ASPS Conference Proceedings 1: 1013-1017 (2022)

Proceedings of

12th Structural Engineering Convention-An International Event (SEC 2022)

Available at https://asps-journals.com/index.php/acp

Damage Detection of FRP Composite Plates from Dynamical Responses using Finite Element Model Updating: Equivalent Material Properties as Parameters

S. Das [1, *], S. Chakraborty [2]

[1] Department of Civil Engineering, Research Scholar, Indian Institute of Technology Kharagpur, West Bengal 721302, India
[2] Department of Civil Engineering, Associate Professor, Indian Institute of Technology Kharagpur, West Bengal 721302, India

Paper ID - 070058

Abstract

Fibre reinforced plastic (FRP) composite structures are extensively used in weight sensitive applications, such as in aircrafts, ships, etc. Such structures are susceptible to damages during their usual operation or during extreme loading from environment. Due to the anisotropic nature of FRP composite plates, damage detection is difficult for such layered materials particularly when the damage site is inaccessible. The localised loss of stiffness resulting from damage is reflected into the global dynamic responses of such structures. Finite element model updating is a convenient inverse approach in which these changes in stiffness due to damages are estimated from measured dynamical responses using optimization. The equivalent stiffness changes can be expressed in terms of either geometric or material property or both. In most of the cases, changes in geometric parameters physically represent the actual damage scenario with larger sensitivity. On the other hand, material property changes in the damaged area are a very convenient parameter to deal with. In the present work, updating parameters in the finite element model updating procedure are chosen in terms of material property. Detection of local stiffness changes from experimentally measured natural frequencies, mode shapes and/or frequency response functions are investigated. Experimental modal testing is performed on a rectangular FRP composite plate both in its undamaged and damaged state. Baseline finite element model of the composite plate is correlated with experimental model, followed by a sensitivity based finite element model updating algorithm. The results show the rapid convergence and accurate determination of local stiffness change in terms of elastic material parameters alone in all three orthogonal directions. This indicates that material properties like the in-plane Young's moduli and in-plane Shear modulus within the localised region of damage, can well be used as convenient means for detecting equivalent stiffness loss in damaged structures.

Keywords: Damage Detection, Experimental Modal Testing, Dynamic Responses, Finite Element Model Updating, FRP Plate

1. Introduction

Composite plates are extensively used in modern engineering application such as aircraft, spacecraft and deep sea structures. The importance of damage detection in such structures is very high as these structures are mostly subjected to undesirable damages due to various environmental forces. Hence, to ensure the integrity and safety of such structures early damage detection is essential. One of the most efficient damage identification techniques is finite element model updating (FEMU) approach which also involves estimation of unknown parameters [1].

Jaishi and Ren [2] proposed a sensitivity based FEMU method, using modal flexibility residual as the objective function to detect damages in a simply supported concrete beam through numerical simulation and experimental investigation. Perera et al. [3] presented a FEMU procedure in a single and multi-objective framework, with no updated baseline model available. Damage in beam and frame structures was characterized by reduction in element bending stiffness. The above optimization problems were solved using Genetic Algorithm (GA). Weng et al. [4] proposed a two-step damage detection procedure for a steel frame structure and a RC frame. Damage was defined by reduction ratio of rotational flexibility at joint. A progressive FEMU and a large scale optimization using a non-linear least square technique was performed for damage assessment. Mojtahedi et al. [5] performed damage detection of offshore steel jacket-type structure through FEMU combined with an algorithm based on artificial immune system with weighted attributes. The updating procedure was carried out in FEMTools software in which parameters considered for updating was initial Young's elastic modulus of all the members. Moaveni et al. [6] made an attempt to identify progressive damage in a three-story, two-bay infilled RC frame using an equivalent linear FEMU strategy. Damage was identified by updating effective modulus of elasticity at each damage state of the structure. Simoen et al. [7] performed study on uncertainty quantification through Bayesian linear finite-element model updating. Progressive damage was induced in a full scale seven-story reinforced

*Corresponding author. Tel: +918895406565; E-mail address: shradha.das57@gmail.com

Proceedings of the 12th Structural Engineering Convention (SEC 2022), NCDMM, MNIT Jaipur, India| 19-22 December, 2022

