Structural Damage Detection Using Modal Flexibility Method in Honeycomb Composite Sandwich Beam

Sattar MOHAMMADI ESFARJANI
Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran, satar.iran@gmail.com

Abstract: - In this study, the modal flexibility method, which is a vibration-based damage detection technique, was tested in order evaluate the performance of the modal flexibility, using the displacement of nodes to detection damage. The method was tested on a honeycomb composite beam structure. By using this technique, damage was identified from the change in displacement responses data, obtained from the free vibration analysis method. This is the first study of evaluation of the modal flexibility method using the displacement of nodes. The location of the damage was determined by the flexibility diagrams. The finite element (FE) analysis was conducted using the commercial FE package ABAQUS. MATLAB was employed for numerical analysis. The purpose of the paper is a present application of the displacement responses for structural damage detection using the modal flexibility method. The results showed that the modal flexibility method was able to detect damage through the displacement of nodes. Also, this study highlighted the importance of applying simulation methods to develop VBDD techniques, especially in complex structures.

Keywords: Structural health monitoring, damage detection, vibration, modal flexibility method, honeycomb composite sandwich beam.

1. INTRODUCTION

The honeycomb composite sandwich structure consists of two thin face sheets (skin) separated from each other by a lightweight core. It is high specific strengths and stiffness, thus is widely used in aerospace industries [1, 2]. During the manufacturing process or impact loads, debonding can occur between the skin and the honeycomb core. Debonding can produce catastrophic failure of the overall structure. In addition, it effects on mechanical properties. Thus, detection debonding is crucial at an early stage [3, 4]. Traditional Non-Destructive Testing (NDT) methods have been proposed for detecting of structural damage. However, they cannot always detect structural defects, especially in the core. In recent years, Vibration-Based Damage Detection (VBDD) methods are widely used for detecting defects in sandwich structures and components [5-10]. An increase in structural flexibility can use as a good indicator of the degree of structural deterioration. Modal flexibility, which depends on both natural frequencies and mode shapes, is measured parameters related to vibration tests were adopted as the original information in structural damage detection. Previous studies indicate that the changes in flexibility in structure apply for damage detection and Structural Health Monitoring (SHM) and it can be applied successfully to real life structures [11, 12]. The modal data of the intact and damaged structure must be acquired under the same or similar ambient conditions [13]. This method has been utilized applied for damage detection such as in bridge [14, 15], in timber structures [16], the cable stayed bridge [13], honeycomb structure in reinforced concrete beam models [17-19], a suspension bridge [20-22], in suspended cables [23, 24]. The flexibility method has advantages and disadvantages like other methods of detecting damage in the structure. This method is very sensitive to local damages and it is also accurate in localizing single-damage. But, the flexibility method's accuracy is not sufficient when there are multiple damages located in the beam structure [13, 25].

Static test and dynamic test are widely applied for SHM. Each has one its own advantages and disadvantages. The focus of previous research has been on dynamic strain, frequency, mode shape measurements for the utilized damage detection method. In [26] the comparison showed that the dynamic load test can supplement the static load test for the structural evaluation of new viaducts; it may also be taken as an alternative for the monitoring of operational viaducts. In this study, dynamic test is applied to obtain displacement responses data. This paper presents a performance evaluation of the modal flexibility method using the displacement of nodes for damage detection. In recent years, the use of simulation models to develop vibration based damage detection techniques has become very popular, because it's a less expensive and time-consuming procedure than real structures or experimental models [27-29]. Also, experimental setup is also a fairly difficult process. Since the Finite Element (FE) method has been widely accepted as an analysis tool in SHM the above mentioned constraints can be overcome by using a validated FE model to simulate the real structure [2, 6-8]. In this paper, FE analysis is performed using the commercial package ABAQUS, with the use of MATLAB for applied numerical analysis. The remainder of this work is structured as follows: Section 2 introduces the theory of modal flexibility. FE modeling and analysis of a honeycomb composite sandwich beam is presented in Section 3. The conclusion is reported in Section 4.

