been taken to cover the *Beam 1* along its length and 30 scanning points were set for the *Beam 2*. The free-free (all edges free) boundary conditions have been simulated during experiment by hanging up the beam with two thin threads. In order to simulate the clamped-clamped (two ends fixed) boundary conditions experimentally, two vices have been used to fix ends of the beam (5 mm from both sides) with the clamped torque equal 20 Nm. The beam has then been excited by an input periodic chirp signal generated by the internal generator with a 4800 Hz bandwidth through a piezoelectric actuator (PZT). The excitation with small piezoelectric discs works via the radial expansion of the disc causing a bending moment to the beam surface. As a result of this excitation the beam starts to vibrate within the frequency band of the input signal. After the measurement is performed in one point, the vibrometer automatically moves the laser beam to another point of the scan grid, measures the response using the Doppler principle and validates the measurement with the signal-to-noise ratio. The procedure is repeated until all scan points have been measured. The modal frequencies and corresponding mode shapes are obtained by taking the Fast Fourier Transform of the response signal.

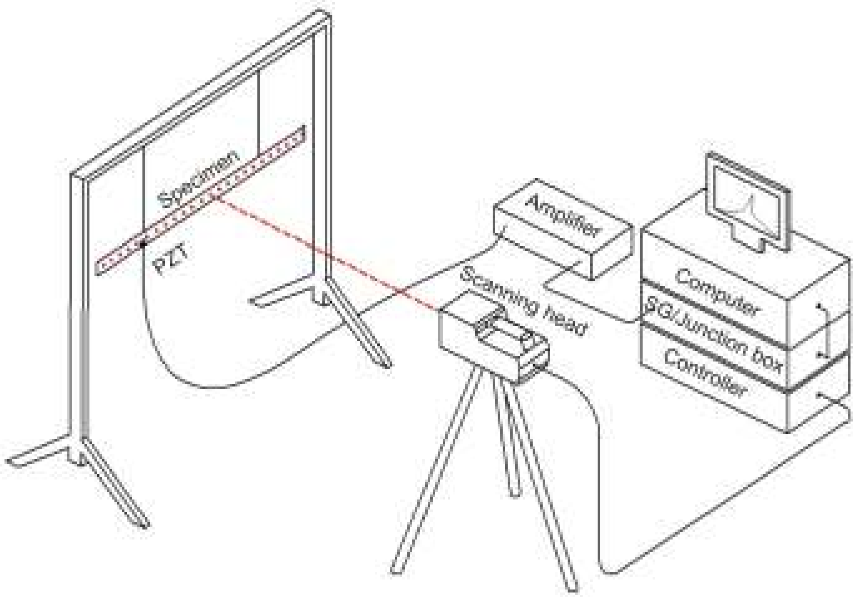
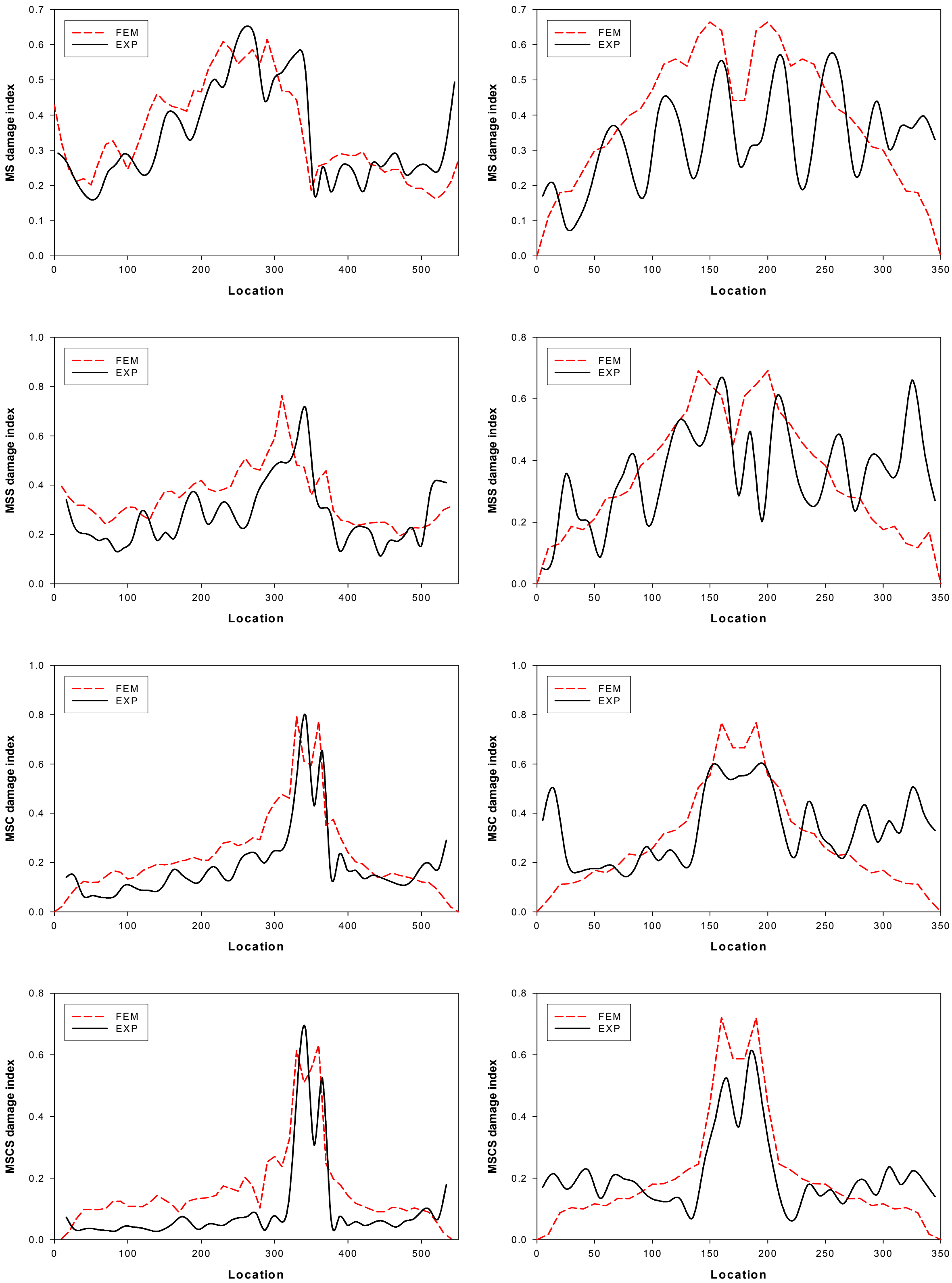