Published online: December 19, 2022
doi:10.38208/acp.v1.614

concrete building slice by subjecting it to seismic records of increasing intensity on shake table. Wang et al. [8] applied multi-layer genetic algorithm for damage diagnosis on complex steel bridges to overcome the tedious and lengthy convergence of traditional optimization process. The objective function considered was modal strain energy correlation. Kernicky et al. [9] performed damage characterization on a full-scale building structure subjected to damage due to internal blast load. A modal parameter based objective function was optimized using genetic algorithm for structural identification and damage characterization. Yu et al. [10] proposed a finite element model updating procedure based on FRF and natural frequencies, for detection of earthquake-induced damage on a one-bay, five-story, reinforced concrete wall slab building. Flexural stiffness and stiffness of the rotational springs are considered as updating parameters. Niu et al. [11] proposed a damage identification method based on response surface model updating. Cracking damage was identified by updating cross-sectional moment of inertia of the beam. Bearing damage was identified by updating vertical, transverse and longitudinal spring stiffness of real bridge. Altunisik [12] applied an automated model updating technique for damage detection on multi cracked cantilever beam with box cross section based on Bayesian parameter estimation using FEMTools software.

The current literature mostly considers geometric properties such as thickness as updating parameter because of their ability to physically represent the actual damage scenario. However, when damage is characterised as stiffness loss, material parameter is also a viable parameter to deal with. The present study is focussed on detection of damage as local stiffness loss in terms of material properties, through an Inverse Eigen-sensitivity method based finite element model updating algorithm.

2. Experimental Modal Testing of FRP Plates

A FRP composite plate was fabricated using thirteen layers of unidirectional E-Glass fibre within Epoxy resin matrix. The dimension of the undamaged FRP plate is 400 mm x 300mm x 3.86 mm. Experimental Modal Testing was carried out on the undamaged FRP plate with free boundary conditions. An instrumented impact hammer of type 8206-002 of Brüel & Kjær has been used to excite a broad range of frequency. A Delta Tron 4507 accelerometer of Brüel & Kjær has been used to measure the resulting responses from the applied excitation force. The excitation force and acceleration response are simultaneously measured in time domain and later Fast Fourier Transformation of both the measurements was carried out using 3560-C-L4 spectrum analyzer of Brüel & Kjær. The Frequency Response Functions were computed through PULSE Labshop software and then modal properties, such as frequencies and mode shapes were obtained using MEScope software. Fig. 1 shows the undamaged FRP composite plate along with impact hammer and accelerometer.

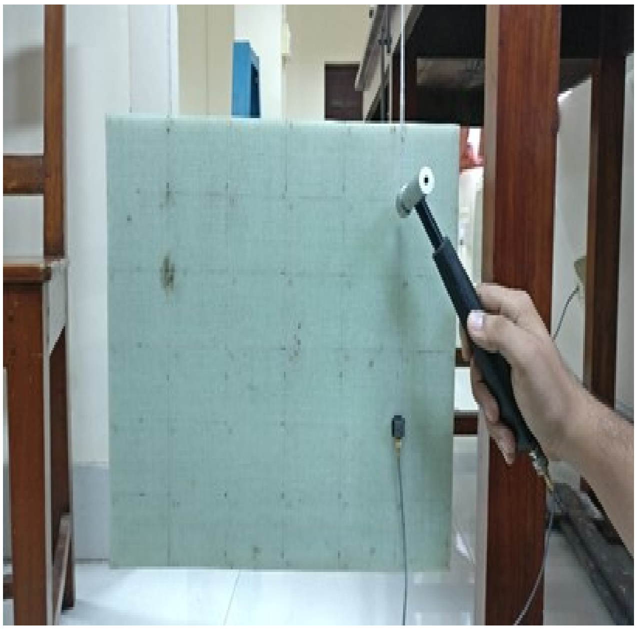

Fig. 1. Modal Testing on Undamaged FRP Composite Plate

Local reduction of stiffness has been considered as damage in this particular investigation. Stiffness reduction can be realized by adjusting material parameter or geometric parameter or their combination. Here, physical damage has been replicated by reducing thickness of a small region in the undamaged FRP composite plate. Fig. 2 shows the damaged FRP composite plate.

The experimentally measured natural frequencies for undamaged FRP plate and damaged FRP plate are shown in Table-I. The frequencies of damaged FRP plate are reducing for each mode compared to frequencies of undamaged FRP plate, indicating stiffness loss. Fig. 3 shows the mode shapes captured through experimental modal testing of undamaged FRP plate and damaged FRP plate.