2. THEORY OF THE MODAL FLEXIBILITY METHOD

The flexibility matrix is the inverse of the stiffness matrix, whose column vector represents the deformation pattern associated with a unit static force applied at a particular point of a structure. Although its origin lies in static, the flexibility matrix $[F]$ can be synthesized using dynamically measured modal properties, which is called as the modal flexibility matrix [11]. Derivation of flexibility matrix is as follows: [29, 30]

$$[m]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=[f(t)] \tag{1}$$

Where

$$u=\phi \sin \omega t \tag{2}$$

Substituting Eq. 2 into Eq. 1, it becomes:

$$[\varphi]^T[K][\phi]=[\omega^2][\varphi]^T[M][\varphi] \tag{3}$$

Where the mode-shape vectors have been mass-normalized such that $[\varphi]^T[M][\phi]=[I]$ where $[I]$ is $n\times n$ an identity matrix.

$$[K]^{-1}=[\phi][\frac{1}{\omega^2}][\varphi]^T \tag{4}$$

$$[F]=[\phi][\frac{1}{\omega^2}][\varphi]^T=\sum_{i=1}^{n}\frac{1}{\omega^2}\phi_i\phi_i^T \tag{5}$$

Where $[F]$ is the modal flexibility matrix; $[\varphi]$ the mass normalized modal vectors; and $[1/\omega^2]$ a diagonal matrix containing the reciprocal of the square of natural frequencies in ascending order. If the modal parameters are estimated from two sets of data: one from the initial reference structure denoted by u, and another from the damaged structure denoted by d, the corresponding flexibility matrices $[F_u]$ and $[F_d]$ may be constructed in a dimension of measured DOF. A simple damage localization method was proposed by Pandey and Biswas [11], which consists of calculating the flexibility change matrix and then observing the maximum value of each column. The change in flexibility is defined as [11, 31]:

$$[F]=[F_u]+[F_d] \tag{6}$$

Damage in a structure will result in higher flexibility values for the elements near the damage point. A flexibility change vector is defined as [11]:

$$\{\Delta F_v\}=\{F_{jj}^d\}-\{F_{jj}^u\} \tag{7}$$

The flexibility vectors for the damage and intact structure are [11]:

$$\{F_{jj}^d\}=\{f_{11}^d\dots f_{jj}^d\dots f_{nn}^d\}^T \tag{8}$$

$$\{F_{jj}^u\}=\{f_{11}^u\dots f_{jj}^u\dots f_{nn}^u\}^T \tag{9}$$

3. FE MODELLING AND ANALYSIS OF HONEYCOMB COMPOSITE STRUCTURE BEAM

Due to difficulties in creating internal defects in practice, numerical simulation is used. The use of simulation method provides the possibility to create internal defects easily. Simulation methods are used as a timesaving and cost-efficient replacement to the

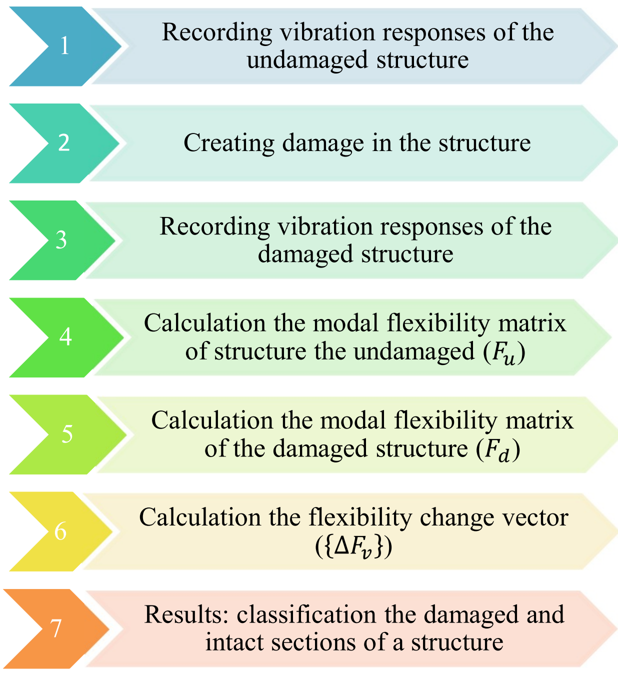


Figure 1. Damage detection process using the Modal Flexibility Method.

