Structural Health Monitoring of Composites using System Identification

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Abstract

In this paper, we propose a new damage detection method using system identification based on Eigen System Realization (ERA) from the time domain dynamic response of the structure. A methodology has been developed to reconstruct the full stiffness matrix from the reduced system matrix identified by ERA and to estimate the bending stiffness values of the damaged sections using an iterative procedure. The validity and accuracy of the method were first assessed using test cases of isotropic beams with delaminations, whose response was simulated using Sate-Space based Finite Element System Model (SS-FESM) and transient finite element method. The proposed methodology was then applied to damage assessment in numerical test cases of quasi-isotropic composite beams with delaminations of different sizes and located at various axial and interface positions. In every case the proposed damage assessment technique was able to assess the size and location of the delamination accurately and the reduction in the bending stiffness of the delaminated elements with error less than 3%.

Keywords: System Identification, Structural Health monitoring, CFRP, ERA, SS-FESM.

1. Introduction

The use of composite materials in engineering structures has been growing over the last few decades, due to their low density and attractive mechanical properties [1-2] In particular, fibre reinforced laminated polymer composites are being employed more than ever in weight critical applications such as the aerospace [3] and off shore structures [4], since their mechanical properties can be tailored to provide minimum factors of safety along desired load paths by appropriate selection of ply orientations and stacking sequences. However, one of the weaknesses of laminated composites is their low inter-laminar strength, making them vulnerable to impact damage and predisposed to internal damage in the form of delaminations [5].

Vibration monitoring has been employed for several decades in Health and Usage Monitoring Systems, but has been slow to find applications in Structural Health Monitoring, despite its obvious advantages of providing on-line, in-situ, and instantaneous identification of initiation of damage to structural components [6]. Although the incidence of damage affects all structural dynamic properties, most of the previous research in vibration based structural damage monitoring have concentrated on frequency measurements [7], since frequency shifts can be measured more accurately and reliably without requiring a large number of sensors to be mounted on the structure. However, one of the disadvantages of frequency monitoring is that, while it readily indicates the presence of damage, identification of the location and severity of damage requires complex information processing using mathematical or intelligent inverse algorithms tools such as Neural Networks [8] and Genetic Algorithm [9]. Research on application of such techniques to detection of delaminations in composites is still ongoing and has so far yielded mixed results.

In recent years, vibration based damaged detection using System Identification has been employed in civil engineering domain [10]. Fraraccio, G., et al.[11] employed an Eigen Realization Algorithm (ERA) for system identification, and employed it identify damage in the form of stiffness reduction in column of a four-story steel frame subjected to the various types of base excitation. However, they have modelled the structure as a spring and lumped mass system, which is a very simplistic approximation that can only be applied to simple structures. Jang, S., et al. [12] estimated the dynamic characteristics of bridge using ERA with test data from a lab-scale truss bridge model in order to identify the damage. Hong V.-M., et al. [13] demonstrated ERA based structural health monitoring of metal plate where the damage was simulate by attaching a piece of magnet on the plate surface. Johnson et al. [14] modelled a multistory building as spring and lamped mass system to obtain the response for validating their proposed technique based on ERA. So far, it does not appear that the Eigensystem Realization Algorithm for ambient vibration measurement using laser Doppler vibrometers there have been any studies of application of ERA for damaged detection in continuous structures modeled with distributed mass and stiffness. Further, while the above applications of ERA have been more or less successful in identifying the presence and location of the damage from local changes in the system parameters, in none of them the severity of damage has been quantified, i.e. the loss of structural stiffness due to the damage has been fully estimated. This paper presents the application of an ERA based system identification technique for damage detection in a continuous structure using a distributed structural model. The proposed ERA based damage detection method is applied to isotropic and composite beams. While there have been many studies in the past for delamination detection in composite beams using techniques such as neural networks [15], dynamics-based damage detection [16], genetic algorithm [17], wavelet transformations[18], graphical detection [19] and frequency based method [20] so far system identification does not seem to have been attempted for delamination detection in laminated composite structures. Further we have developed a methodology to estimate the reduction in structural stiffness caused by the damage, which has been successfully validated.

Damage assessment methods based on frequency shifts require frequency measurements to be taken both on the undamaged and damaged structures. This is true for methods using mode shapes or their derivatives. Taking measurements on the pristine structure or having its frequency or mode shape data is not always possible and thus limits the practical implementation of methods using changes in modal parameters to real structures. Damage detection using system identification, however, requires measurements to be taken only on the damaged or the suspected structure, since damage is identified by changes in local system parameters (stiffness or damping) relative to those of the other sections of the system. This is one of the major advantages of the system identification method proposed herein, in that it does not require the prior history of the structure to be known.

This paper describes the methodology and implementation of an ERA based System Identification technique for damage assessment in laminated composite structures. We employ the Eigen-system Realization Algorithm (ERA) [13, 21] for system identification from its dynamic response to an impulse load. The local changes in the system stiffness are employed to identify the presence of delaminations, to determine their locations and assess their severity. ERA is a modal analysis technique which generates as system realization of the structure from known input and measured frequency response data [22]. A Sate-Space based Finite Element System Model (SS-FESM) is employed to generate transient impulse the response signals of laminated beams with and without delaminations. The impulse response and the input signals are fed into the ERA to estimate the dynamic properties, namely the stiffness and damping coefficients of all elements in the structure. Variations in the dynamic properties readily identify the presence, location and severity of the damage. The method is also validated using finite element simulation of 8 ply laminated composite beams with delaminations. Numerical test cases demonstrate that delaminations as small as one percent of the beam length in size can be identified and assessed using the present method.