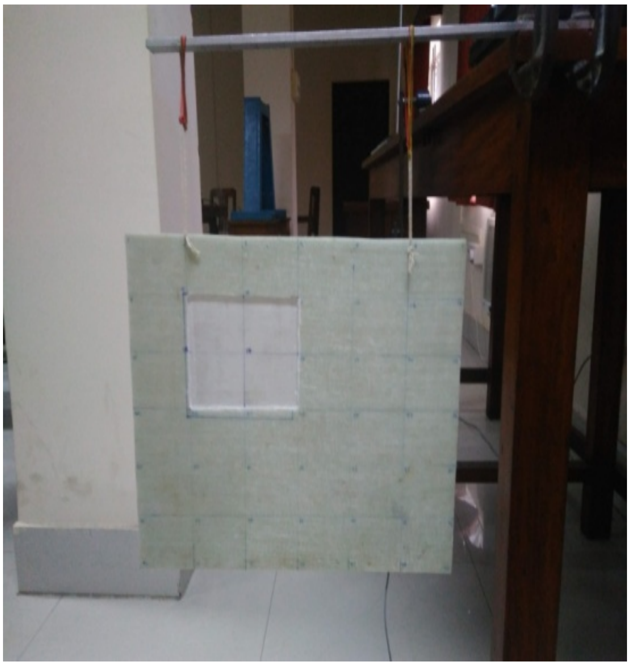

Fig. 2. Damaged FRP Composite Plate

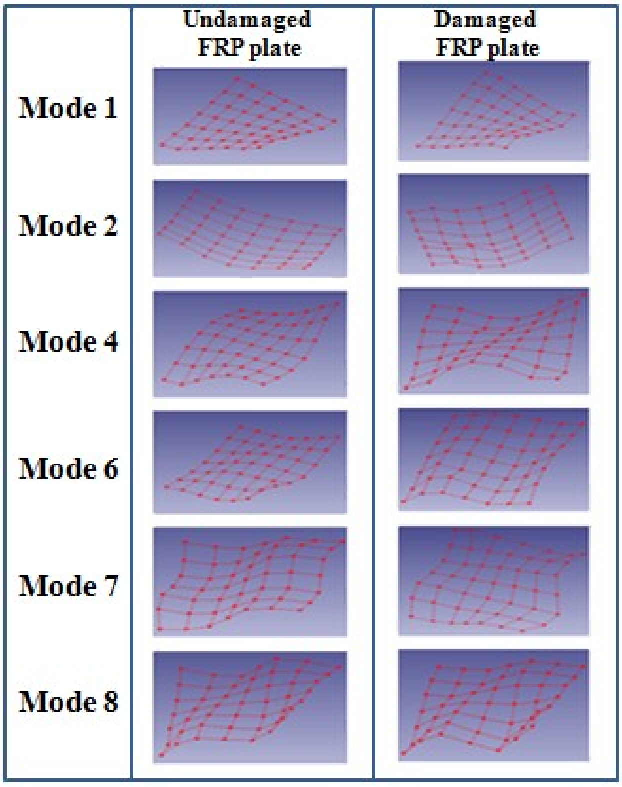

Fig. 3. Mode Shapes of Undamaged and Damaged FRP Composite Plates

Table-1. Experimentally measured frequencies for undamaged and damaged FRP plate

	Frequencies (Hz)	
	Undamaged FRP plate	Damaged FRP plate
Mode 1	47.7	44.2
Mode 2	113	103
Mode 3	-	-
Mode 4	145	141
Mode 5	-	-
Mode 6	254	241
Mode 7	307	297
Mode 8	343	322

3. Establishment of Baseline Finite Element Model

A FRP composite plate with initial assumed material property is simulated. The dimension of the plate has been kept similar to the undamaged FRP plate used in experimental modal testing. Initially assumed elastic constants are E_x = 25 GPa, E_y = 15 GPa and G_{xy} = 5 GPa. S8R shell element having eight nodes and six degree of freedom at each node is implemented through ABAQUS [13]. 12 x 12 mesh grid division is found to be representing dynamic behaviour of the FRP plate appropriately, hence adopted here. The comparison between frequencies of initial finite element model and experimentally obtained frequencies for undamaged FRP plate is shown in Table-II. It can be observed that the frequencies are not well correlating with each other. The geometric properties were more or less same for both the models; hence, variation in elastic material properties is the probable reason for such

Table-2. Frequencies obtained for initial FE model, Undamaged FRP plate and Baseline FE model

	Frequencies (Hz)		
	Initial FE model	Undamaged FRP plate	Baseline FE Model
Mode 1	54.68	47.7	47.117
Mode 2	89.82	113	111.93
Mode 3	124.96	-	143.46
Mode 4	142.29	145	147.22
Mode 5	165.32	-	170.94
Mode 6	249.27	254	265.44
Mode 7	269.93	307	309.91
Mode 8	296.68	343	338.75

difference in frequencies. This issue can be resolved through finite element model updating and also by selecting appropriate updating parameter, which in this case are the elastic material constants like the in-plane Young's moduli and in-plane Shear modulus [14]. The updated elastic material constants are E_x = 38.98 GPa, E_y = 19.80 GPa, and G_{xy} = 3.6 GPa. Table-II shows the frequency comparison between baseline model and experimental undamaged FRP plate and they are very close to each other.

