Identification of Damage Size Effect of Natural Frequency on Sandwich Material using Free Vibration Analysis

Identifikacija učinka prirodne frekvencije na veličinu oštećenja na sendvič materijalu pomoću analize slobodnih vibracija

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Abstract

One of the most innovative developments in the field of advanced materials is sandwich materials. Sandwich material applications need standard requirements to be applied to marine structures, especially on ship construction. Sandwich material research is conducted on a laboratory scale to obtain the appropriate material composition in its development. In the process of developing this material, the material can be damaged. Most damage occurs in the core material, which results in difficulties in the identification process. This study compares damage identification methods based on free vibration analysis on the side sandwich plate of the ship's hull. Damage-based identification is carried out to determine the response of vibration to the damage that occurs. Moreover, the method in this research uses a numerical approach and experimental vibration measurement. Numerical modelling is used to determine the appropriate boundary conditions and is shifted in experimental measurement. Damage modelling assumes that the material experiences core failure with a numerous variation model. Quantification of damage on the core correlates with natural frequency reduction due to a decrease in the stiffness of the sandwich material. Hence, the difference in the deviation value is used to determine the accuracy of damage identification.

KEY WORDS
Sandwich Material
Marine
Damage Identification
Free Vibration Analysis
Experimental

Sažetak

Jedna od najinovativnijih razvojnih tehnologija u području naprednih materijala su sendvič materijali. U primjeni sendvič materijala na pomorskim konstrukcijama, a posebno u brodogradnji, potrebno je slijediti postavljene standarde. Istraživanje sendvič materijala provodi se u laboratoriju kako bi se dobio odgovarajući sastav materijala. U postupku razvijanja ovog materijala može doći do njegova oštećenja. Najviše oštećenja nastaje u materijalu jezgre, što dovodi do poteškoća u procesu identifikacije. Ova studija uspoređuje metode identifikacije oštećenja temeljene na analizi slobodnih vibracija na bočnom sendvič panelu trupa broda. Identifikacija na temelju oštećenja provodi se kako bi se odredio odgovor vibracije na oštećenje koje nastaje. U ovom istraživanju korišten je numerički pristup i eksperimentalno mjerenje vibracija. Numeričkim modeliranjem koristi se za određivanje odgovarajućih graničnih uvjeta i pomiče se u eksperimentalnom mjerenju. Modeliranje oštećenja pretpostavlja da materijal doživljava oštećenje jezgre s modelom brojnih varijacija. Kvantifikacija oštećenja na jezgri korelira sa smanjenjem prirodne frekvencije zbog smanjenja krutosti sendvič materijala. Zbog toga se razlika u vrijednosti odstupanja koristi za određivanje točnosti identifikacije oštećenja.

KLJUČNE RIJEČI
sendvič materijal
pomorski
dentifikacija oštećenja
analiza slobodne vibracija
eksperimentalno

1. INTRODUCTION / *Uvod*

Sandwich Material is an innovation in the maritime field, especially in the shipbuilding and marine industry sectors. Sandwich material has the strength to substitute a part of steel plate, although lightweight sandwich is more reliable than existing material. This advantage is valuable during construction, reducing cost production and increasing payload due to weight reduction [1–4]. Moreover, this material is constructed with adhesive which also prevents the risk of vibrations. Increased vibration may lead to failure in the sandwich structure. It is assumed that damage can occur during production, more specifically during the pouring and moulding process. In the course of this process, initiative crack propagation threatens the safety and durability of the sandwich material [5], [6].

Standards and regulations that are ignored during the ship construction process may damage the ship's structure. Sandwich materials are widely used in numerous structures, especially in ship structures, such as weather decks [7–9], side hull [2], [10], [11], and deckhouses [12]. Hence damage often occurs in the inner surface of plates and is detected inside core material. Damage in the surface core is difficult to observe over a wide area. However, the location and amount of damage are difficult to detect and an appropriate method needs to be improved. In-situ examination has the ability to detect defects. However, this examination requires a considerable amount of time. Damage assessment is also carried out with a non-destructive test (NDT) using a vibration-based method [13], [14]. Damage can be detected based on several indicators, including natural frequency [15]–[19], mode shape [14], [20], [21], frequency response function (FRF) [22–24], curvature method [25–27], modal damping [28], and frequency-time domain [29–31]. The simplest method is to observe the natural frequency changes.

