IOP Conf. Series: Journal of Physics: Conf. Series **842** (2017) 012084 doi:10.1088/1742-6596/842/1/012084

Delamination detection in laminated composite using Virtual crack closure technique (VCCT) and modal flexibility based on dynamic analysis

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Abstract. The delamination problem is very important failure mechanism in certain types of composite structures. Detecting this type of damage using vibration data is currently a problem of interest to the structural health monitoring community. In this paper, we used finite element method with embedded interface for analysing damaged laminated composite structures. The flexibly modal method, in which analysis data is related to finite element modelling, is used to detect and localize delamination. Several numerical examples are presented in order to evaluate the accuracy this approach.

1. Introduction

The ability to monitor a composite structure and detect, locate damage at the earliest possible stage is pervasive throughout the civil, mechanical, and aerospace engineering communities. The mechanics of delamination in composite structures has been largely studied in the recent years by procedures that employ fracture mechanics parameters. A finite element model for damage identification in such structures is presented using finite element SI12 [1]. The proposition of virtual crack closure technique is possibly the most adopted fracture mechanic's theory to simulate the propagation of delamination structure composite [2]. In recent years, a growing interest has emerged in the application of cohesive zone models to study delamination damages in laminated composite structures [3-5]. The ultrasonic assessment of a damaged CFRP after impact proved that the FBG sensor was better than the PZT sensor to identify damage [6]. Different damage detection diagnosis approaches, vibration based damage detection (VBDD) techniques [7-11] have received increased attention recently. This is particularly due to their relative simplicity and the moderate cost of dynamic analysis measurements with different structures, such as beam , trusses, and simple structures in reinforced concrete and steel [12]. A method for damage detection and localization in beam like and complex structure using co-ordinate modal assurance criterion combined with firefly and genetic algorithms was proposed in [13]. In [14], the authors presented an new approach of inverse damage detection and localization in composite beam

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structure graphite-epoxy based on model reduction. This problem was formulated as an inverse problem where an optimization algorithm was used to minimize the cost function expressed as the normalized difference between a frequency vector of the tested structure and its numerical model. A new damage detection and localization technique based on the changes in vibration parameters using BAT and Particle Swarm Optimization algorithm for detecting and locating damage in composite structure was presented in [15]. The authors in [16], used residual modal force vectors for damage localization because the residual force method is effective in damage localization using modal data. Furthermore, the authors in [17] demonstrated that the cyclic behaviour was related to the phase velocity of the converted wave modes in the two subsystems after delamination. The damage indicator based on vibration data was used to detect and locate defects in stratified beam structures in [18].

In [19], experimental free vibration of CFRP cantilever beam elements were investigated by dynamic tests. The damage introduced to the CFRP specimens were due to double notches close to the fixed end with different reduction of section and bending stiffness. The experimental and theoretical analysis of damaged and undamaged Carbon Fibre Reinforced Polymer (CFRP) laminate elements under free vibration of CFRP laminate specimens were experimentally investigated using a mechanical apparatus capable of simulating hinge conditions at the edges of simply supported laminate beams [20]. The analysis of vibration of undamaged and damaged Carbon Fibre Reinforced Polymer (CFRP) is carried out in this work using beam finite elements. Finite element method is a well established numerical technique, is widely used in academia and industries and have wide range of applications [21-29]. Recently, FEA was with Computer Added Design (CAD) and extended to Isogeometric analysis (IGA), which was originally introduced by Hughes et al. [30, 31]. IGA makes use of non-uniform rational B-spline (NURBS) basis functions to describe the exact geometry of a structure and approximate its field variables and has many applications including composite structures [32-43].

In the present paper, we used virtual crack closure technique (VCCT) and modal flexibility based on dynamic analysis in clamped-free and simply supported beam composite laminate to detect delamination between layers using embedded interface.