2. Theory

Figure 1 shows the schematic of a cantilever beam with delamination and the co-ordinate system used. The length of the beam is L, and width “b”. The delamination has a length “a” and its mid-point is located at a distance X_c from the fixed end of the beam. The full beam thickness and the thicknesses of the upper and lower sub-laminates are respectively indicated by “t”, “t_1” and “t_2”.

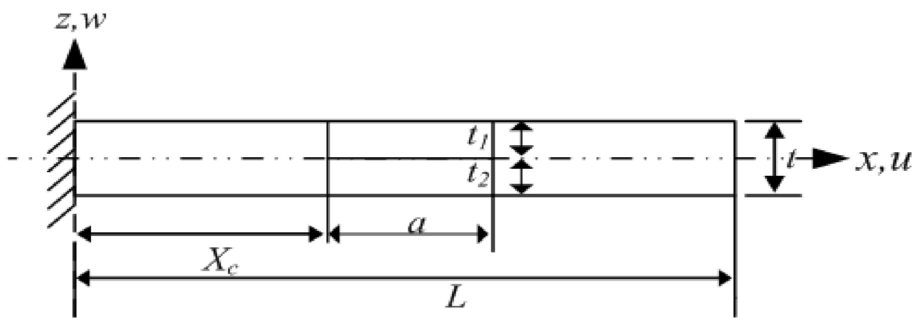


Figure 1: Beam with Delamination

2.1 Finite Element Model for Beam Flexural Vibration

The equation of motion for finite element that includes formulas for stiffnesses, masses and nodal loads can be developed by using the principle of virtual work [23]. Therefore, equation of motion for finite element is expressed by equation (1).

$$M\ddot{w}(t) + C\dot{w}(t) + Kw(t) = F(t) \quad (1)$$

Where, $F(t)$ is the forcing function and M , C , and K respectively represent the global mass, damping and stiffness matrices of the structure which can be assembled from the respective element mass matrices. Figures 2(a) and 2(b) respectively show the assembly procedure using superposition for the global mass matrix M from the element mass matrices (M_e) represented by equation 2(a) and the global stiffness matrix K from the element stiffness matrices (K_e) represented by equation 2(b), respectively. It may be noted if elements with four degrees of freedom (two at each node) are used, the assembled global stiffness matrix will be a banded diagonal matrix with a bandwidth of 4 and the elements outside this diagonal band will be zero. In the current study we only use changes in the local stiffness coefficients to identify and assess damage, so we may set the C matrix to zero. The element mass matrix M_e and the element stiffness matrix K_e for flexural deflection of a beam element with two degrees of freedom (out of plane translation and rotation) at each end node is given by [23]:

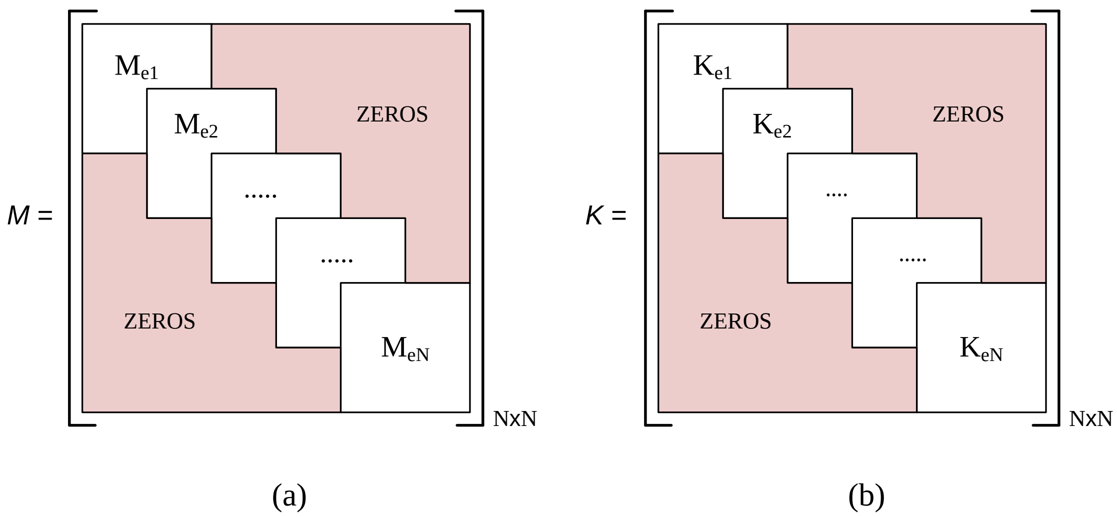


Figure 2: Assembly of Global Matrices by Superposition (a) Mass Matrix M (b) Stiffness Matrix K

$$K_e = \frac{EI}{l^3}\begin{bmatrix} 12 & 6l & -12 & 6l \\ 6l & 4l^2 & -6l & 2l^2 \\ -12 & -6l & 12 & -6l \\ 6l & 2l^2 & -6l & 4l^2 \end{bmatrix} \quad (2a)$$

$$M_e = \frac{\rho Al}{420}\begin{bmatrix} 156 & 22l & 54 & -13l \\ 22l & 4l^2 & 13l & 13l^2 \\ 54 & 13l & 156 & -22l \\ -13l & -3l^2 & -22l & 4l^2 \end{bmatrix} \quad (2b)$$

Where, l is the length of the element. For a composite laminate the effective flexural stiffness EI_{eff} is given by:

$$EI_{eff} = \frac{b}{d_{11}} \quad (3)$$

where "b" is the width of the beam and d_{11} is the flexibility coefficient relating the axial curvature to the axial moment resultant of the composite beam obtained from the inverse matrix of the full stiffness matrix for a composite laminate as per classical laminate plate theory [25].