experimental methods of manufacturing, testing, modifying, and retesting. There are some of the advantages to performing a simulated the modal flexibility method rather than the experimental method. There are no limits to the number of sensor nodes to be simulated and objects which can be used in simulation. Vibration responses of the intact and damaged structure are obtained via numerical simulation with the commercial FE package ABAQUS, and MATLAB was used for numerical analysis. A typical procedure for the method is depicted as shown in Figure. 1.

3.1. Test sample

The test specimen was a light aluminum honeycomb composite sandwich beam. A sandwich-structured composite is a special class of composite materials that is fabricated by attaching two thin but stiff layers to a lightweight but thick core [32]. They are widely used in the aerospace industry for this reason.

The core material was closed cell 5052 aluminum with a total thickness of 1.2 mm (See Figure 2(a)). The overall dimensions of the beam were $40 \times 4 \times 2$ (mm), as shown in Figure 2(b), and the face sheets were made of 2024-T6 aluminum. The material properties are listed in Table 1.

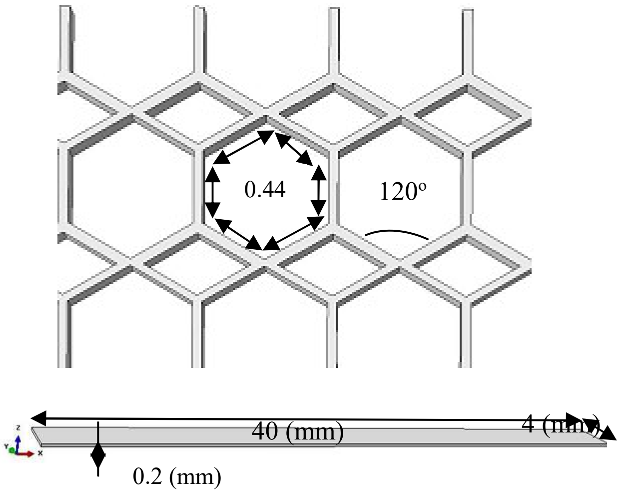


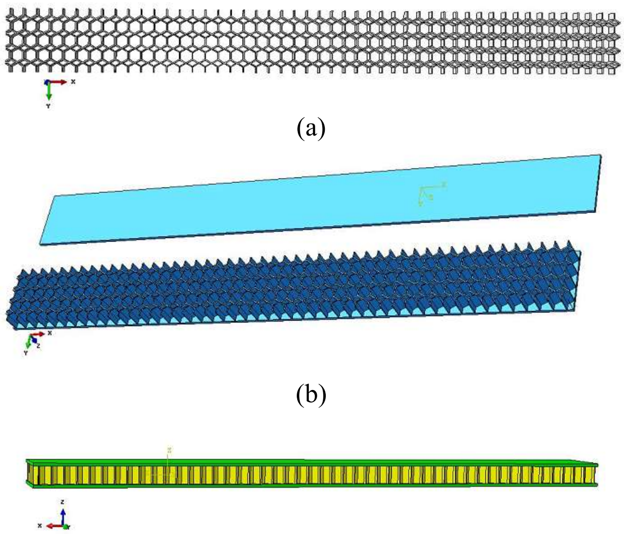
Figure 2. Geometrical dimensions of (a) the core and, (b) the face sheets in a composite honeycomb sandwich beam.