2. Damage detection method using flexibility matrix

In this paper the structural damage detection does not cause mass variation, but only a reduction in the structural stiffness. The flexibility matrix is defined as the inverse of the stiffness matrix. The reduced stiffness caused by damage results in increased flexibility and is written:

$$F = K^{-1} \tag{1}$$

Damage is detected by comparing the matrix of the flexibility of the damaged structure with undamaged structure. The sensitivity matrices F_s and F_e of undamaged and damaged structures are written, respectively, as:

$$F_s = \sum_{i=1}^{n} \frac{1}{\omega_{si}^2} \phi_{si} . \phi_{si}^T \tag{2}$$

$$F_e = \sum_{i=1}^{n} \frac{1}{\omega_{ei}^2} \phi_{ei} . \phi_{ei}^T \tag{3}$$

where:

ω_{si} and ω_{ei} : Natural frequencies of undamaged and damaged structures.

ϕ_{si} and ϕ_{ei} : Eigenvectors of undamaged and damaged structure.

n : mode number measured.

Having the eigenvectors of the undamaged and damaged structure with the introduction of some damage, the variation of the flexibility ΔF caused by the damage is:

$$\Delta F = Fs - Fe = [\delta_{ij}] \tag{4}$$

where:
δ_{ij} : The elements of the matrix of variation of flexibility ΔF .

In the following, the quantity of $\overline{\delta}_j$ represents the maximum of the absolute values of the elements j^{th} column of the variation in flexibility ΔF :

$$\overline{\delta}_j = \max\left|\Delta F_{ij}\right| \tag{5}$$

Then $\overline{\delta}_j$ is taken as a measure of the variation of flexibility at each location. The column of the flexibility matrix corresponding to the greatest change is indicative of the element where the damage is found. The presentation of this method is shown in Figure 1.