The effective bending stiffness EI_d of a delaminated element may be expressed as

$$EI_d = EI_1 + EI_2 \tag{4}$$

where EI_1 and EI_2 represent the bending stiffnesses of the two sub-laminates as calculated by equation (3). Equation (1) can be solved to obtain the dynamic response of the beam, with appropriate boundary conditions, due to any transient load denoted by $F(t)$

2.2 State Space representation

The state-space form of a dynamic distributed beam model can be written as:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}z(t) \tag{5}$$

where,

$$\mathbf{A} = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 \\ -M^{-1}F \end{bmatrix}, \quad \mathbf{x}(t) = \begin{bmatrix} w(t) \\ \dot{w}(t) \end{bmatrix}$$

M , K and C respectively denote the global Mass, Stiffness and Damping matrices. The vectors x(t) represents the state vector consisting of the displacement and velocity vectors ($w(t)$ and $\dot{w}(t)$) and z(t) denotes input forcing function for state space model. The vectors $w(t)$, $\dot{w}(t)$ and F(t) denote the displacement, velocity and forcing functions. The matrix **A** is the system matrix which consists of the dynamic parameters such as mass, stiffness and damping of the system. The matrix **B** is the input influence matrix dependent on the input location and the type of force input to the system. Equation (5) is the Sate-Space Finite Element System Model (SS-FESM) for the flexural vibration of the beam. Once the system matrix **A** is determined from the mass, damping and stiffness coefficients, the time domain dynamic response of the structure can be numerically obtained from the SS-FESM for any given impulse input **B**.

2.3 Matrix condensation

In practice it is difficult to measure the rotations due to flexural vibrations at each node of the structure. It is therefore expedient to link the rotational degrees of freedom to the translational degrees of freedom in the structural dynamic model. We therefore assign the rotational degrees of freedom as slaves and the translations as master degrees of freedom, to reduce the system using the Guyan dynamic condensation method [27]. It may be noted that reducing the system using the dynamic condensation method still retains effects of the rotational stiffness at the nodes, unlike using a beam model with only translational degrees of freedom. For the dynamic condensation, we rearrange and partition the vectors and matrices into the slave and masterdegrees of freedom (represented by vectors w_a and w_b) as follows:

$$\begin{bmatrix} M_{aa} & M_{ab} \\ M_{ba} & M_{bb} \end{bmatrix} \begin{bmatrix} \ddot{w}_a \\ \ddot{w}_b \end{bmatrix} + \begin{bmatrix} K_{aa} & K_{ab} \\ K_{ba} & K_{bb} \end{bmatrix} \begin{bmatrix} w_a \\ w_b \end{bmatrix} = \begin{bmatrix} F_a \\ F_b \end{bmatrix} \tag{6}$$

In equation (6) the subscript **a** denotes the slave (rotational) degrees of freedom (to be removed) and the subscript **b** refers to the Master (translational) degrees of freedom which will be preserved.

Solving Equation (6) for the vector of rotational degrees of freedom w_a in equation (6), and through matrix manipulations we can separate out the equation for the master (translational) degrees of freedom as [**30**]:

$$(M^*_{bb})\ddot{w}_b + K^*_{bb} w_b = F_b \tag{7}$$

Where,

$$K^*_{bb} = K_{bb} - K_{ba} K^{-1}_{aa} K_{ab} \quad \text{And} \quad M^*_{bb} = M_{aa} K^{-1}_{aa} K_{ab} + M_{bb} \tag{8}$$

The condensed stiffness and mass matrix K^*_{bb} and M^*_{bb} respectively in Equation (8) are transformed from the full stiffness K matrix and the M matrix.

Similarly, if necessary, we can obtain the reduced damping matrix C^*_{bb} from the full damping matrix C; however, the damping matrix is not employed in the current model. We can now use the reduced dynamic equation (Equation 8) for the distributed system to build the Sate-space based finite element system model (SS-FESM). Note that the system matrix A* in the reduced model is now given as:

$$\mathbf{A}^* = \begin{bmatrix} 0 & I \\ -M^{*-1}K^* & -M^{*-1}C^* \end{bmatrix} \tag{9}$$

Where, $M^* = M^*_{bb}$, $K^* = K^*_{bb}$, as given by Eqns.(8) and $C^* = C^*_{bb}$

2.4 System Identification using Eigen Realization Algorithm

Equation (5) and equation (7) can be used to determine the transient response of a system if the system parameters are known. However, for system identification we need to solve the inverse problem, i.e., identify the system parameters (the **A** matrix or M, K and C matrices) from its dynamic response to known force inputs. There are numerous techniques available for system identification. In our work, we use the Eigen Realization Algorithm (ERA) [26] which is quite robust, reliable and has the capacity to handle large amount of time domain data. The first and foremost condition of ERA is the response data should be from a pulse response. The ERA essentially involves three steps [21]: 1) determination of the Hankel matrix, 2) Singular value decomposition, and 3) system parameter evaluation. These are briefly described below.

2.4.1 The Hankel matrix

The Hankel matrix is constructed from Markov Parameters, which are pulse response samples, as follows [29]:

$$[H(k-1)]=\begin{bmatrix} \mu(k) & \mu(k+1) & \dots & \mu(k+p) \\ \mu(k+1) & \ddots & & \vdots \\ \vdots & & & \\ \mu(k+r) & \cdots & & \mu(k+p+r) \end{bmatrix} \tag{10}$$

Where $\mu(k)$ is the pulse response data at time step "k", i.e. the vector of displacement data of all the nodes at time step k for each input location. Where, the parameter p and r denotes the number of column and row in Hankel matrix. The parameter p should be ten times the number of modes to be indentified and r should be selected to be 2~3 times of p to achieve reasonable accuracy [22] The two Hankel matrices $H(0)$ and $H(1)$ are evaluated from Equation (10) to perform the singular value decomposition and determine the system parameters.