Table 1: Material properties for 2024-T6 aluminum and 5052 aluminum

	Density (ρ) (g/cc)	Poisson's Ratio(v)	Modulus of Elasticity (E) (Gpa)
2024-T3 Aluminum Skin	2.78	0.33	71.3
5052 Aluminum Core	2.68	0.33	70.3

3.2. Simulation modelling and analysis of intact structure

First, a FE model of the composite honeycomb sandwich beam was created using ABAQUS (See Figure 3). The clamped end of the beam has no displacement in x and y directions (See Figure 4). Multiple runs showed that the type of mesh has an in non-significant effect on results, while free meshing is more suitable on the damaged section, so free meshing with 4-node linear tetrahedron (C3D4) is utilized to model of a honeycomb composite beam structure. C3D4 is a 4-node linear tetrahedron element and three degrees of freedom at each node. Finally, the model was investigated with the free vibration analysis. Free vibration analysis parameters are showed in Table 2. As shown Essential data needed, including displacements responses for 21 points of the structure were obtained from the results of FE analysis using ABAQUS. The position of the measurement points for displacements responses is showed in Figure 5. Displacements responses of undamaged structure showed in Figure 6.



(a)

(b)

(c)

Figure 3. A FE model of (a) the core (b) the face sheets of honeycomb composite sandwich beam (c) and assembly parts were created using ABAQUS.

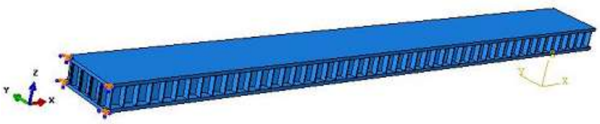


Figure 4. Boundary condition in the modal.

Table 2: Free vibration analysis parameters.

Mode NO	Eigen value	Frequency (RAD /TIME)	(CYCLES /TIME)	Generalized Mass	Composite OMPOSITE Modal Damping
1	192.21	13.864	2.2065	68054.	0.0000
2	312.96	17.691	2.8155	68214.	0.0000
3	9046.5	95.113	15.138	56957.	0.0000
4	14339.	119.75	19.058	61608.	0.0000
5	37147.	192.74	30.675	1.26154E+05	0.0000

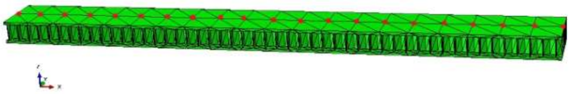


Figure 5. The position of the measurement points for displacements responses.

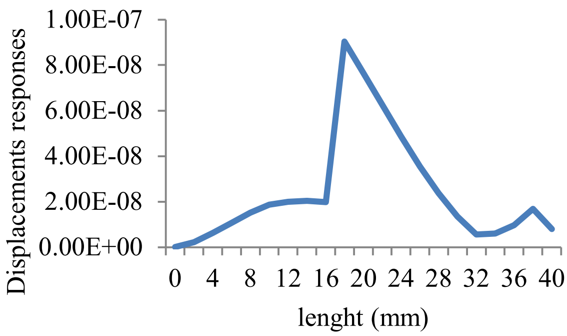


Figure 6. Displacements responses of undamaged structure

3.3. Simulation modelling and analysis of damaged structure

One of the advantages of using software such as ABAQUS in engineering analysis is the ability to create very small damage in a specimen. By removing the very narrow strip between the core and the face sheet, a debonding defect was created in the model. The size of the debonding is $4 \times 0.4 \times 0.01$ (mm) which is located at 18 (mm) from the fixed end. To do this, firstly, a rectangle the size of 4×0.01(mm) is selected, and then 0.4 (mm) depth is determined for it. Next, the selected area cut out from the specimen (See Figure 7). Finally, the damaged model was investigated with the free vibration analysis. Data needed, including displacement, responses, for 21 points obtained from the results of finite element analysis using ABAQUS. Displacements responses of damaged structure are given in Figure 8. In general, damage decreases the natural frequency of the structure. With increasing number or size of defect, the natural frequency of the structure will be further reduced [8]. In this study, the size of debonding defect was very small; length 4 (mm), thickness 0.01 (mm) and widths 0.4(mm). As a result, the natural frequency of the structure will not change significantly changes and it will remain almost the same for the undamaged and damaged beam.

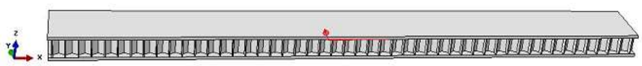


Figure 7. The debonding defect was created in the model.