Research concerning sandwich material for structural applications has been conducted using a free vibration approach by numerical and experimental modal analysis methods. However, its application in the maritime area is still very limited. It is necessary to conduct an in-depth study regarding the application of sandwich materials on ship structures. This depends on the location of the construction, the thickness of the material and the base composition of the material, which must comply with the strength index in order to convert the existing steel into a sandwich material. Furthermore, to study damage detection using the free vibration-based method, two approaches must be performed to validate the results with one another, and also with experimental modal analysis and the finite element method in order to obtain accurate results. Free vibration analysis on sandwich material is investigated using clamps on both sides and damage variation is used to assess the percentage of decrease in stiffness for each damage size.

In this study, a damage detection method was developed to identify the free vibration influence of sandwich material. There is limited research in the assessment of damage size effect on sandwich panel constructing polyurethane and plate combinations as part of ship construction due to damage issues. This is crucial in cases where damage occurs inside the core of sandwich materials, which may lead to fatigue or structure failure. This can be identified through observing the response of vibration due to the free vibration types of sandwich material. Therefore, the amount of damage to the core can be determined in terms of percentage of natural frequency reduction.

2. METHODOLOGY / *Metodologija*

2.1. Free vibration analysis on the design of sandwich material / *Analiza slobodne vibracije u izradi sendvič materijala*

Free vibration analysis was performed to determine the dynamic behaviour of the construction. In this analysis, no external load act caused movement. The general equation used to calculated force in vibration is as follows (1) [32]:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = F \qquad (1)$$

Nomenclatures of (Eq. 1) mass (M), damping (C), and stiffeners matrices (K). Nodal points of displacement, velocity, and acceleration are represented by U, $\dot{U}$, and $\ddot{U}$. The basic principle is to compare the natural frequency conditions on intact and damaged materials. The natural frequency decrease indicates that the material is damaged. The degree of stiffness loss of the object affects the results. In general, free vibration analysis is performed to obtain the natural frequency reduction value as the basis to determine the extent of damage. Aside from free vibration analysis, several studies investigated damage using the finite element method. Analysis was done to validate experimental data and numerical simulation. Results showed 12% of damage comparison and that is good agreement [24].

However, to reach the appropriate thickness of sandwich material design, the plate and core material must be examined. Verified design refers to the LR Standard with minimum limitation of hull construction. The faceplate and core must comply with the minimum strength ratio of material to substitute the current plate. The strength ratio (R) of minimum thickness is determined by the following equation (5):

$$R = 0.01\, A_R[0.1\ \ (b^2/d\ (t_1 + t_2) + 11.7\ (b.t_c/d^2)^{1.3}]\ kP_{eq,R} \qquad (2)$$

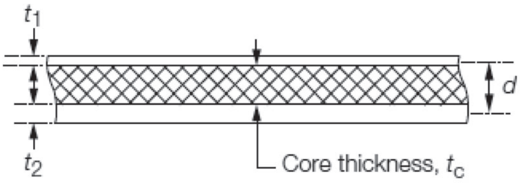


Figure 1 Structure details of sandwich material [9]
Slika 1. Pojedinosti structure sendvič materijala [9]

2.2. Geometry of Sandwich Material Plate by FEA / *Geometrija sendvič panela izvedena analizom konačnih elemenata (FEA)*

Finite element analysis (FEA) was performed to obtain the response of free vibration analysis of intact and damaged material conditions. To solve this issue, a damage size evaluation of sandwich material constructed of steel faceplate and polyurethane elastomer matrix fibre was developed in this analysis. The critical contribution of this research is to identify the effect of damage size between faceplate and core due to free vibrations. This numerical study was performed by comparing simulation results using ABAQUS package [33], [34] with the experimental results to verify the damage case. In the finite element model, the sandwich material was modelled using the layer of solid or shell elements. Moreover, the faceplate material was analysed using the 8-node quadrilateral core-shell element (SC8R) and the core material was defined using the 8-node linear brick element (3C3D8R) [35]. The geometry model follows advice from rules while the faceplate was created by shell and core defined by the solid model.

Interaction modelled between layers of material was generated using tie constraints. The boundary condition was assumed to be identical to field condition. A clamp in both materials represented the plate stiffness by ordinary frames (CFCF) used. Core failure was modelled as a reduction in volume at the core-edge of the material. The core defect size was generated by a damage percentage in order to improve the ratio of damaged area to the entire core edge area of the sandwich material. During the pre-processing step, core failure was defined as the reduction of core between the core and plate layers. The geometry was analysed using data properties of the material. Material properties were applied based on the data obtained from the experiment. The mechanical properties of the materials can be seen in Table 1.