2.4.2 Singular Value Decomposition (SVD):

The SVD of Hankel matrix $H(0)$ is performed using:

$$[H(0)]=[U]^T[\Sigma][V] \tag{11}$$

Where, U and V are the left and right eigenvector matrix of $H(0)$ respectively, and $[\Sigma]$ is the diagonal matrix of singular values. Singular values of very small magnitude do not contribute to the system, hence only singular values of finite magnitude determine the order of the system matrix [29].

2.4.3 System Parameter Evaluation:

If "n" is the number of singular values chosen from the Σ matrix on the basis of singular values of finite magnitude, we reduce the columns and rows of eigenvector matrices U, V and the singular value matrix Σ as denoted by $[U]_{n,}^T$ $[\Sigma]_n$ and $[V]_n$.

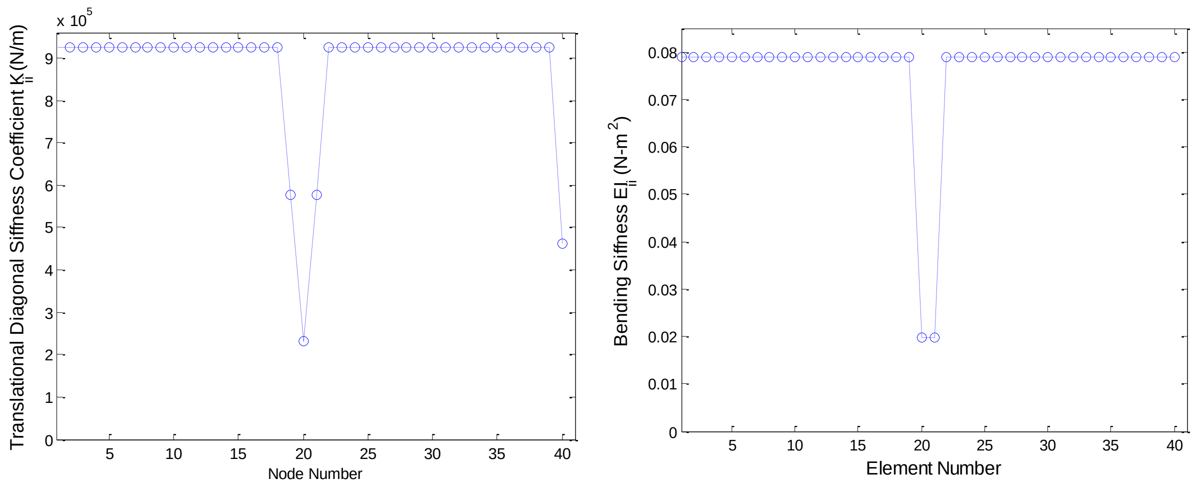
The system matrices A, B and C can now be evaluated from

$$\left.\begin{aligned} A &= [\Sigma]_n^{-1/2}[U]_n\ [H(1)][V]_n^T[\Sigma]_n^{-1/2} \\ B &= [\Sigma]_n^{-1/2}[V]_n^T[E]_n^P \\ C &= [E]_n^L[U]_n^T[\Sigma]_n^{1/2} \end{aligned}\right\} \tag{12}$$

Where, $[E]_n^L = [I\ \ 0]$ and $[E]_n^P = [I;0]$ and the C matrix is employed to calculate the mode shape of the structure. In the current work, we only use the system matrix A.

3. Damage assessment using ERA system identification

Damage in a structure changes the local stiffness (and damping) of the structure and hence alters the values of the coefficients of the system matrix **A**. Hence if we identify the system by estimating the system matrix **A** from the response of the structure to an impulse load using the ERA system identification methodology outlined in section 2.4, we can identify the incidence or presence of damage. We assume that the effect of the damage on the mass distribution of the structure is negligible, and the matrix M or M* will remain unchanged. Hence from the system matrix A identified using ERA, we can extract the stiffness matrix K **(see equation 8)**. Any unexpected change in the values of the coefficients of the K matrix indicates the presence of damage. In practice we only need to look at the values of the diagonal elements of the K matrix, since these are most affected by changes to stiffness of the elements. For illustration, Figure 3(a) shows a plot of the translational diagonal coefficients K_{ii} (i=1,3,5,..) of the full stiffness matrix K identified using ERA from the impulse response of an isotropic cantilever beam with a simulated delamination in the mid-plane in two elements (Element nos. 20 and 21). In a pristine cantilever beam model all the odd diagonal values of the stiffness coefficient will be the same ($=24EI/l^3$), except for the last one, which will be half this value, as it will only contain the translational bending stiffness coefficient of the last element. As seen in Figure 3(a), the translational diagonal values exhibit a drastic reduction at the three nodes associated with the damaged elements (Nodes 19, 20 and 21), which indicates the presence of damage. However the reduced K_{ii} values at these nodes do not directly yield the bending stiffness values of the damaged elements, due to the superposition of the contribution of the bending stiffnesses from elements on either side to the reduction in the K_{ii} value at each node. Thus it is not easy to gauge the severity of the damage directly from the K values of the identified system. Figure 3(b) shows the plot of the element bending stiffness values against element number. It is immediately evident from the figure that element numbers 20 and 21 have damage. It can also be seen that the EI values in these elements have dropped to about 25% of the bending stiffness of the undamaged elements, which is to be expected for a mid-plane delamination in an isotropic beam.