Fig.3. Scheme of vibration experiment set-up

Results of damage detection

Results of the mode shape based damage detection methods are given in Figures 3 and 4. For comparison purposes the damage indexes are also calculated employing the mode shape information obtained via the finite element simulations. From the results presented in Figure 3 (beams with the free-free boundary conditions) it is seen that MSC and MSCS damage index methods as well as the proposed MSCSM damage index method succeeded in pointing out the location of low-velocity impact introduced damage. Size of the damage is assessed between two (the first and the last) of the largest peaks. In order to realize the effect of the boundary conditions on mode shape information, it was decided to test the same beams with the clamped-clamped (CL) boundary conditions. Again, two out of four methods included in the investigation for comparison purposes as well as the proposed MSCSM damage index method were capable of indicating the location and size of the damage. MSCS and MSCSM damage index plots for the beams with the CL boundary conditions are presented in Figure 4.


FEM
EXP
MS damage index
MSS damage index
MSC damage index
MSCS damage index
Location

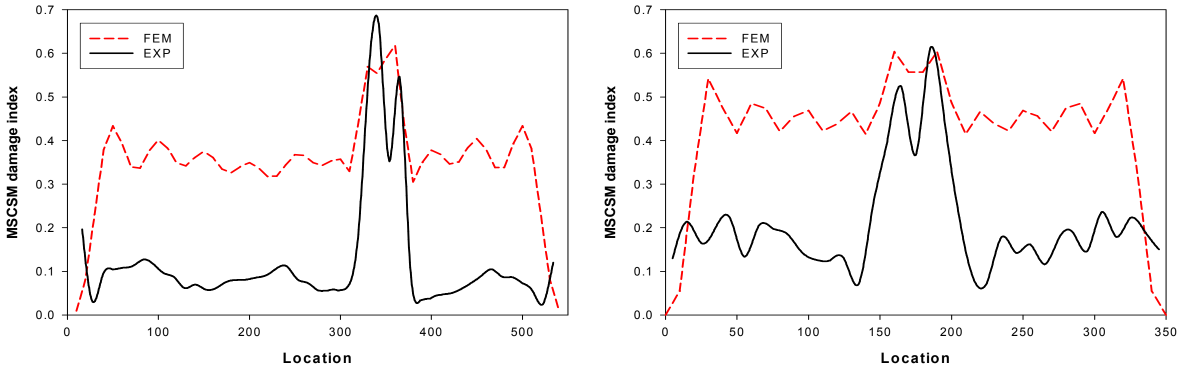


Fig.4. Damage detection methods for beams with FF boundary conditions; *Beam1* – left; *Beam 2* – right.

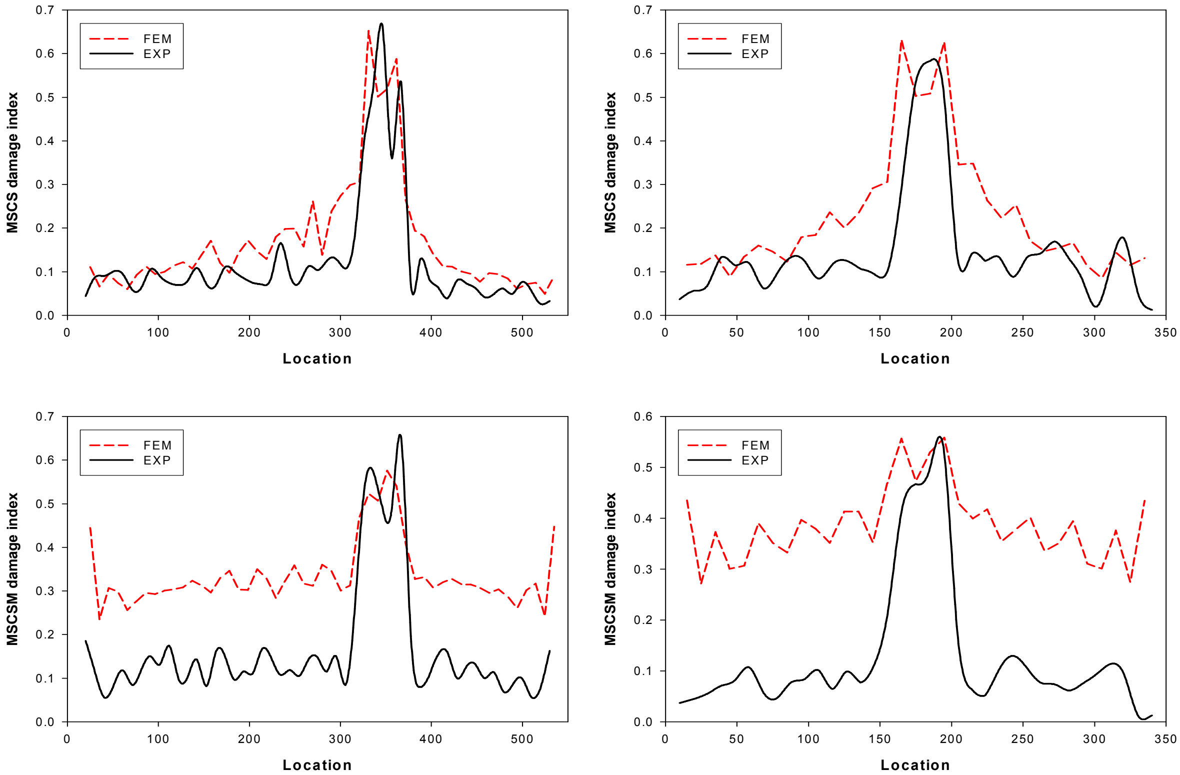


Fig.5. Damage detection methods for beams with CL boundary conditions; *Beam1* – left; *Beam 2* – right.