Table 1 Mechanical properties of Sandwich Material

Tablica 1. Mehanička svojstva sendvič materijala

Properties	*Faceplate (Carbon Steel)*	*Core (Polyurethane elastomer matrix fibre)*	*Unit*
Density	7850	1098	kg/m^3
Modulus Young	200e9	901.95e6	Pa
Poisson's Ratio	0.3	0.36	-

The dimension of the sandwich material was 300 mm x 300 mm x 28 mm. The model used in this research is similar to the model used in [17]. Core damage was performed by volume reduction, the following dimensions follow the vibration test. In this study, the finite element (FE) focused not only on the descent of natural frequencies, but also on evaluation damage results in comparison to experimental modal analysis. A finite element analysis model was developed to determine the vibration characteristics from the sandwich plate in both intact and damaged conditions. Observation of the attributes was assessed using natural frequencies. Figure 2 shows the 3D geometry of the sandwich material.

Moreover, the convergence of this model was proposed to obtain the optimal element values for FEA simulations. Optimum elements provide accurate results and more efficient analysis time [36]. Discretization can be analysed by performing simulations with frequency steps in order to obtain the response mode of the plate material. The natural frequency element values were used as parameters in the intact and damaged model conditions, resulting in a convergence study in five modals that are summarized in Table 2.

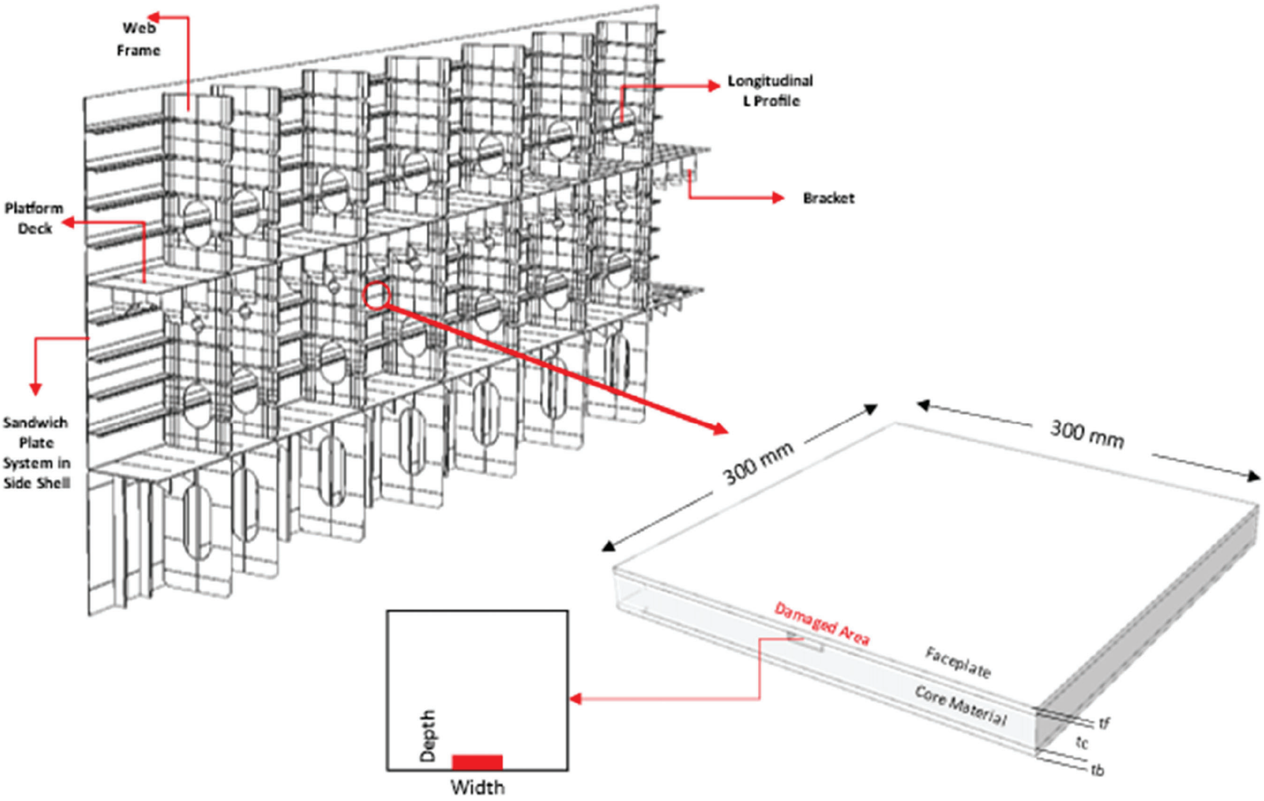


Figure 2 Sandwich material geometry and damaged area

Slika 2. Geometrija sendvič materijala i oštećeno područje

Table 2 Convergence study for the intact polyurethane elastomer matrix fibre

Tablica 2. Analiza konvergencije za netaknuta poliuretanska elastomerna matrična vlakna