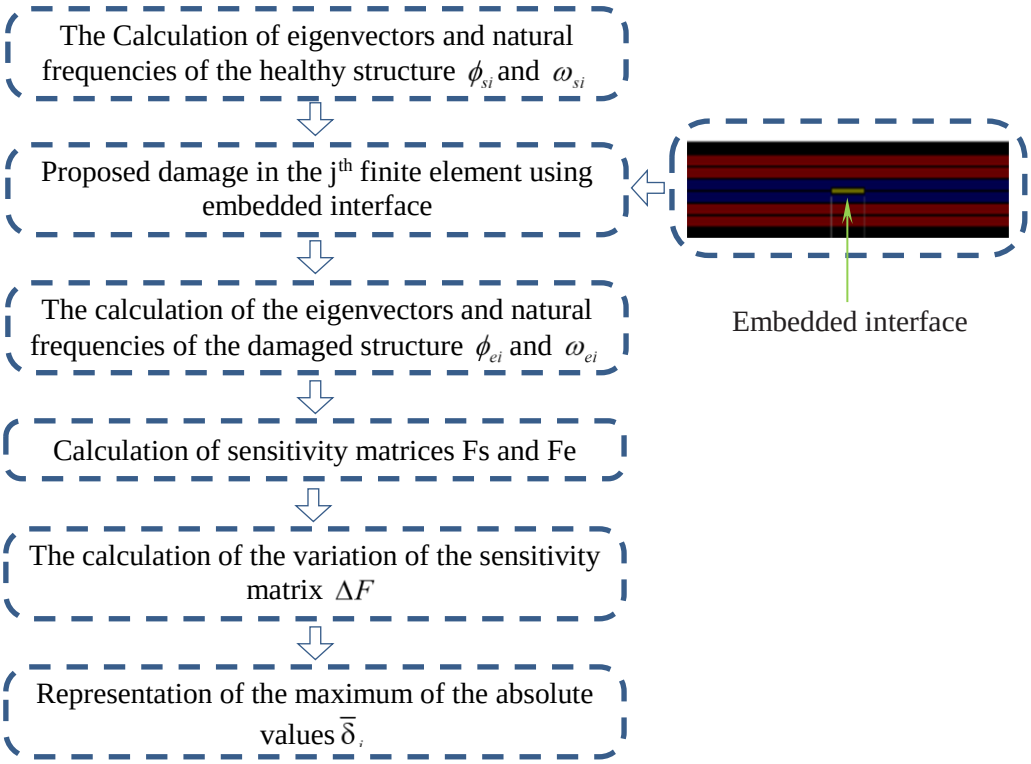


Figure 1. The Flowchart of the Flexibility Matrix Method

3. Numerical simulations

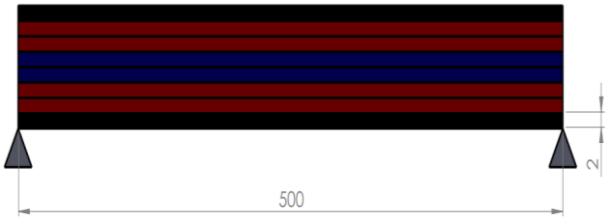
The suggested cracked element is very important for modelling the laminated composite beams structure. A triangle element with an interface crack in the two-dimension space and used it for analysis of cracked beam [44]. In [45, 46], the authors developed the formulation of a triangular finite element with an embedded interface, which can properly simulate the crack propagation phase. In our study, we used this technique in dynamic analysis of composite structure with 8 layers modelled using FEM software (PATRAN). The mechanical and geometric properties of the composite beam are given in Table 1.

Table 1. Mechanical and geometrical properties

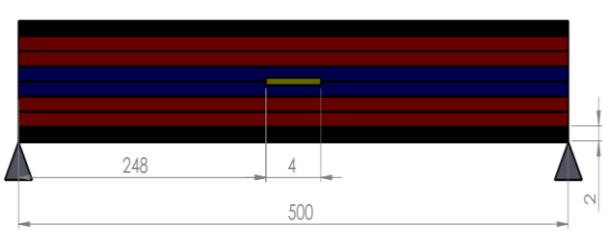
Mechanical and geometrical properties	Values
Length L	0.5 m
Width B	0.03 m
Thickness E	0.016 m
Young's Modules	$E_1 = 144.7 GPa$ and $E_2 = E_3 = 9.65 GPa$
Shear modulus	$G_{12} = G_{13} = 4.14 GPa$ and $G_{23} = 3.45 GPa$
Poisson's coefficients	$\nu_{12} = 0.3$ and $\nu_{13} = \nu_{23} = 0.011$
Density	$\rho = 138.23 Kg/m^3$

4. Results and discussion

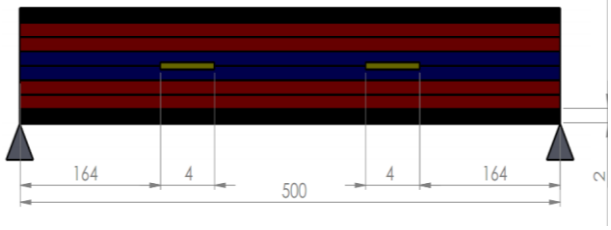
In order to determine the dynamic properties of our structure, we performed some tests on three types of structures, namely a) undamaged, b) damaged with a single delamination and c) damaged with two delamination with two different types of boundary conditions, clamped-free and simply-supported, as shown in Figure 2.



(a) Undamaged simply – supported beam



(b) Simply – supported beam with 1 damage



(c) Simply – supported beam with 2 damage

Figure 2. Different structures studied with position of delamination

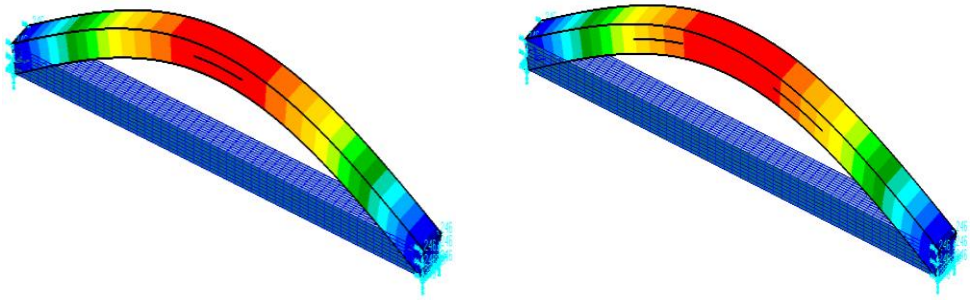
4.1. Simply – supported beam laminate

In this case, we consider the structure delamination using the same data and changing only the boundary conditions, i.e. simply-supported beam. The natural frequencies of simply-supported beam structure of undamaged and damaged with one and two delamination are listed in Table 2.