(a) (b)

Figure 3: System parameters of delaminated isotropic beam (a) Translational Diagonal Stiffness coefficient Kii (b) Element bending stiffness EI

As mentioned earlier, in reality we cannot identify the full system matrix A, as it is not straight forward to measure the rotations of the beam at its nodes. We can therefore use only the out of plane displacement response of the structure to identify the system, which will give us only the reduced system matrix A* (as given by equation (9)). Figure 4 shows a plot of the values the diagonal values of the reduced system matrix K* obtained from the identified system matrix A* for the same beam. The diagonal values of the K* values show more variation at the nodes in the vicinity at either end of the beam and in the vicinity of the damage. It is not easy to identify the damaged elements or estimate the severity of the damage from the values of reduced stiffness matrix K* We have therefore developed a methodology to estimate the diagonal elements of the full stiffness matrix K from the diagonal elements of the reduced system matrix K* using an iterative procedure to solve equation (8) in reverse starting with initial guess values and iterating until convergence is obtained. Using this methodology we can estimate the diagonal values of the full stiffness matrix K of the system, from which we can estimate the bending stiffnesses EI of the elements of the beam. This methodology is adopted in the current study identify the exact location (elements) which are damaged and the severity of the damage in terms of the reduction in bending stiffness. The proposed damage identification methodology is validated using numerical test cases and finite element modelling in the following sections.

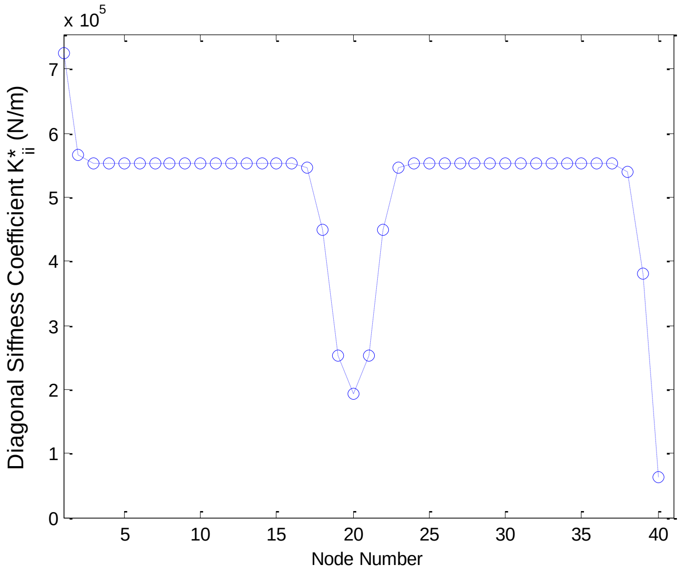


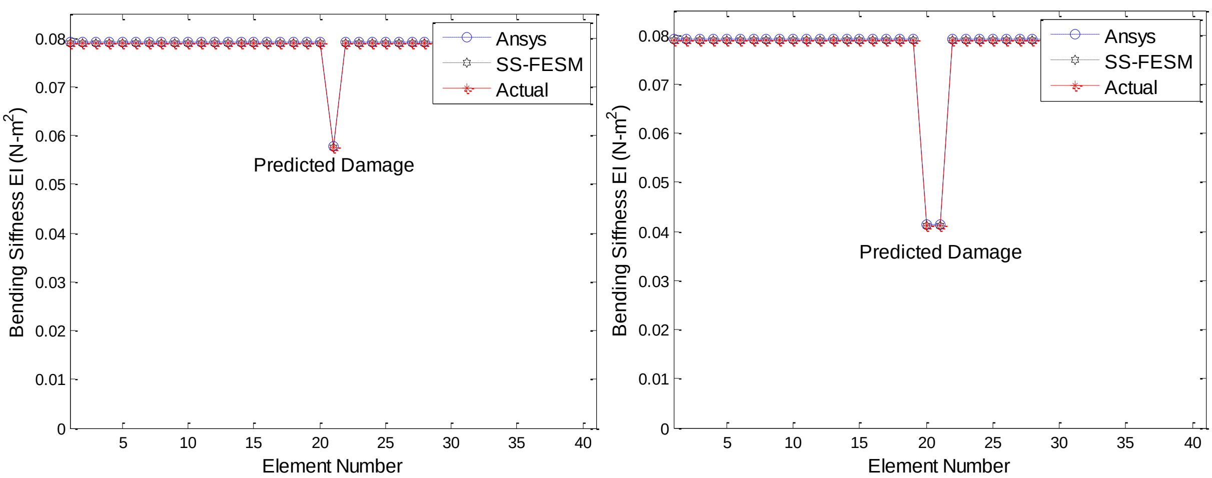
Figure 4: Diagonal Stiffness coefficients K^*_{ii} from the reduced Stiffness matrix identified with ERA