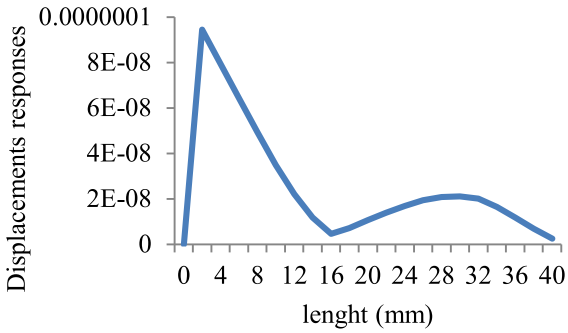


Figure 8. Displacements responses of damaged structure

3.3. Results and discussion

The result of the modal flexibility method for the detection of the delamination in composite honeycomb sandwich beam is shown in Figure 9. As structural deterioration theoretically increases flexibility, an increase in structural flexibility can serve as a good indicator of the degree of structural deterioration [10]. Consider Figure 9, which area sharper than other areas are marked in red. These areas indicated damaged sections along the beam. As shown in Figure 9, damage location is predicted between 170 (mm) to 230 (mm) from the fixed-end of the beam. As it is evident from Figure 9, the modal flexibility method is able to detect the delamination in a composite honeycomb sandwich beam as well as its location with a close approximation.

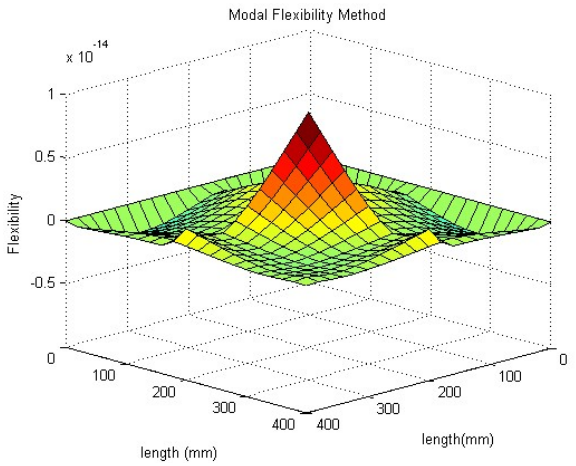


Figure 9. Damage detection via analysis of displacement responses, employing the modal flexibility method technique to detect the debonding defect in a composite honeycomb sandwich beam.

4. CONCLUSIONS

This paper presents a performance evaluation of the modal flexibility method using the displacement of nodes for the detection of debonding damage in a composite honeycomb sandwich beam. This is the first study of evaluation of the modal flexibility method using the displacement of nodes. The use of real structures or experimental models to develop modal flexibility technique is an expensive and time-consuming procedure. The finite element (FE) analysis was conducted using the commercial FE package ABAQUS. Also, MATLAB was employed for numerical analysis. The location of the damage was determined by the flexibility diagrams. The results showed that the modal flexibility method was able to detect the delamination in a composite honeycomb sandwich beam as well as its location with a close approximation, in other words, the modal flexibility method was able to detect debonding damage through the displacement of nodes.

REFERENCES

[1] Xiong J., Du Y., Mousanezhad D., Eydani Asl M., Norato J., Vaziri A., Sandwich Structures with Prismatic and Foam Cores: A Review, *Advanced Engineering Material*, Vol. 21, No. 1, 2019, p. 1800036. (19 pages). doi:10.1002/adem.201800036

[2] Mohammed D. F., Ameen H. A., MashlooshK. M. Experimental and numerical analysis of AA3003 honeycomb sandwich panel with different configurations, *American Journal of Scientific and Industrial Research*, Vol. 6, No. 2, 2015, pp. 25-32.

[3] Bragagnolo G., Crocomb A.D., Ogin S.L., Mohagheghian I., Sordon A., Meeks G., Investigation of skin-core debonding in sandwich structures with foam cores, *Materials & Design*, Vol. 186, 2020, p. 108312. doi: 10.1016/j.matdes.2019.108312

[4] Butukuri R.R., Bheemreddy V.P., Chandrashekhara K., Berkel T.R., Rupel K., Evaluation of skin-core adhesion bond of out-of-autoclave honeycomb sandwich structures, *Journal of Reinforced Plastics and Composites*, 2012, Vol. 31, No. 5, 2012, pp. 331-339. doi: 10.1177/0731684412437267.