Element Size (m)	Element Number	Mode (Hz)				
		1	2	3	4	5
0.009	3600	586.96	762.43	1183.9	1291	1330.4
0.008	5780	583.79	760.32	1181.2	1289	1325.7
0.007	7605	583.81	760.58	1181.5	1288.9	1325.3
0.006	12140	583.8	760.34	1181.7	1288.9	1325.3
0.005	17496	583.87	760.87	1181.1	1288.9	1325.1
0.004	32368	583.24	759.72	1180.7	1289	1324.6
0.003	**79200**	**582.99**	**759.55**	**1180.0**	**1289.1**	**1324.3**

Mesh convergence aims to ensure the accuracy of the numerical simulation results. According to theory, small sized elements of meshing size obtain more stable results. Mesh convergence aims to ensure the accuracy of the numerical simulation results.

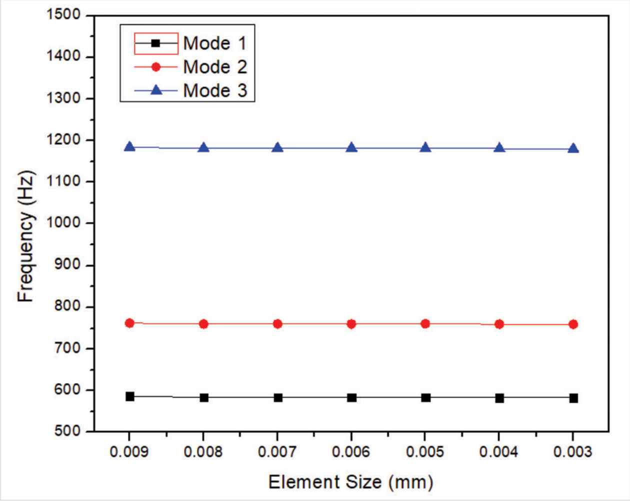


Figure 3 Mesh Convergence Study

Slika 3. Analiza konvergencije mreže

As stated in theory, smaller sized elements of mesh obtain more stable results. In the assessment of convergence analysis for intact and damaged conditions, it was decided that mesh is stable at a size of 3 mm. This specific size was also used in a different study on the identification of truss core sandwich material. Figure 3 illustrates the convergence study carried out by comparing the first three modes of natural frequencies and the number of intact geometry elements. Mesh with size ranged between 0.009 – 0.003 m was observed in the first three modes. It was concluded that 79200 elements ensured excellent accuracy with medium computational efficiency.

In this study, among the faceplate and core surface, the performed contact is presented in Figure 4. To ensure that the core sandwich and faceplate did not lose contact, tie constraint-based was used. The constraint couples the structure area and ensures that it deforms together as one part of the configuration. The constraint generates a master surface and slave surface between the structure [37]. The master surface is known to be stiffer compared to the slave surface. The top and bottom part of the faceplate are defined as the master surfaces, meanwhile both surfaces of the sandwich material are defined as the slave surface. The model of the sandwich uses clamped boundaries on the sides.

2.3. Experimental Modal Analysis Procedure / *Postupak eksperimentalne modalne analize*

Analysis of sandwich material is performed to understand the real condition in scale setup. To represent the operation condition response when plates are clamped on both sides, ship shells were supported by ordinary frames. According to experimental testing presented in [32], clamps are applied to set the material in a fixed position. The analysis was performed in two conditions, where the measurement of intact material was used as initial data and the analysis of damaged material was used to show vibration response. Numerous models of damaged material were used to illustrate the behaviour of the material and ensure that the material was appropriate. The specimen used in this test was a sandwich material with dimension of 300 mm x 300 mm, faceplate thickness of 4 mm and core size of 20 mm. Damage was designed in several dimensions that are represented in Table 3.

Table 3 Dimension of Damage Case in the Material

Tablica 3. Dimenzija oštećenja materijala

Material	Unit	Dimensions	Volume
Intact	mm	0	0
Damage Case 1	mm	25 x 10 x 5	125
Damage Case 2	mm	58 x 50 x 8	232
Damage Case 3	mm	96 x 60 x 8	498

Experimental modal analysis (EMA) measuring method exists as works. Sandwich material was clamped at both edges and fastened with nuts (A). Force was applied by a modal hammer onto the surface of the faceplate (B). The response showed gain in the accelerometer and presence of signal wave response by time field (C). Measurement of natural frequency showed values ranging from 500 Hz to 1500 Hz. The input force was set on the lower boundary with value of 120 mV to 200 mV to reach a steady wave response. Response data was obtained using PicoScope software (D). The data read the input force numerous formulas used in the data collecting process are defined (3).

$$X(\omega) = H(\omega) \, . \, F(\omega) \tag{3}$$

Significance ranges were based on frequency rate. Analysis response of the composition is also available in terms of displacement, velocity and acceleration. Equation 3 is transformed into equation (4) in favour of obtaining frequency.