Identification of damage extent

Once the location and size of the damage was determined the following interest was to identify damage extent or reduction of stiffness caused by low-velocity impact. The extent of the damage was identified via modal frequencies by using a mixed numerical-experimental technique. The method is based on the minimization of the discrepancy between the numerically calculated and experimentally measured frequencies. For this the first 10 flexural frequencies of the beams with the free-free boundary conditions have been used. The free-free boundary conditions were selected because of the best correlation between the numerically calculated and experimentally measured modal frequencies.

It was proposed to introduce damage extent coefficient K, which will be used for the modelling of the damage in the finite element models of the beams. Damage in the beams is modelled by reducing flexural stiffness EI of the selected elements, thus for the healthy beam flexural stiffness $EI*K$ $(K=1)$ is assumed for all elements, while for the damaged beam reduced stiffness $EI*K$ $(K<1)$ is used for the damaged elements. Now the damage extent coefficient K is selected as the parameter to be identified.
From the MSCSM damage index plots given in Figures 3 and 4 it is assumed that the beginning of the damaged region for the *Beam 1* is located at the distance of L_1 = 320 mm and ending of it at the distance of L_2 = 370 mm. Damage is assumed to be uniform through out the whole region and therefore constant damage extent coefficient K for whole damage region is selected. Since only the flexural modes were considered in this study then mainly the longitudinal Young's modulus E_x has an effect on modal frequencies and thus in the damaged region flexural stiffness is modelled by reducing the longitudinal Young's modulus E_x by the damage extent coefficient K ($E_x^d = E_x*K$).
For the *Beam 2* the beginning of the damaged region is located at the distance of L_1 = 150 mm and ending of it at the distance of L_2 = 200 mm. Again, damage is assumed to be uniform through out the whole region and employing previously described assumptions, flexural stiffness in the damaged region is modelled by reducing the longitudinal Young's modulus E_y by the damage extent coefficient K ($E_y^d = E_y*K$).
The domain of interest for damage extent coefficient K for the *Beam 1* was selected as follows

$$0.55 \leq K \leq 0.75 \tag{13}$$

And for the *Beam 2*

$$0.7 \leq K \leq 0.9 \tag{14}$$

Step of 0.1 was selected for the damage extent coefficient K and the finite element calculations in this domain were performed. Then employing the response surface approach the obtained data were used to build the approximating functions (second order polynomial functions) for all 10 flexural frequencies. These approximating functions represent the relationship between the modal frequencies ω_i and the damage extent coefficient K of the damage elements. For the identification of the damage extent two identification functionals were proposed. The first one uses modal frequencies from both, the healthy and the damaged states of the beam and is defined by

$$\Phi_1(h_1) = \sum_{i=1}^{I} \left[\frac{\left(\omega_{i\,FEM}^{h} \dfrac{\omega_{i\,EXP}^{d}}{\omega_{i\,EXP}^{h}} \right)^2 - \left(\omega_{i\,FEM}^{d}(K) \right)^2}{\left(\omega_{i\,FEM}^{h} \dfrac{\omega_{i\,EXP}^{d}}{\omega_{i\,EXP}^{u}} \right)^2} \right]^2 ; \qquad i = 1,2,\ldots,I \tag{15}$$

where $\omega_{i\,EXP}^{h}$ and $\omega_{i\,EXP}^{d}$ are the experimentally measured modal frequencies of the healthy and the damaged states of the beams, respectively. $\omega_{i\,FEM}^{h}$ are numerically calculated modal frequencies of the healthy state of the beams and $\omega_{i\,FEM}^{d}(K)$ are approximating functions representing the relationship between the modal frequencies and the damage extent. I is the number of frequencies used in the functional. The idea of this functional is based on the assumption that the numerical frequency ratio $\omega_{i\,FEM}^{h} / \omega_{i\,FEM}^{d}$ should be close to the experimental one $\omega_{i\,EXP}^{h} / \omega_{i\,EXP}^{d}$.
The second proposed identification functional uses modal frequencies only from the damaged state of the beam and is given as

$$\Phi_2(h_1)=\sum_{i=1}^{I}\left(\frac{{\omega_{i\,EXP}^{d}}^{2}-\left(\omega_{i\,FEM}^{d}(K)\right)^{2}}{{\omega_{i\,EXP}^{d}}^{2}}\right)^{2}; \qquad i=1,2,\ldots,I \tag{16}$$

The damage extent coefficient K is obtained by solving the minimization problem

$$\min_{K}\Phi(K) \tag{17}$$

Subjected to

$$K^{\min}\leq K\leq K^{\max} \tag{18}$$

where $K^{\min}$ and $K^{\max}$ are the lower and upper bounds of identification parameter.