[5] Mohammadi Esfarjani S., Salehi M., Evaluation of the damage detection capability of inner product vector for LOP and LOSWF defects in V groove weld, *Modares Mechanic Engineering*, Vol. 6, No. 6, 2016, pp. 7-16. (In Persian)

[6] Mohammadi Esfarjani S., Salehi M., Detection of metallic impurities in alloys using the IPV and AMV methods, *Romanian Journal of Acoustics and Vibration*, Vol. XIII, No. 2, 2016, pp. 131-137.

[7] Mohammadi Esfarjani S., Salehi M., Optimization the inner product vector method and its application to structural health monitoring. *Journal of Vibroengineering*, Vol. 19, No. 4, 2017, pp. 2578‑2585. doi: 10.21595/jve.2017.18062

[8] Mohammadi Esfarjani S., Salehi M., Ghassemi A., Effect of the multiple damages and temperature changes on the natural frequency, *Journal of Theoretical and Applied Mechanics*, Vol. 55, No. 3, 2017, pp. 813-822. doi: 10.15632/jtam-pl.55.3.813

[9] Esfarjani S., Evaluation of effect changing temperature on lamb-wave based structural health monitoring, Journal of Mechanical and Energy Engineering (JMEE), Vol. 3(43), No.4, 2020, pp. 329-336. doi: 10.30464/jmee.2019.3.4.329

[10] Mohammadi Esfarjani S., Salehi M., Inspection above ground pipeline using vibration responses, *Journal of pipeline system engineering and practice,* Vol. 11, No. 3, 2020, p. 04020021. doi: 10.1061/(ASCE)PS.1949-1204.0000463.

[11] Pandey A. K., Biswas M. Damage detection in structures using changes in flexibility, *Journal of Sound and Vibration*, Vol. 169, No. 1, 1994, pp. 3-17. doi: 10.1006/jsvi.1994.1002

[12] Liu H., Li Z., An improved generalized flexibility matrix approach for structural damage detection, *Journal Inverse Problems in Science and Engineering,* 2019, 17 pages. doi: 10.1080/17415977.2019.1683174.

[13] Ni Y.Q., Zhou H. F., Chan K. C., Ko J. M., Modal flexibility analysis of cable-stayed ting Kaubridge for damage identification, *Computer-Aided Civil and Infrastructure Engineering*, Vol. 23, No. 3, 2008, pp. 223-236. doi: 10.1111/j.1467-8667.2008.00521.x

[14] Farrar C.R., Jauregui D.A., Comparative study of damage identification algorithm applied to a bridge: I. Experiment., *Smart Materials and Structures*, Vol. 7, No. 50, 1998, pp. 704-719. doi: 10.1088/0964-1726/7/5/013

[15] Liu H., Song G., Jiao Y., Zhang P., Wang X., Damage Identification of Bridge Based on Modal Flexibility and Neural Network Improved by Particle Swarm Optimization, *Mathematical Problems in Engineering*, 2014, Article ID. 640925, 8 pages. doi: 10.1155/2014/640925

[16] Choi F., Li J., Samali B., Crews K., Application of the modified damage index method to timber beams, *Eng. Structures*, Vol. 30, 2008, pp. 1124-1145. doi: 10.1016/j.engstruct.2007.07.014

[17] Dawari V. B., Vesmawala G. R., Modal curvature and modal flexibility methods for honeycomb identification, *Procedia Engineering*, Vol. 51, 2013, pp. 119-124. doi: 10.1016/j.proeng.2013.01.018

[18] Meruane V., Fierro V. d., Ortiz-Bernardin A. A maximum entropy approach to assess debonding in honeycomb aluminum plates, *entropy*, Vol. 16, 2014, pp. 2869-2889. doi: 10.3390/e16052869