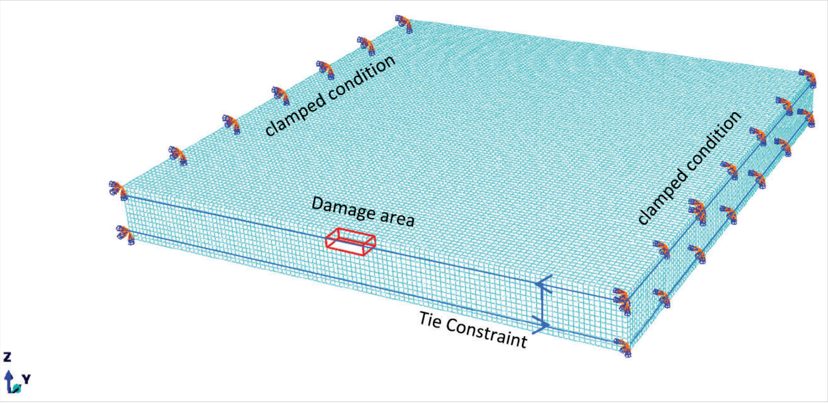


Figure 4 Details of configuration model in the constraint and boundaries

Slika 4. Pojedinosti konfiguracijskog modela u površinskom ograničenju i granicama

$$\ddot{X}(\omega) = H(\omega) . F(\omega) \tag{4}$$

Inertance or acceleration is separated over the force the measurement modifies according to the frequency. By EMA, the ratio of vibration modulus with damping pattern received natural frequency. The vibration response of the material determines the input force used in the response signal. The data was transformed into a frequency response function (FRF).

Figure 5 shows power supply (E) that influences impact hammer (F) to gain instrument responsiveness. Calibration was completed by recording and processing data obtained from data acquisition. Results showed the sensitivity of 1.052 mV/ms2 for the accelerometer and 1.148 mV/N for the hammer. Proper configuration was accomplished prior to the experiment.

Coherence parameters were performed to select valid data with values close to one. This is because data with values close to zero indicate the presence of noises. Adjustment of the mode value and natural frequency value was verified using numerical results to determine the frequency and location of the mode. The mode selection was matched by observing the vibration response of the FRF obtained from the experiment [18].

3. RESULTS AND DISCUSSION / *Rezultati i rasprava*

3.1. Sandwich plate configuration / *Konfiguracija sendvič panela*

With consideration to Equation (5), sandwich material was designed following Llyoid's Register to fulfil strength index criteria. Minimum value was used for the thickness of the sandwich material to obtain optimum thickness of the plate. The plate was designed with thickness of 3 mm to 6 mm, whereas the criteria R had to be less than 1. The numerous design configurations are presented in Table 4.

Table 4 Design of Sandwich material

Tablica 4. Dizajn sendvič materijala

Thickness of Layer (mm)			LR Strength Index (R)	Acceptance Criteria
Top (t_1)	Core (tc)	Bottom (t_2)		
3	20	3	1.090	x
4	**20**	**4**	**0.804**	√
5	20	5	0.631	√
6	20	6	0.515	√

Light composition of the material results in weight saving and unexpected mechanical, practical, and economic benefits in the implementation on marine structures [3]. This design is especially applied to ship construction according to the design principle. Analysis has performed to a 100 TEUS had provided to conventional side shell upgrade by sandwich plate, therefore contributing in saving weight up to 17% with acceptable stress according to classification criteria [10]. Furthermore, sandwich materials are composed of a top and bottom layer made of plate, and a core construct made of polyurethane foam with matrix fibre. Therefore, the dimension size selected was 4-20-4 mm due to the lightweight composition that completes the acceptance criteria of the regulation.