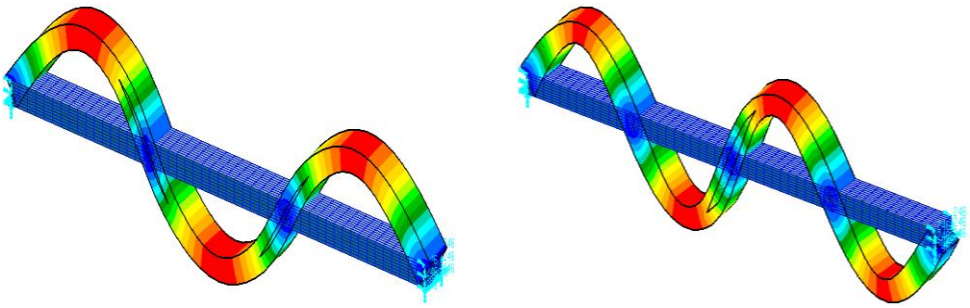
Table 2. The natural frequencies of simply-supported beam structure undamaged, damaged.

Frequencies	undamaged	Damaged with one delamination	Damaged with two delamination
Mode 1	175.927	175.202	174.439
Mode 2	688.848	677.088	679.459
Mode 3	1498.769	1493.571	1403.227
Mode 4	2551.43	2420.205	2455.505
Mode 5	3789.749	3768.298	3645.006
Mode 6	5161.819	4788.613	4500.532

The mode shapes with one and two delamination of simply supported beam are presented in Figure 3.



(a) Mode 1 with one delamination (b) Mode 1 with two delamination



(c) Mode 3 with two delamination (d) Mode 4 with one delamination

Figure 3. Presentations of modes with one and two delamination of simply-supported beam

In the first section, we were able to model our structure with the software PATRAN, while introducing the mechanical, physical characteristics of the beam as well as the boundary conditions. All the results obtained with eigenvectors will be used to add data in flexibility modal method in second section. In all tests, the delamination is located between layer 4 and 5 with same demensions.

4.2. Scenario 1: Simply – supported beam with one delamination

For this case, details of scenario 1 is shown in Figure 4 and the results found by the variation of flexibility are given in Figure 5. Figures 5.a to 5.c show that the variation of the flexibility is important on all nodes of the surfaces. In figure 5.d, we note that the variation in flexibility is greater in the zone where the defect is located. Furthermore, in figure 5.e, we note that the variation in flexibility is important in the zone where the defect is located is zero in the rest of the surfaces. The geometrical symmetry is reproduced due to the symmetry of the results with respect to the neutral axis of the beam.

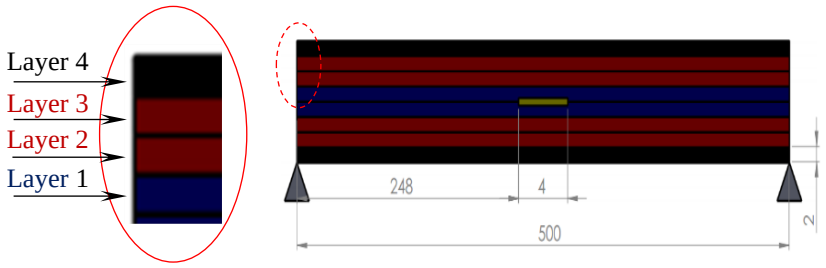
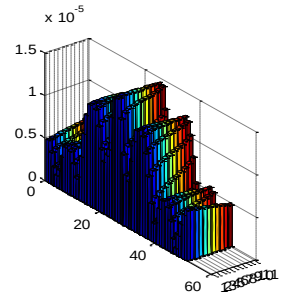
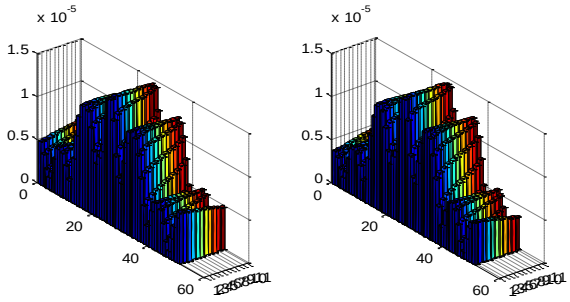