Minimizing the first identification functional (15), the following damage extent coefficient K were obtained: for the *Beam 1* - K = 0.628 mm, for the *Beam 2* - K = 0.768 mm. Employing the second functional (16): for the *Beam 1* - K = 0.636 mm, for the *Beam 2* - K = 0.772 mm. Now, when the damage extent coefficient was obtained, it was of interest to evaluate the accuracy of the identification. Verification of the obtained results was performed by numerically calculating modal frequencies in the point of optimum (using the identified damage extent coefficient K). In Tables 1 and 2 modal frequencies for the first 10 flexural modes for both, the healthy and damaged state of the beams with the free-free boundary conditions, have been listed. Residuals characterizing differences between experimental and numerical frequencies were calculated by the expression

$$\Delta_i=\frac{\left|\omega_i^{FEM}-\omega_i^{EXP}\right|}{\omega_i^{EXP}}\times 100 \tag{19}$$

According to the results given in Tables 1 and 2, the frequency residuals between the numerically calculated and experimentally measured frequencies for the healthy beams are very small, which indicate that the finite element model has been constructed correctly. On the other hand, frequency residuals for the damaged beams are larger indicating that the damage representation in finite element model has some imperfections. This is explained by the fact that the damage introduced by low-velocity impact is not uniform through out the damage region (as it is assumed in this study for the simplicity of calculations) and therefore should be modelled using approximating functions representing changes of stiffness of the damaged elements through out the damage region. Additionally for the identification of damage extent torsional mode shapes should be taken in account thus allowing reduction of other elastic constants (transverse Young's modulus and shear modulus) of structure giving a possibility for better characterization of damage.

Table 1

Flexural frequencies and residuals for the *Beam 1* with FF boundary conditions

Mode	*Beam 1*							
	Healthy			**Damaged**				
	$\omega_{i\,EXP}^{h}$ (Hz)	$\omega_{i\,FEM}^{h}$ (Hz)	Δ_i (%)	$\omega_{i\,EXP}^{d}$ (Hz)	$\omega_{i\,FEM}^{d}$ (K=0.628) (Hz)	Δ_i (%)	$\omega_{i\,FEM}^{d}$ (K=0.636) (Hz)	Δ_i (%)
1	51.55	52.25	1.34	50.25	48.94	2.68	49.02	2.50
2	142.10	142.50	0.28	137.50	137.04	0.34	137.19	0.23
3	278.55	278.00	0.20	268.50	276.75	2.98	276.81	3.00
4	460.42	463.75	0.72	447.25	442.88	0.99	443.36	0.88
5	687.72	699.25	1.65	650.75	675.20	3.62	675.56	3.67
6	960.44	959.50	0.10	898.75	940.86	4.48	941.44	4.53
7	1278.54	1258.25	1.61	1192.50	1243.68	4.12	1244.56	4.18
8	1642.01	1627.50	0.89	1574.00	1606.07	2.00	1607.24	2.07
9	2050.82	2042.25	0.42	1903.50	2004.11	5.02	2005.36	5.08
10	2504.94	2517.00	0.48	2448.50	2448.67	0.01	2450.24	0.07
Aver.			0.77			2.62		2.62