3.2. Comparison of FEA and EMA / *Usporedba analize konačnih elemenata (FEA) i eksperimentalne modalne analize (EMA)*

Experimental accuracy can be influenced by the boundary conditions of the specimen where stiffness of the clamp is needed. Therefore, a test to find a suitable clamp is needed. The uniformity of vibration measurement is also sensitive to noise and affects the results that need to be compared. The measurement of the vibration response was done by applying a force impulse to the surface of the sandwich material. The magnitude was represented as a sinusoidal graph in the form of low impact energy. The force impulse became a parameter and was captured by sensors. The intensity of force impulse determined the distance of the sensor reader. The force input was recorded in ADC (Analogue Digital Converter). The force was processed into a frequency response function to obtain the vibration amplitude with a time domain. Furthermore, the vibration response of the object was transformed into a frequency domain using the fast Fourier Transform (FFT). The accuracy of the EMA is indicated by the consistency of values, where the average value was 0.994085 for intact material and 0.994955 for damaged material. Since these values are close to 1, it can be said that the EMA results are accurate. Figure 6 shows outputs of: a). Input force, b). vibration response, and frequency response function (c).

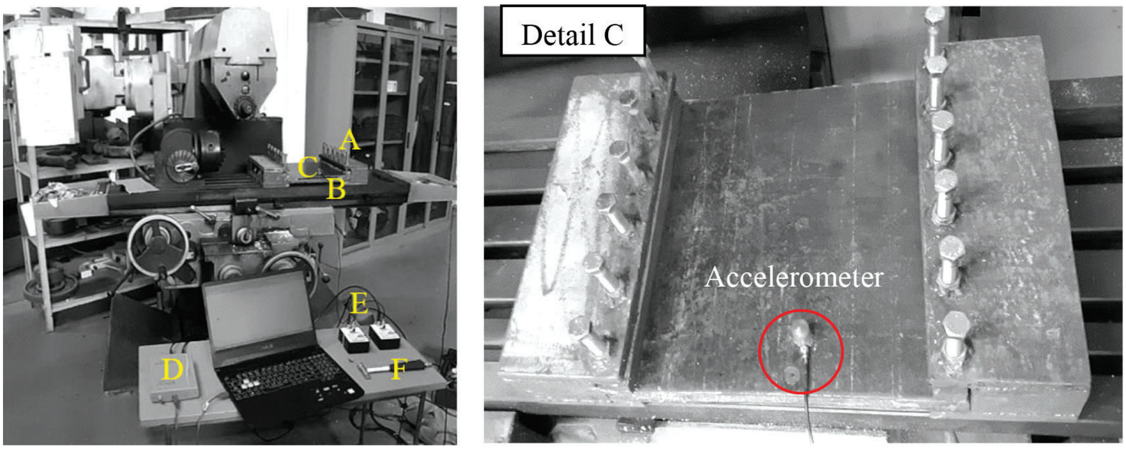
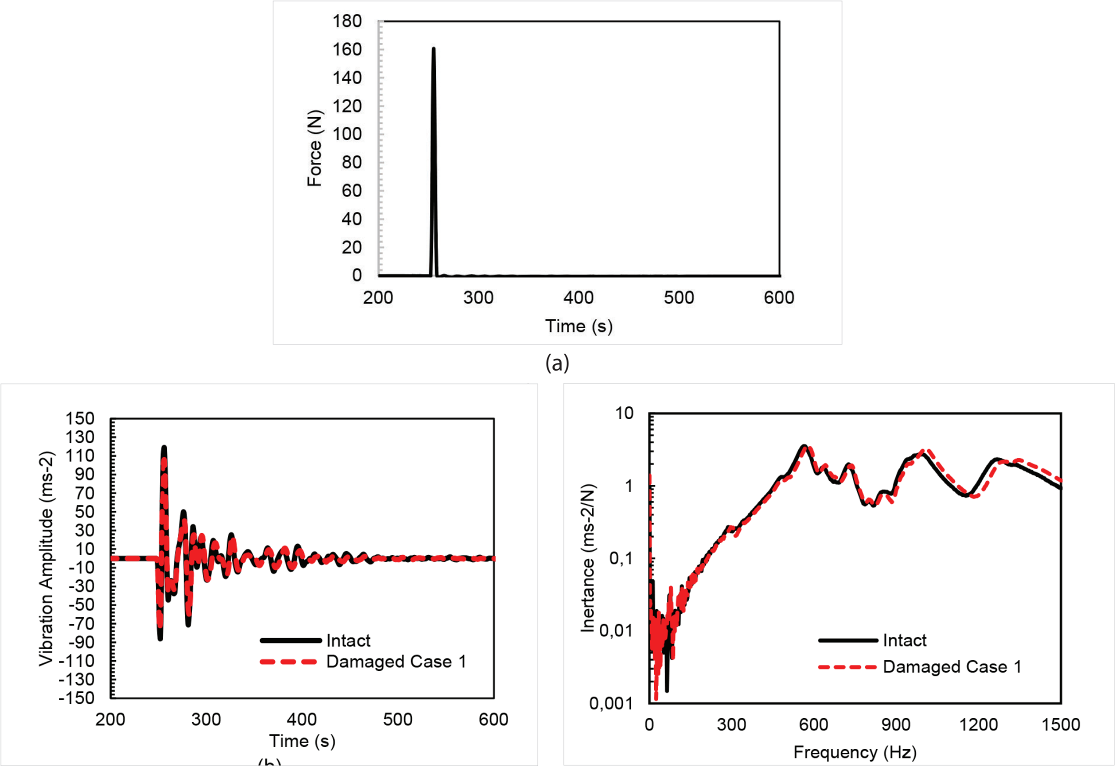