[19] Mirsadeghi M., Santi M., Hugo R., Park S. Experimental vibration-based damage detection in aluminum plates and

blocks using acoustic emission responses, *NDT in Canada Conference, Edmonton, AB Canada*, June 15-17, 2015.
[20] Wickramasinghe W. R., Thambiratnam D.P., Chan T.H.T., Damage detection in a suspension bridge using modal flexibility method, *Engineering Failure Analysis*, Vol. 107, 2020, p. 104194. doi: 10.1016/j.engfailanal.2019.104194
[21] Meng F., Yu J., Alaluf D., Mokrani B., Preumont A., Modal flexibility based damage detection for suspension bridge hangers: A numerical and experimental investigation, *Smart Structures and Systems*, Vol. 23, No. 1, 2019, pp. 15-29. doi: 10.12989/sss.2019.23.1.015
[22] Wasanthi R. Wickramasinghe, David P. Thambiratnam and Tommy H.T. Chan, Modal flexibility method for structural damage detection in suspension bridges, *The 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure Hong Kong*, 9-11 December, 2013.
[23] Wickramasinghe W., Thambiratnam D., Tommy Chan T., Use of modal flexibility method to detect damage in suspended cables and the effects of cable parameters, *Electronic Journal of Structural Engineering*, Vol. 14, No. 1, 2015, pp. 133-144.
[24] Reynders E., De Roeck G., A local flexibility method for vibration-based damage localization and quantification, *Journal of Sound and Vibration*, Vol. 329, No. 12, 2010, pp. 2367-2383. doi: 10.1016/j.jsv.2009.04.026
[25] Bernagozzi G., Ventura C.E., Allahdadian S., Kaya Y., Landi L., Diotallevi P.P., Application of modal flexibility-based deflections for damage diagnosis of a steel frame structure, *Procedia Engineering*, Vol. 199, 2017, pp. 2026-2033. doi: 10.1016/j.proeng.2017.09.468amage
[26] Laura M., Francesco C., Antonio F., Static and dynamic testing of highway bridges: a best practice example*, Journal of Civil Structural Health Monitoring*, Vol. 10, 2020, pp. 43–56.doi: 10.1007/s13349-019-00368-1
[27] Altunışık A.C., Okur F. Y., Karaca S., Kahya V., Vibration-based damage detection in beam structures with multiple cracks: modal curvature vs. modal flexibility methods*, Nondestructive Testing and Evaluation*, Vol. 34, No. 1, 2019, pp. 33-53. doi: 10.1080/10589759.2018.1518445
[28] Nadjafi S., Ghodrati Amiri G., Zare Hosseinzadeh A., Seyed Razzaghi S.A., An Effective Approach for Damage Identification in Beam-Like Structures Based on Modal Flexibility Curvature and Particle Swarm Optimization, *Journal of Rehabilitation in Civil Engineering*, Vol. 8, No. 1, 2020, pp. 109-120. doi: 10.22075/JRCE.2019.553.1081
[29] Shih, H.W., Thambiratnam, D.P. and Chan, T.H. Vibration based structural damage detection in flexural members using multi-criteria approach, *Journal of Sound and Vibration,* 2009, Vol. 323, No. 3-5, pp. 645-661. doi: 10.1016/j.jsv.2009.01.019
[30] Shih, H.W., Thambiratnam, D and Chan, T.H.T. Damage localisation in beams and plates using vibration characteristics, *Structural Health Monitoring in Australia, Nova Publishers*, Vol. 3. 2011, pp. 33-53.
[31] Moragaspitiya P. H. N., Thambiratnam D. P., Perera N. J., Chan T. H. T., Development of a vibration based method to update axial shortening of vertical load bearing elements in reinforced concrete buildings, *Engineering Structures*, 2013, Vol. 46, pp. 49-61. doi: 10.1016/j.engstruct.2012.07.010
[32] Ramakrishnan G., Ramnath V., Vignesh C., Vignesh L., Perunddevan T., VidhyaRajan M., Sandwich and Natural fiber composites - A review, *The 3rd International Conference on Materials and Manufacturing Engineering 2018, IOP Conf. Series: Materials Science and Engineering*, Vol. 390, 2018. p. 012067. doi:10.1088/1757-899X/390/1/012067