Table 2

Flexural frequencies and residuals for the *Beam 2* with FF boundary conditions

Mode	*Beam 2*							
	Healthy			**Damaged**				
	$\omega_{i\,EXP}^{h}$ (Hz)	$\omega_{i\,FEM}^{h}$ (Hz)	Δ_i (%)	$\omega_{i\,EXP}^{d}$ (Hz)	$\omega_{i\,FEM}^{d}$ (K=0.628) (Hz)	Δ_i (%)	$\omega_{i\,FEM}^{d}$ (K=0.636) (Hz)	Δ_i (%)
1	95.75	95.73	0.02	93.25	91.31	2.12	91.41	2.01
2	262.25	263.87	0.62	251.00	263.49	4.74	263.51	4.75
3	515.25	517.21	0.38	509.00	503.08	1.18	503.39	1.12
4	857.50	854.82	0.31	826.50	847.33	2.46	847.55	2.48
5	1301.00	1276.68	1.87	1265.00	1251.81	1.05	1252.34	1.01
6	1793.75	1782.72	0.61	1736.25	1753.70	1.00	1754.45	1.04
7	2399.00	2372.86	1.09	2284.00	2340.46	2.41	2341.20	2.44
8	3039.75	3047.03	0.24	3021.00	2985.42	1.19	2986.89	1.14
9	3793.50	3805.17	0.31	3712.50	3759.96	1.26	3761.09	1.29
10	4565.25	4647.26	1.80	4499.25	4554.94	1.22	4557.02	1.27
Aver.			0.72			1.86		1.86

Conclusions

The present study focuses on the identification of low-velocity impact introduced damage location, size and extent in laminated composite beams by extracting dynamic characteristics obtained from vibration experiments. It was proposed to use the magnitude of the mode shape curvature square for the detection of the damage location and size. Compared to the existing damage detection methods such as MSC and MSCS damage index methods, the advantage of the proposed method is that it requires mode shape information only from the damaged state of the structure. In order to reduce the influence of measurement noise on the damage detection from the experimentally measured mode shape information it was proposed to use the average sum of the mode shape curvature squares for all modes. Effectiveness and robustness of the present method is demonstrated by two composite beams subjected to different low-velocity impact energy introduced damage at different locations. In order to realize the effect of the boundary conditions on mode shape information, it was decided to test the beams with both the free-free and the clamped-clamped boundary conditions. Obtained results showed that both boundary conditions are eligible for the detection of the damage location and size. The extent of the damage has been identified via modal frequencies by using a mixed numerical-experimental technique. The proposed method is based on the minimization of the discrepancy between the numerically calculated and experimentally measured frequencies. For the simplicity of calculations it was assumed that damage is uniform through out the whole region and therefore constant damage extent coefficient K for whole damage region was selected. From obtained results it can be concluded that both identification functionals were capable to identify the damage extent, which suggests that the damage location, size and extent in the beam structure can be obtained without prior knowledge of the healthy state of structure.

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S. Ručevskis, M. Wesolowski un A. Čate. Bojājumu identifikācija slāņainā kompozītmateriāla sijās izmantojot svārstību parametrus

Piedāvātās bojājumu identifikācijas metodes pamat ideja ir tāda, ka bojājums kā dažādu veidu materiāla sagrūšanas formu kombinācija izraisa konstrukcijas stinguma samazināšanos un tādejādi ietekmē tās dinamiskos raksturlielumos, tādus kā svārstību frekvences, svārstību formas un svārstību dzišanas koeficents. Līdz šim ir piedāvātas daudzas bojājumu identifikācijas metodes, kas izmanto dinamiskos raksturlielumos bojājumu noteikšanai, tomēr lielākajai daļai no tām ir nepieciešami nesagrautās konstrukcijas raksturlielumi to realizācijai. Dotajā darbā tiek piedāvāta bojājumu identifikācijas metode, kas izmanto konstrukcijas svārstību parametrus iegūtus tikai no bojātas konstrukcijas. Piedāvātās metodes efektivitāte un robustums ir pierādīts, izmantojot divas kompozītmateriāla sijas, kas pakļautas dažādiem zema ātruma triecieniem dažādās to vietās. Pirmās 10 eksperimentālās svārstību frekvences un atbilstošās svārstību formas tika nomērītas, izmantojot lāzera vibrometru un pjezoelektrisko svārstību ierosinātāju . Tālāk no svārstību formām, izmantojot centrālo diferencēšanas metodi, tika iegūti svārstību formu izliekumi Lai izskaustu nevēlamo mērījumu troksni, kā arī maldinošos bojājumu noteikšanas indeksus, tika piedāvāts lietot katras svārstību formas izliekuma kvadrātu vidējo svērto vērtību summu. Ar kompozītmateriāla sijām, kam piemēroti gan brīvi, gan iespīlēti robežnoteikumi, tika pierādīts, ka svārstību formas izliekuma kvadrāti var tikt izmantoti bojājumu noteikšanai. Trieciena izraisīto bojājumu pakāpes noteikšanai tika izmantotas svārstību frekvences un skaitliskā-eksperimentālā metode. Metode ir balstīta uz identifikācijas funkcionāļa, kas raksturo starpību starp eksperimentāli nomērītajām un skaitliski aprēķinātajām svārstību frekvencēm, minimizēšanu. Skaitliski svārstību frekvences tika aprēķinātas, izmantojot galīgo elementu modeli, kas ietver trieciena rezultātā radīto bojājumu. Sekojoši atbildes virsmas metodes aproksimācijas tika izmantotas, lai būvētu apgrieztās sakarības (otrās pakāpes polinomus) starp svārstību frekvencēm un bojājumu pakāpes koeficentu. Bojājumu pakāpes koeficents tika iegūts minimizējot identifikācijas funkcionāli.