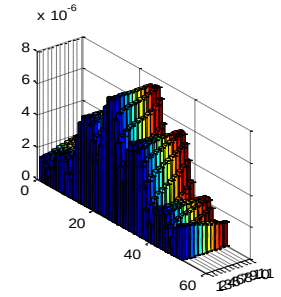
Figure 4. Presentation of Simply – supported beam with one delamination



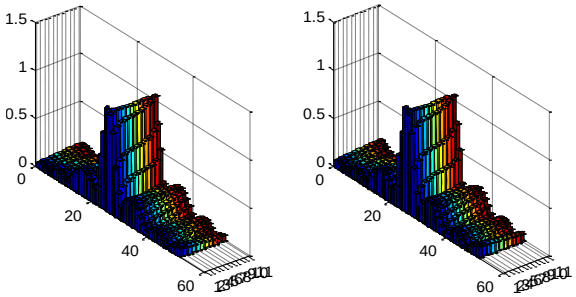
(a) The variation of the flexibility $\overline{\delta}_j$, 'lower layer 1 and Higher layer 8'.



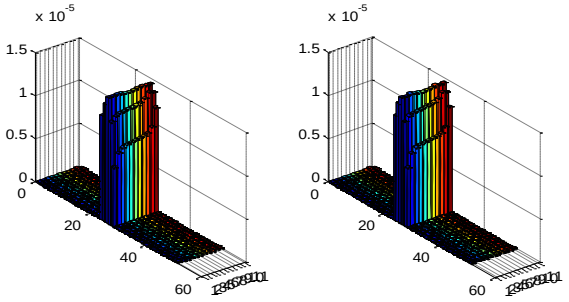
(b) The variation of the flexibility $\overline{\delta}_j$, 'Higher layer 1 and lower layer 8'.



(c) The variation of the flexibility $\overline{\delta}_j$, 'lower layer 2 and Higher layer 7'.



(d) The variation of the flexibility $\overline{\delta}_j$, 'lower layer 3 and Higher layer 6'.



(e) The variation of the flexibility $\overline{\delta}_j$, 'lower layer 4 and Higher layer 5'.

Figure 5. The variation of flexibility of Simply-supported beam with one delamination

4.3. Scenario 2: Simply – supported beam with two delamination figure 6.

For this case, details of scenario 2 is shown in Figure 6 and the results found by the variation of flexibility are given in Figure 7. The presence of delamination reduces the rigidity of the composite structure studied. As the flexibility is the inverse of the rigidity, then the reduction of rigidity generates the increase in the flexibility of the structure, hence the change in flexibility can be used to detect and locate delamination. In this study, we found that the results obtained from this method can localize the delamination failure by the variation of the flexibility.

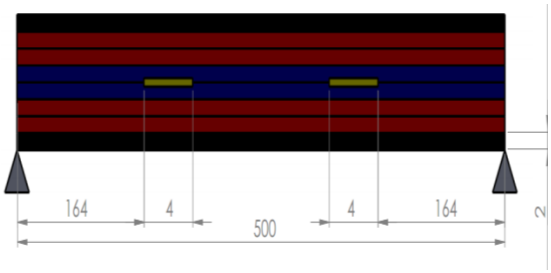
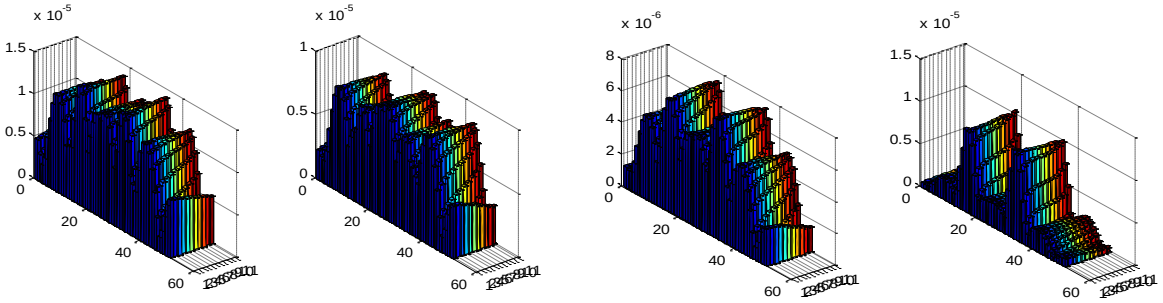
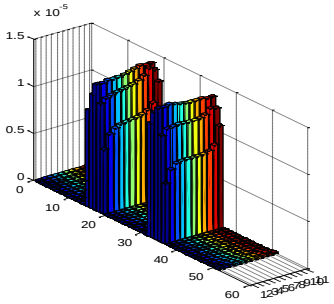