Figure 5 Experimental setup [38]

Slika 5. Postavljanje pokusa [38]



(a)

(b) (c)

Figure 6 Experimental Results of Modal Analysis: (a) Force Impulse, (b) Vibration Response, and (c) Inertance [26]

Slika 6. Rezultati pokusa modalne analize: (a) *Impuls sile, (b) Odgovor vibracije, and (c) Inertnost [26]*

Mode selection is chosen by looking at the vibration response of the FRF obtained from the experiment. Data extraction of natural frequency values was obtained from the peak frequency response function, which was based on the consistency of the natural frequency results of the three damage scenarios. There was a decrease in natural frequency in the damaged material I, II and III. In this condition, it present that there is an increase in the natural decrease in frequency. The decrease in natural frequency was seen in the material without damage. Therefore, the greater the damage, the less decrease in natural frequency. Validation process was performed by modelling the sandwich material with a free vibration analysis approach using the finite element method. Vibration response was obtained by looking at the natural frequency of the intact model and the damaged model. The variation of damage was adjusted to the criteria in the case set in the experiment, which is expected to be able to provide accurate results. The numerical results of the natural frequency showed a downward trend similar to the measurement of frequency obtained, which is summarized in Table 5.

For more details, the difference in the decrease of natural frequency by EMA and FEA in the experiment is summarised in Figure 7.

Experimental data was obtained from an average of eight repetitions of the slab test to ensure the data was accurate. Based on each case of intact and damaged material, data showed good agreement between numerical and experimental simulations, with an average error of 3.78%. The percentage of natural frequency decrease is summarized in Table 8, and a more detailed illustration is presented in Figure 6.

Table 5 Natural Frequency results by FEA

Tablica 5. Rezultati prirodne frekvencije prema analizi konačnih elemenata (FEA)

Mode	Intact (Hz)		Damaged 1 (Hz)		Damaged 2 (Hz)		Damaged 3 (Hz)	
	FEM	EMA	FEM	EMA	FEM	EMA	FEM	EMA
1	582.82	576.29	571.45	563.30	556.89	561.30	533.87	560.55
2	759.19	737.16	750.61	724.67	739.46	721.42	722.12	716.68
3	1180.00	1007.45	1175.50	995.21	1056.10	960.98	782.16	798.61
4	1288.70	1293.25	1285.90	1268.50	1245.00	1268.50	985.57	940.75
5	1324.10	1347.90	1316.90	1334.90	1286.90	1334.90	1232.80	1212.00