4. Application to beams with delaminations

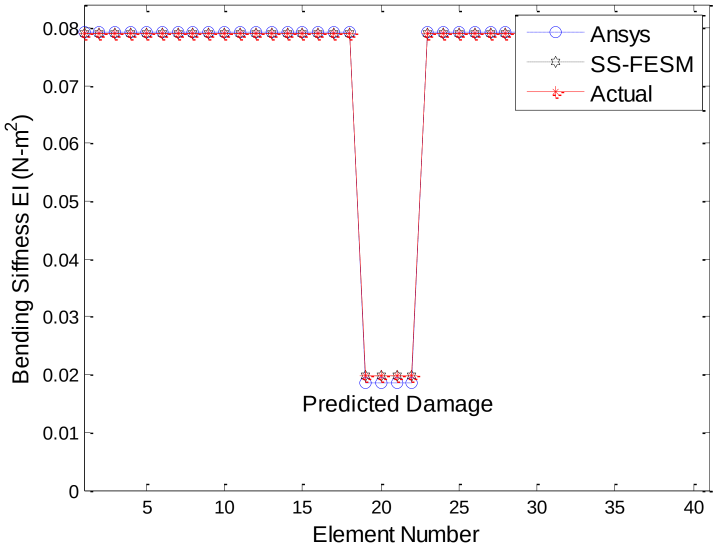
The damage assessment methodology described in section 3 using the ERA system identification technique is applied here to beams with simulated delaminations. In the first instance the method is applied to an isotropic beam with delaminations of different lengths at different through thickness locations to check the validity and accuracy of the damage assessment algorithm. The methodology is then applied to a laminated composite beam with simulated delaminations of different sizes at different locations at different interfaces.

4.1 Validation using Isotropic beams with delamination

A cantilever beam with properties of aluminium alloy (Young's Modulus 72.8GPa, Poisson's ratio 0.33 and density 2780kg/m^3) of length 508mm, width 25.4mm and thickness 1mm, was modelled using 40 elements (each element having a length of 12.7 mm) with the State-Space Finite Element System Model (SS-FESM) described in section 2.2 to generate the dynamic response under an impulse load. Three different scenarios of damage in the form of delaminations with different lengths at different through thickness locations were investigated. The actual interface locations (t_1/t) and the elements in which the delaminations were modelled are shown in Columns 2 and 3 in Table 1. The same beams were also modelled using the finite element software ANSYS using element Beam 3 (one dimensional 2-node line element with six degrees of freedom at each node), in which the dynamic analysis was performed to generate the dynamic response for a known impulse load. To model the delaminated sections using the one dimensional beam elements, the value of the Young's Modulus of these elements were proportionally reduced so as to yield the same effective bending stiffness EI for the delaminated sections as calculated from theory. The translational responses (out of plane displacements in the time domain) from the SS-FESM and the ANSYS models were input into the ERA based system identification algorithm to extract the reduced system matrix A* from which the bending stiffness EI values were estimated for all the elements, as outlined in section 3. Figures 5(a), 5(b) and 5(c) respectively show the plots of the bending stiffness values EI calculated from the diagonal coefficients of the reduced stiffness matrix K* obtained from the reduced system matrix A* identified by ERA from the responses from the SS-FESM and ANSYS models. The actual values of the bending stffinesses input into these models are also plotted for comparison. It can be seen that the agreement in the bending stiffness values of the undamaged as well as the delaminated segments between those estimated from the SS-FESM and the ANSYS response and the actual values are very good. Still, there are some small discrepancies when the actual figures are compared, as can be seen from the values of normalised bending stiffness values (ratio of bending stiffness of delaminated element to the bending stiffness of the undamaged elements) listed in the last two columns of Table 1. However the discrepancy between the identified reductions and the actual normalised EI values is less than 0.1% except the test case ISO-3.



(a) (b)



(c)

Figure: 5. Results of Damage Identification in Isotropic Beams with delamination
(a) ISO-1 (b) ISO-2 (c) ISO-3

Table 1: Results of Damage Identification in Isotropic Beams with Delaminations

Test Case	Interface Location of delamination t1/t	Element numbers with delamination modelled	Elements in which delamination was detected	$\frac{EI_{delam}}{EI_{undam}}$ Actual	$\frac{EI_{delam}}{EI_{undam}}$ from SS-FESM response	$\frac{EI_{delam}}{EI_{undam}}$ from ANSYS response
Iso-1	0.125	El 21	El 21	0.672	0.672	0.6774
Iso-2	0.25	El 20, 21	El 20, 21	0.4375	0.4375	0.4414
Iso-3	0.50	El 19, 20, 21, 22	El 19, 20, 21, 22	0.25	0.25	0.24

4.2 Application to damage assessment in composite beams

An 8 layer quasi-isotropic composite beam with a lay-up of $[0/45/-45/90]_s$ and the material properties of Carbon Fibre Reinforced Plastic (CFRP) (E_{11} = 137.45 GPa, E_{22} = 11.71 GPa, G_{12} = 5.2 GPa, ν_{12}= 0.32, density 1371.5 Kg/m^3) was modelled as a cantilever in ANSYS using one dimensional Beam 3 elements. The length of the beam is 200mm, width 20mm and the ply thickness 0.125mm. A total of 80 elements were employed along the length of the beam. Once again, the delaminated sections were modelled by setting the value of the Young's Modulus of the beam elements in these sections to an appropriate value so as to yield the same effective axial bending stiffness EI for the delaminated sections as calculated from theory. The dynamic response at the 80 nodes along the length of the beam subjected to an impulse load was generated with transient dynamic analysis in ANSYS and input into the ERA based system identification algorithm from which the reduced system matrix A*, and thereby the reduced stiffness matrix K* were identified. The effective bending stiffnesses of the elements of the beam were then evaluated using the iterative procedure described in section 3.

Three different damage scenarios in the composite beam were investigated as illustrated in Figures 6, 7 and 8. In the first scenario, test case 1, mid-plane delaminations were simulated at four locations along the beam, each one extending over two adjacent elements as shown in Figure 6. In the second scenario, a delamination extending over two elements (Element nos. 31 and 32) was simulated at the mid-plane in four different test cases: at interface 1 (the outermost interface) in Case 2a, at the next topmost interface (interface 2) in Case 2b, at the second innermost interface (interface 3) in Case 2c, and at the mid-plane (interface 4) in Case 2d. These are illustrated schematically in Figure 7. The third damage scenario, Test case 3, investigates delaminations of different lengths at the mid-plane: Case 3a has a delamination in only one element (Figure 8(a)), Case 3b has delamination one extending over 3 elements (Figure 8(b)) and Case 3c has delamination extending over 4 elements (Figure 8(c)) The actual interface locations of the delaminations and the thickness ratio of the upper sub-laminate (t_1/t) in these test cases are listed in Columns 2 and 3 in Table 2.