Figure 6. Simply – supported beam with two delamination



(a) The variation of the flexibility $\overline{\delta}_j$, 'lower layer 1 and 2'.

(b) The variation of the flexibility $\overline{\delta}_j$, 'lower layer 3 and 4'.



(c) The variation of the flexibility $\overline{\delta}_j$, 'lower layer 5'.

Figure 7. The variation of flexibility of Simply – supported with two delamination.

5. Conclusion

In this paper, we used a flexibly modal method analysis based on finite element modelling to localize and detect delamination in composite beam structures having 8 layers. For detecting this type of damage, we used virtual crack closure technique (VCCT). The Finite Element Method with embedded interface crack for analysing damaged laminated composite structures was proposed. The results found by flexibly modal method, show that this approach can detected the delamination with higher accuracy.

6. References

[1] Rikards R 1991 *Riga: Riga Technical University*
[2] Krueger R 2004 *Applied Mechanics Reviews* **57**(2) 109-143
[3] Tay T 2003 *Applied Mechanics Reviews* **56**(1) 1-32
[4] Mi Y, Crisfield M, Davies G and Hellweg H 1998 *Journal of composite materials* **32**(14) 1246-1272
[5] Camanho PP, Davila C and De Moura M 2003 *Journal of composite materials* **37**(16) 1415-1438
[6] Tsuda H 2006 *Composites science and technology* **66**(5) 676-683
[7] Zhou Y-L and Abdel Wahab M 2017 *Engineering Structures* **141** 175-183
[8] Zhou Y-L, Maia NMM, Sampaio R and Wahab MA 2016 *Structural health monitoring* **DOI: https://doi.org/10.1177/1475921716680849**
[9] Zhou Y-L, Maia N and Abdel Wahab M 2016 *Journal of Vibration and Control* doi: 10.1177/1077546316674544
[10] Zhou Y-L and Abdel Wahab M 2016 *Journal of Vibroengineering* **18**(7) 4491-4499
[11] Gillich G-R, Praisach Z-I, Abdel Wahab M, Gillich N, Mituletu IC and Nitescu C 2016 *Shock and Vibration* **2016**(Article ID 2086274) 10 pages; http://dx.doi.org/10.1155/2016/2086274
[12] Materazzi AL and Ubertini F 2011 *Journal of sound and vibration* **330**(26) 6420-6434
[13] Khatir A, Tehami M, Khatir S and Abdel Wahab M 2016 23rd International Congress on Sound and Vibration (ICSV23) ed editors) International Institute of Acoustics and Vibration
[14] Khatir S, Belaidi I, Serra R, Wahab MA and Khatir T 2016 *Mechanics* **21**(6) 472-479
[15] Khatir S, Belaidi I, Serra R, Wahab MA and Khatir T 2016 *Journal of Vibroengineering* **18**(1)
[16] Ricles J and Kosmatka J 1992 *AIAA journal* **30**(9) 2310-2316
[17] Gao H, Ali S and Lopez B 2010 *NDT & E International* **43**(4) 316-322
[18] BEHTANI A and BOUAZZOUNI A 2011 *20ème Congrès Français de Mécanique, 28 août/2 sept 2011-25044 Besançon, France (FR)*
[19] Capozucca R 2014 *Composite Structures* **116** 211-222
[20] Capozucca R and Bonci B 2015 *Composite Structures* **122** 367-375