4. Damage Detection: Equivalent Material Properties as Parameters

The objective function is formed by taking the weighted summation of the error in natural frequencies and in mode shapes and can be expressed as

$$E = (W_\omega \times E_\omega) + (W_\Phi \times E_\Phi) \tag{1}$$

where, E_ω, E_Φ are the error functions corresponding to frequency and mode shape respectively. In addition to that, W_ω, W_Φ are the weighting factors, corresponding to the frequency error function and mode shape error function respectively. The objective function is minimised using Inverse Eigen-sensitivity method based finite element model updating algorithm implemented through FEMTool software [15]. The sensitivity equation [16] can be expressed as

$$\{\Delta f\} = [S]\{\Delta r\} \tag{2}$$

Where, $\{\Delta f\} = f(r) - f(\bar{r}), \{\Delta r\} = r - \bar{r}$ an $[S] = \left[\partial f / \partial r\right]_{r=\bar{r}}$

Also, $f_i(r)$ = Measured eigenvalues and eigenvectors of the structure, and $f_i(\bar{r})$ = Modal properties or response properties of the initial finite element model of the structure. The frequencies and mode shapes of undamaged and damaged FRP plate are correlated through FEMTools software. The first procedure for correlation is node-point pairs followed by degree-of-freedom pairs and then mode shape pairs. The selection of appropriate updating parameter is a very crucial step. In this investigation, material properties such as in-plane Young's moduli (E_x and E_y) and in-plane Shear modulus (G_{xy}) within the localised region of damage are selected as updating parameters. Fig. 4 (a) shows the change in E_x at each step of iteration. Fig. 4 (b) shows the change in E_y at each step of iteration. Fig. 4 (c) shows the change in G_{xy} at each step of iteration.

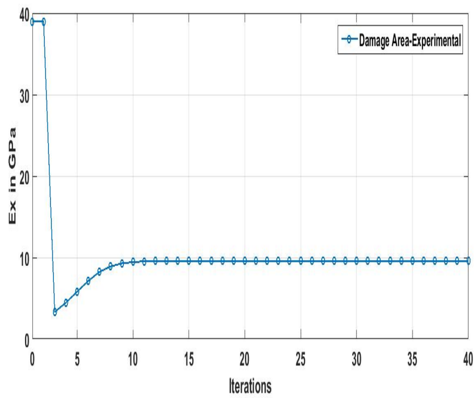

Fig. 4 (a). Change of E_x at each step of iteration

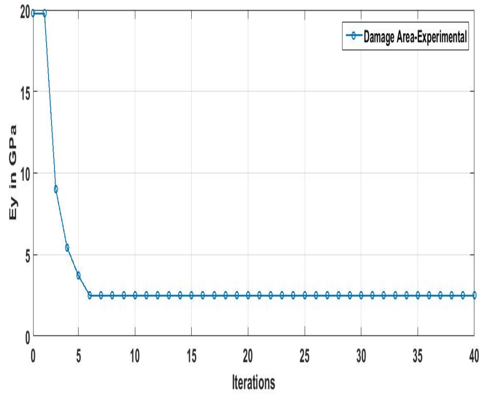

Fig. 4 (b). Change of E_y at each step of iteration

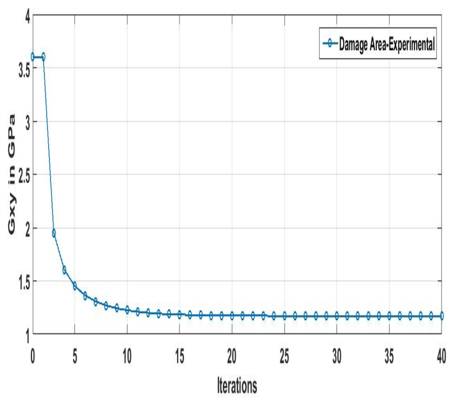

Fig. 4 (c). Change of G_{xy} at each step of iteration

The Frequencies and mode shapes were regenerated using updated elastic parameters as input in ABAQUS. Table-III shows the frequency comparison of initial FE model, updated FE model and experimental damaged FRP plate.

The frequencies of updated FE model and experimental damaged FRP plate are found to be very close to each other. The reproduced dynamic responses are found to be similar to the dynamic responses of experimental damaged FRP composite plate, indicating successful estimation of damage as localised loss of stiffness in terms of changes in the in-plane Young's moduli (E_x and E_y) and the in-plane Shear modulus (G_{xy}).