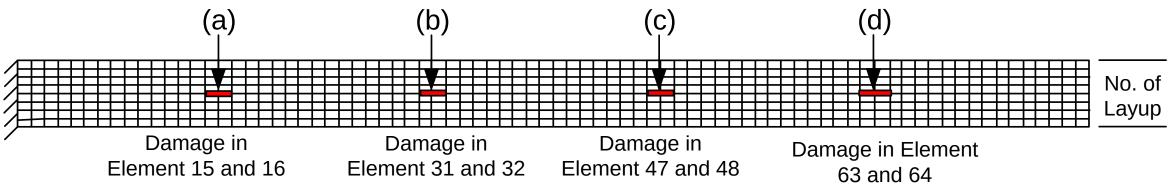


Figure 6: Damage Case 1 delaminations in quasi-isotropic composite beam at (a) location 1 (b) location 2 (c) location 3 and (d) location 4.

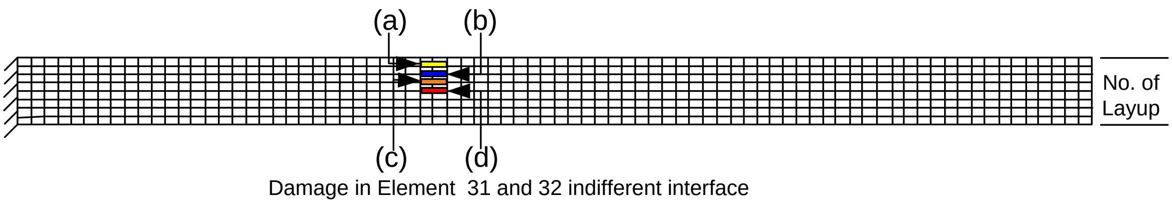


Figure 7: Damage Case 2 delaminations in quasi-isotropic composite beam at (a) interface 1 (b) interface 2 (c) interface 3 and (d) interface 4.

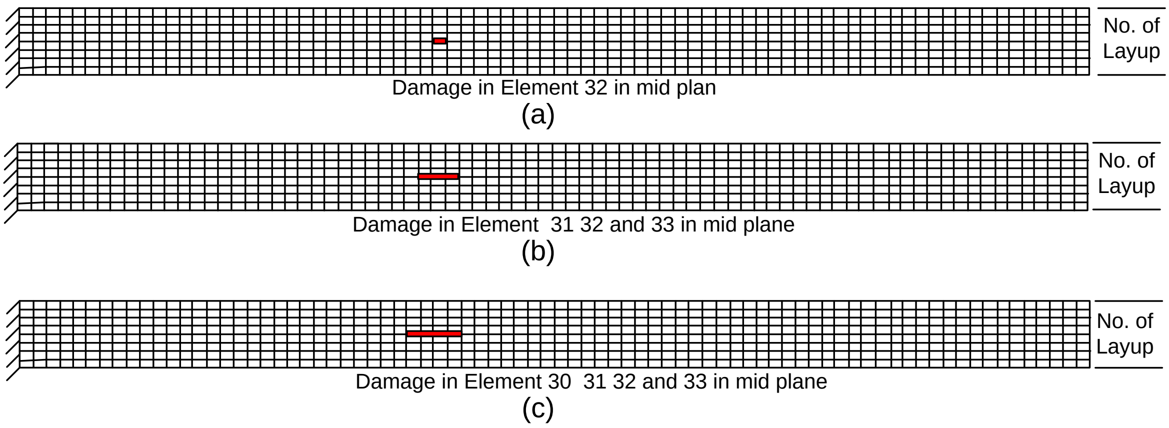


Figure 8: Damage case 3 in quasi-isotropic composite beam (a) mid-plane delamination over 1 element, (b) mid-plane delamination over 3 elements, and (c) mid-plane delamination in 4 elements.

The results of damage assessment in the composite beam using the ERA based algorithm, in terms of the estimated bending stiffness values at all elements along the length of the beam are shown in Figures 9(a), 9(b) and 9(c). Figure 9(a) shows the results of first damage case scenario, having five mid-plane delaminations at five different axial locations. Figure 9(b) shows the bending stiffness EI values evaluated using ERA in the second damage scenario, with delaminations in successive interfaces from the mid-plane to the outermost. It is to be noted that each analysis contained delamination only at one interface, although the results are showed simultaneously in Figure 9(b). Figure 9(c) shows the bending stiffness EI values obtained by ERA system identification plotted against element number for the three cases of mid-plane delaminations extending over 4 elements, 3 elements and one element. It is evident that in all cases shown in Figure 9(a), (b) and (c), the proposed damage identification algorithm has correctly identified the number of damaged elements (NDE) those have the delamination. The values of the bending stiffness estimated after system identification by the ERA algorithm in the above cases are tabulated along with the actual bending stiffness values used as input into the finite element software in Table 2. The bending stiffness values in the table are normalised with respect to the bending stiffness of the undamaged composite beam. It can be seen from the figures that the discrepancy between the estimated values of the reduced stiffnesses in the delaminated elements and the actual values are small (1% or less in all cases except the case 3a which has discrepancy of 2.3%) proving that the proposed ERA based damage assessment technique can successfully estimate the location, size and severity of delaminations in composite beam with more than **97%** accuracy.