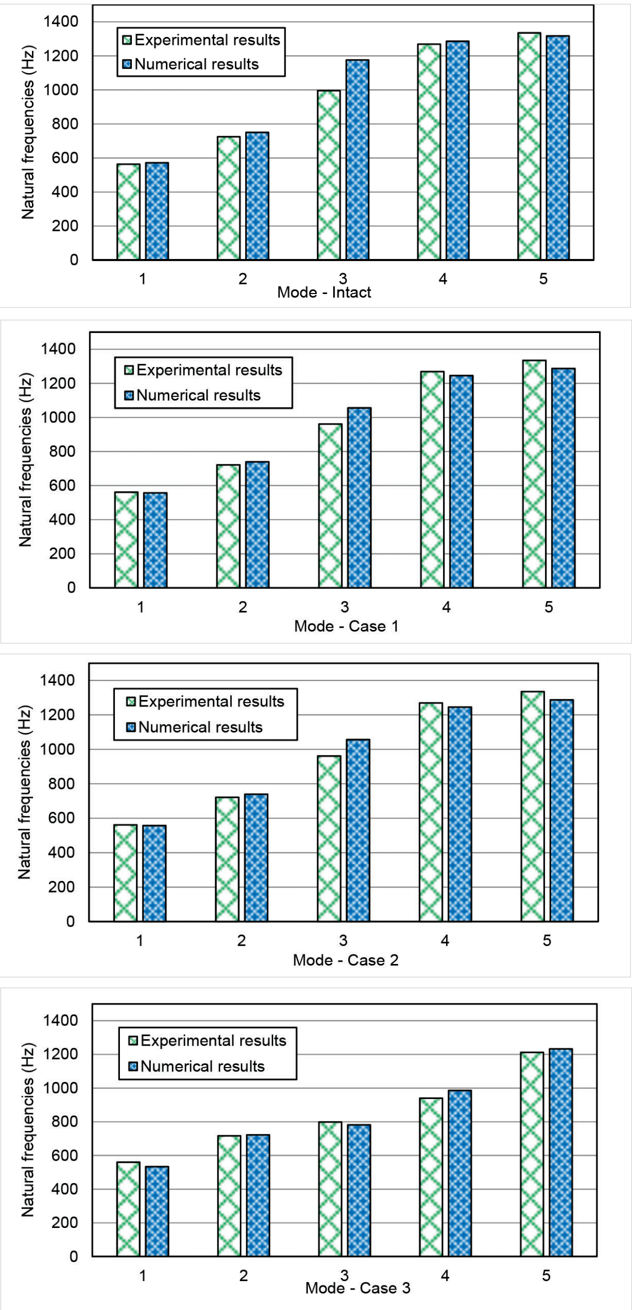


Figure 7 Comparison of the numerical and experimental results of natural frequency
Slika 7. Usporedba numeričkih i eksperimentalnih rezultata prirodne frekvencije

Table 6 Percentage of natural frequency derivation in each case
Tablica 6. Postotak derivacije prirodne frekvencije za svaki pojedini slučaj

Mode	Mean of natural frequency percentage					
	Case 1 (Hz)	Derivation (%)	Case 2 (Hz)	Derivation (%)	Case 3 (Hz)	Derivation (%)
1	12.18	2.15%	20.46	3.66%	32.34	5.91%
2	10.54	1.43%	17.74	2.43%	28.78	4.00%
3	8.37	0.77%	85.18	8.45%	303.34	38.38%
4	13.78	1.08%	34.22	2.72%	327.81	34.04%
5	10.1	0.76%	25.1	1.91%	113.6	9.29%

The natural frequency obtained using a numerical approach has a slightly larger value than the results obtained by the experiment. In addition, it can be seen that damage causes a decrease in natural frequency value and occurs in high mode, therefore damage in the local area is sensitive. It can be concluded that the effect of local damage on natural frequency depends on the formed mode. This finding expands the possibility of developing damage identification techniques using vibration-based methods.

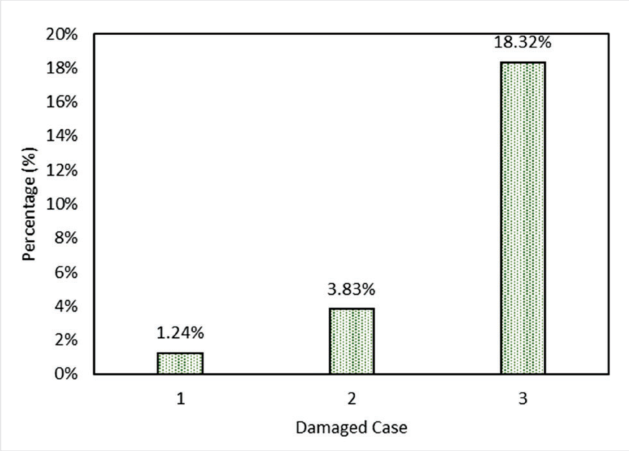


Figure 8 Percentage of natural frequency derivation of damaged cases
Slika 8. Postotak derivacije prirodne frekvencije u oštećenjima

Lastly, the average decrease in natural frequencies was calculated. The amount of damage can be predicted by observing the average decrease. A significant decrease in the average of natural frequency in the experimental and numerical analysis was seen in the intact model and each damaged model.

4. CONCLUSION / *Zaključak*

The process of the use of free vibration analysis for damage identification of sandwich material in a side shell plate is presented in this research. Experimental and numerical free vibration analysis was performed for a sandwich material model resembling a structure of a side shell. The model was generated for intact and damaged conditions (core sandwich failure). According to the results obtained in this research, it can be concluded that:

1. Free vibration analysis has the ability to detect damage through the decrease in natural frequency caused by stiffness decrease. It can be assumed that when the damage increases, the natural frequency decreases. The modes also illustrate that higher modes are more sensitive to damage.
2. The correlation between damage size and free vibration analysis response was discussed.
3. An experimental modal analysis was formulated. There was a good agreement between the numerical and experimental analysis results. The purpose of executing FEA was to determine a proper boundary for the experimental model.

Therefore, numerical modelling (FEA) and experimental analysis (EMA) are comparable with adequate accuracy, and the method proposed in this research can be implemented.

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