Table-3. Frequencies obtained for baseline FE model, updated FE model and damaged FRP plate.

	Frequencies (Hz)		
	Baseline FE Model	Updated FE Model	Damaged FRP plate
Mode 1	47.117	43.23	44.2
Mode 2	111.93	102.84	103
Mode 3	143.46	-	-
Mode 4	147.22	138.27	141
Mode 5	170.94	-	-
Mode 6	265.44	239.41	241
Mode 7	309.91	298.28	297
Mode 8	338.75	324.55	322

5. Conclusions

The present investigation considered localised material properties of FRP composite plate as updating parameters in finite element model updating procedure for damage detection, while most of the current literature explored only geometric properties of structures. Such localisation may or may not involve depth-wise differences in properties, as after all these parameters are anyway equivalent in nature. In the present investigation, the Inverse Eigen-sensitivity method implemented through FEMTools software was able to successfully detect damage in the FRP plate in terms of material elastic constants in three orthogonal directions such as the two in-plane Young's moduli and in-plane Shear modulus. Hence, loss of stiffness can be detected as changes in geometric properties as well as material properties or their combination can also be explored.

Disclosures

Free Access to this article is sponsored by SARL ALPHA CRISTO INDUSTRIAL.

References

1. Mottershead, J.E., Link, M., Friswell, M.I., 2011. The sensitivity method in finite element model updating: a tutorial. Mech. Syst. Signal Process. 25 (7), 2275–2296.
2. Jaishi, B., Ren, W. X. (2006), Damage detection by finite element model updating using modal flexibility residual,Journal of Sound and Vibration, vol. 290, no. 1–2, pp. 369–387.
3. Perera, R., Fang, S. E., and Huerta, C. (2009), Structural crack detection without updated baseline model by single and multi objective optimization, Mech. Syst. Signal Process., vol. 23, no. 3, pp. 752–768.
4. Weng, J., Loh, C., and Yang, J. N. (2009), Experimental Study of Damage Detection by Data-Driven Subspace Identification and Finite-Element Model Updating, vol. 135, no. December, pp. 1533–1544.
5. Mojtahedi, A., Lotfollahi Yaghin, M. A., Hassanzadeh, Y., Abbasidoust, F., Ettefagh,M. M., and Aminfar, M. H. (2012), A robust damage detection method developed for offshore

jacket platforms using modified artificial immune system algorithm, China Ocean Eng., vol. 26, no. 3, pp. 379–395.

6. Moaveni, B. et al. (2013), Finite-Element Model Updating for Assessment of Progressive Damage in a 3-Story In filled RC Frame, vol. 139, no. October, pp. 1665–1674.

7. Simoen, E., Moaveni, B., Conte, J. P., and Lombaert, G. (2013), Uncertainty Quantification in the Assessment of Progressive Damage in a 7-Story Full-Scale Building Slice, J. Eng. Mech., vol. 139, no. 12, pp. 1818–1830.

8. Wang, F. L., Chan, T. H. T., Thambiratnam, D. P., and Tan, A. C. C. (2013), Damage diagnosis for complex steel truss bridges using multi-layer genetic algorithm, J. Civ. Struct. Heal. Monit., vol. 3, no. 2, pp. 117–127.

9. Kernicky, T., Whelan, M., Weggel, D., and Rice, C. (2014), Structural Identification and Damage Characterization of a Masonry Infill Wall in a Full-Scale Building Subjected to Internal Blast Load,J. Struct. Eng., vol. 0, no. 0, p. D4014013.

10. Yu, E., Kim, S. N., Park, T., and Lee, S. H. (2014), Detection of earthquake-induced damage in a framed structure using a finite element model updating procedure,Sci. World J., vol. 2014.

11. Niu, J., Zong, Z., and Chu, F. (2015), Damage identification method of girder bridges based on finite element model updating and modal strain energy,Sci. China Technol. Sci., vol. 58, no. 4, pp. 701–711.

12. Altunışık, A. C. (2017), Automated model updating of multiple cracked cantilever beams for damage detection, Journal of Constructional Steel Research, vol. 138. pp. 499–512.

13. ABAQUS/Standard User's Manual for Version 6.14.

14. Mondal, S., and Chakraborty, S. Identification of in-plane and out-of-plane elastic parameters of orthotropic composite structures, ICSV22 International Congress on Sound and Vibration, 1-8, (2016).

15. FEMtools Manual, Dynamic design solutions, Version 3.6.1.

16. Chen, J. C. and Garba, J. A. Analytical Model Improvement Using Modal Test Results, AIAA Journal, 18 (6), 684-690, (1980).