[21] Yue T and Abdel Wahab M 2017 *Tribology International* **107** 274-282
[22] Pereira K, Yue T and Abdel Wahab M 2017 *Tribology International* **110** 222-231
[23] Martínez JC, Vanegas Useche LV and Wahab MA 2017 *International Journal of Fatigue* **100, Part 1** 32-49
[24] Kumar D, Biswas R, Poh LH and Abdel Wahab M 2017 *Tribology International* **109** 124-132
[25] Noda N-A, Chen X, Sano Y, Wahab MA, Maruyama H, Fujisawa R and Takase Y 2016 *MATERIALS & DESIGN* **96** 476-489
[26] Gadala I, Abdel Wahab M and Alfantazi A 2016 *MATERIALS & DESIGN* **97** 287-299
[27] Wang C, Sun Q, Abdel Wahab M, Zhang X and Xu L 2015 *Waste Management* **43** 19-27
[28] Vanegas-Useche L, Abdel Wahab M and Parker G 2015 *Waste Management* **43** 28-36
[29] Junyan Ni and Wahab MA 2017 *Computers & Structures* **186** 35–49
[30] Cottrell JA, Reali A, Bazilevs Y and Hughes TJ 2006 *Computer Methods in Applied Mechanics and Engineering* **195**(41) 5257-5296
[31] Hughes TJ, Cottrell JA and Bazilevs Y 2005 *Computer Methods in Applied Mechanics and Engineering* **194**(39) 4135-4195
[32] X. Nguyen H, N. Nguyen T, Abdel Wahab M, Bordas SPA, Nguyen-Xuan H and P. Voa T 2017 *Computer Methods in Applied Mechanics and Engineering* **313** 904-940
[33] Phung-Van P, Qui LX, Nguyen-Xuan H and Wahab MA 2017 *Composite Structures* **166** 120–135
[34] Phung-Van P, Ferreira AJM, Nguyen-Xuan H and Abdel Wahab M 2017 *Composites Part B: Engineering* **118** 125-134
[35] Tran LV, Phung-Van P, Lee J, Wahab MA and Nguyen-Xuan H 2016 *Composite Structures* **140** 655-667
[36] Thai CH, Ferreira AJM, Abdel Wahab M and Nguyen-Xuan H 2016 *Acta Mechanica* **227**(5) 1225-1250

[37] Thai C, Zenkour AM, Abdel Wahab M and Nguyen-Xuan H 2016 *Composite Structures* **139** 77-95
[38] Phung-Van P, Tran LV, Ferreira AJM, Nguyen-Xuan H and Abdel-Wahab M 2016 *Nonlinear Dynamics* 1-16; doi:10.1007/s11071-11016-13085-11076
[39] Tran Vinh L, Lee J, Nguyen-Van H, Nguyen-Xuan H and Abdel Wahab M 2015 *International Journal of Non-Linear Mechanics* **72** 42-52
[40] Tran Vinh L, Lee J, Ly HA, Abdel Wahab M and Nguyen-Xuan H 2015 *International Journal of Mechanical Sciences* **96-97** 65-78
[41] Phung Van P, Nguyen LB, Tran Vinh L, Dinh TD, Thai CH, Bordas SPA, Abdel Wahab M and Nguyen-Xuan H 2015 *International Journal of Non-Linear Mechanics* **76** 190-202
[42] Phung Van P, De Lorenzis L, Thai CH, Abdel Wahab M and Nguyen-Xuan H 2015 *Computational Materials Science* **96** 495-505
[43] Phung Van P, Abdel Wahab M, Liew KM, Bordas SPA and Nguyen-Xuan H 2015 *Composite Structures* **123** 137-149
[44] Löblein J and Schröder J 2005 *Computational materials science* **32**(3) 435-445
[45] Bolzon G and Corigliano A 2000 *International Journal for Numerical Methods in Engineering* **49**(10) 1227-1266
[46] Bolzon G 2001 *Computational Mechanics* **27**(6) 463-473