S. Ručevskis, M. Wesolowski and A. Chate. Vibration-based damage identification in laminated composite beams

The basic idea of the proposed vibration-based damage detection method is that a damage as a combination of different failure modes in the form of loss of local stiffness in the structure alters its dynamic characteristics, i.e., the modal frequencies, mode shapes, and modal damping values. A great variety of methods have been proposed for damage detection by using dynamic structure parameters; however, most of them require modal data of the healthy state of structure as a reference. In this paper a vibration-based damage detection method which uses the mode shape information determined from only the damaged state of the structure is proposed. Effectiveness and robustness of the proposed method is demonstrated by two composite beams subjected to different low-velocity impact energy introduced damage at different locations. The experimental modal frequencies and the corresponding mode shapes for the first 10 flexural modes are obtained by using a scanning laser vibrometer with a PZT actuator. From the mode shapes, mode shape curvatures are obtained by using a central difference approximation. In order to exclude the influence of measurement noise on the modal data and misleading damage indices, it is proposed to use the average sum of mode shape curvature squares for each mode. With the *example of the beams with free-free and clamped boundary conditions, it is shown that the mode shape curvature squares can be used to detect damage in the structures. The extent of low-velocity impact introduced damage is identified via the modal frequencies by using mixed numerical-experimental technique. The method is based on the minimization of the discrepancy between the numerically calculated and the experimentally measured frequencies. The numerical frequencies are calculated by employing a finite-element model for beam with introduced damage. Further, by using the response surface approach, a relationship (second-order polynomial function) between the modal frequencies and the damage extent is constructed. The damage extent is obtained by solving the minimization problem.*

С. Ручевскис, М. Весоловски и А. Чате. Вибрационный метод определения повреждения многослойной композитной балки

Основная идея предложенного вибрационного метода обнаружения повреждения является комплекс различных форм разрушения материала в виде потери локальной жесткости конструкции и изменение ее динамических характеристик, то есть модальных частот, форм и степени затухания. Большинство существующих методов обнаружения повреждения используют динамические параметры структуры. Однако многие из них требуют первоначальные данные модальных параметров не поврежденной конструкции. В данной статье вибрационный метод обнаружения повреждения использует данные форм колебаний полученные из поврежденной конструкции. Эффективность и надежность предложенного метода демонстрируется на примере двух композитных балок, которые предварительно были подвергнуты ударному воздействию в различных местах. С помощью сканирующего лазерного виброметра и пьезоэлектрического возбудителя, получены экспериментальные модальные частоты и соответствующие им формы колебаний первых 10 изгибных форм. Из полученных форм колебаний, определяются изгибные формы колебаний дифференцированием центральной разности. Предлагается использовать квадрат средней суммы изгибных форм колебаний для каждой формы колебаний, чтобы исключить обманчивые повреждения и помехи замера модальных данных. Показана эффективность квадрата средней суммы изгибных форм колебаний для определения повреждения конструкции на примере двух композитных балок с различными граничными условиями. Величина повреждения от ударного воздействия, определяется с помощью модальных частот, используя численно-экспериментальный метод. Данный метод основан на минимизации разницы между численными и экспериментальными частотами. Расчетные частоты собственных колебаний поврежденной балки, определяются из конечно-элементной модели. Используя метод поверхностного отклика, строится зависимость (функция полинома второй степени) между модальными частотами и величиной повреждения. Величина повреждения вычисляется задачей минимизации.