Table 2: Results of Damage Identification in Delaminated Composite Beams

Composite Test Case	*Interface	t1/t	$\frac{EI_{delam}}{EI_{undam}}$ Actual	$\frac{EI_{delam}}{EI_{undam}}$ estimated by ERA
Case 1	Interface 4	0.5	0.1010	0.0998
Case 2a	Interface 1	0.125	0.3426	0.3419
Case 2b	Interface 2	0.25	0.1723	0.1715
Case 2c	Interface 3	0.375	0.1088	0.1077
Case 2d	Interface 4	0.5	0.1010	0.0998
Case 3a	Interface 4	0.5	0.1010	0.0986
Case 3b	Interface 4	0.5	0.1010	0.1007
Case 3c	Interface 4	0.5	0.1010	0.1010

*Note: Interface 1 is outermost and interface 4 is mid-plane

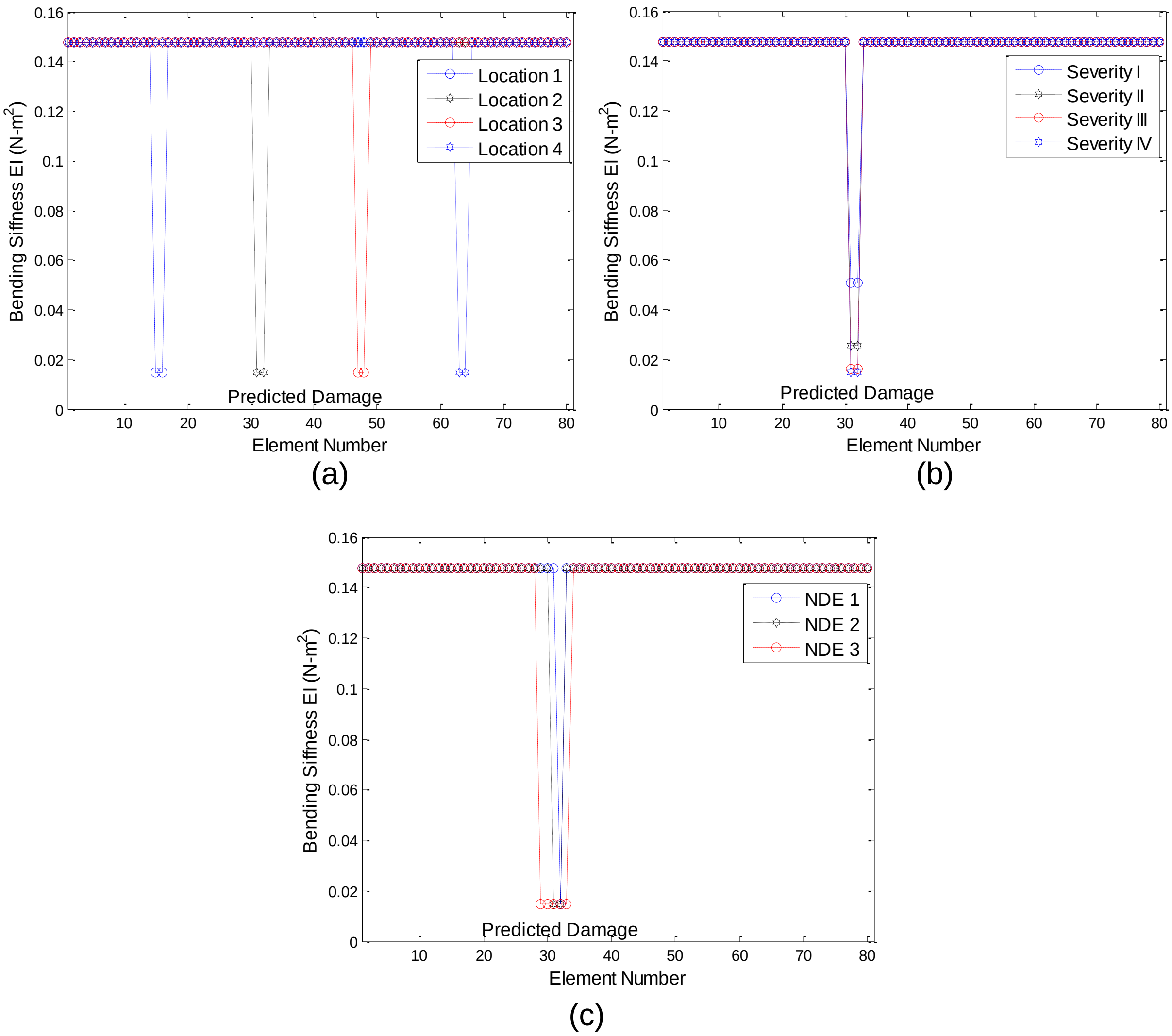


Figure 9: Different sizes, location and severities Damaged in Composite laminates

5. Conclusion

A system identification technique using ERA has been proposed for damage detection and assessment of delaminations in composite beams from the time domain dynamic response of the structure under impulse loading. A methodology has been developed to estimate the severity of the damage in terms of its reduced bending stiffness from the system matrix identified using ERA. The validity and accuracy of the method were first assessed using test cases of isotropic beams with delaminations, whose response was simulated using SS-FESM and transient finite element method. The proposed methodology was then applied to damage assessment in numerical test cases of quasi-isotropic composite beams with delaminations of different sizes and located at various axial and interface positions. In every case the proposed damage assessment technique was able to assess the size and location of the delamination accurately and the reduction in the bending stiffness of the delaminated elements with over **97%** accuracy.

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