

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

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Vol. 8, Issue 10, October 2019

Damage Detection in Composite Plates Using Dynamic Response

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ABSTRACT: Damage in engineering structures has been of concern to the engineering community for many years. The ability to detect and monitor damage using non-destructive testing in structures and mechanical components becomes very important. Many damage identification techniques have been proposed relying on vibration testing. Vibration-based damage identification techniques rely on the fact that existence of a localized damage in a structure affects the global structural dynamic behavior. In the literature, one of the promising techniques rely on combining a finite element model of the undamaged structure with a set of experimentally-measured frequency response functions (FRF) of the structure under investigation to construct a so-called Damage Location Vector (DLV). This paper aims to assess both theoretically and experimentally damage detection using DLVs. The method is first studied theoretically on a composite plate using simulated damage. Then, it is tested experimentally using free-free and fixed-free boundary condition for a plate with middle damage using shaker test. The method is improved through the use of FRFs of the undamaged structure obtained both numerically and experimentally in an attempt to overcome difficulties imposed by initial damage and noise. Finally, a case study has been done to assess the DLV technique on composite plates.

KEYWORDS: Composite structure, Damage location vector, Finite element model and Frequency response function.

I. INTRODUCTION

Since 1990s, Structural damage detection using non-destructive (NDT) vibration tests has received considerable attention [1–7]. Damage usually changes the mass, stiffness and damping properties of the structure. The Change cause changes in the dynamic properties such as, the mode shapes, natural frequencies and damping loss factors. By correlating dynamic response data of a structure before and after damage it enables detection of structural damage location. It is easy to note that any structural damage causes appreciable loss of material can be noted. The most forms of structural damage do not have observable loss of materials but have macro or micro cracks or fracture. Therefore, it is assume that the mass is constant which means that the mass matrix unchanged and only the stiffness matrix is subjected to change due to damage. Huynh, et al. [8] presented structural damage detection using frequency response functions (FRF) obtained from non-destructive vibration tests. They investigated the case of early structural damage assuming no appreciable change in mass and damping. The resulting change in structural stiffness matrix is reflected in changes of frequency response spectrum which can be exemplified by calculating damage location vector (DLV). H.Monajemi, et al. [9] presented that by extracting a set of load vectors from flexibility shifts that cause the same deformation in damaged and undamaged structures it is obtained the meaning of the damage location vector (DLV). By studying the characterizing stresses of all members the damaged member can be located. By studying the characterizing stresses of all member the damaged member can be located. Yang, and Sun, [10] found that the structural

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damagedetection using vibration-based methods can be described into two categories: (model and non-model) based approaches. The vibration modal parameters (mode shapes, frequencies, and modal damping) are roles of physical properties of the structure. Damping, mass and stiffness can be obtained by the modal identification procedure; this explains the model-based approaches. S.W.Doebling, and et al. [11] pointed out that the damage can be determined by changes in the dynamic properties or response of structures. The modal parameters are roles of the physical properties of the structure. The changes in the physical properties cause changes in the modal properties. Kayed et al. [12] applied the damage location vector to a real structure using experimental FRFs obtained from non-destructive vibration tests. They improved the method the use of FRFs of the intact structure obtained both numerically and experimentally. Lee and chung [13] presented a method of determining the structural damage size and location using natural frequencies and an appropriate FEM model. Kim et al. [14] proposed a method to locate and quantify a crack in beam structure which named single damage indicator (SDI). This technique depended on using changes in few natural frequencies. By relating fractional changes in modal energy to changes in natural frequencies due to damage, a crack location model and a crack size model were formulated. This has prompted research into the use of heuristic search algorithms in conjunction with numerical models that simulate the structural dynamics to seek the damage scenarios that are associated with a certain change in number of natural frequencies [15]. Agarwalla and Parh [16] pointed out that the dynamic behavior of a whole structure changed by the presence of the crack. The cracks in the structure change the frequencies, amplitudes of free vibration and dynamic stability areas to an inevitable result. They studied the effect of an open crack on the modal parameters of the cantilever beam subjected to free vibration. Hassiotis [17] extended the method to include detection in a large number of damaged elements, by using a new optimization procedure based on Markov parameters. Maitithy and Tribathy [18] used genetic algorithm (GA) to detection and estimate the structural damage from changes in natural frequencies. Pawar and Ganguli [19] detected the matrix crack in thin-walled composite structures based on changes in natural frequencies by used the genetic fuzzy system. Pérez et al [20] showed the results of an extensive experimental campaign conducted to investigate the feasibility of using vibration methods to recognized damages sustained by composite laminates due to low-velocity impact, present work is to investigate the damage detection in laminated composite plate using damage location vector (DLV) techniques. The method is first studied numerically on a composite plate using simulated damage. Then, it is tested experimentally using free-free and fixed-free boundary condition for a plate with damage using mechanical exciter test. The method is improved by using of FRFs of the undamaged structure obtained both numerically and experimentally in a trial to defeat difficulties imposed by initial crack and noise. Finally, a case study has been done to assess the DLV technique on composite plates.

II. GEOMETRY AND MATERIAL

The laminated composite plate used in this investigation of dimensions (150 × 150 × 5) mm as shown in Fig. 1. It is formed from ten layers in which the base material (polyester) is the same while the fibers (E-glass) have different orientation in each layer with the same thickness. Five specimens of composite square plates where manufactures with the following fiber orientation [0/0/0/0/0/0/0/0/0/0], [0/30/0/30/0/30/0/30/0/30], [0/45/0/45/0/45/0/45/0/45], [0/60/0/60/0/60/0/60/0/60] and [0/90/0/90/0/90/0/90/0/90] where the various lamina orientation angles refer to the fiber orientation in the layer thickness 0.5mm from the symmetric specimen. Table 1 shows the specification of fiber and matrix material used in composite plate. The glass fiber is E-glass fibers (SIR Company, KSA). The theoretical mechanical properties are determined using mixture rule. They have been obtained experimentally. The results are shown (in Table 2). The polyester resin and hardener types used in this study were of (SIROPOLE-7440) and (MEKP), respectively.

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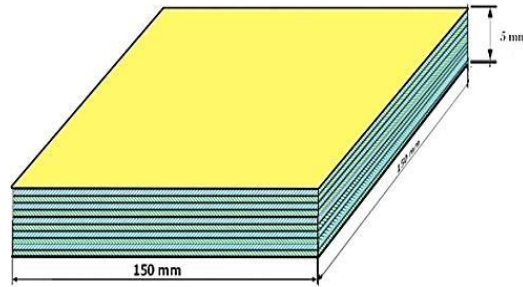


Fig. 1 Laminated composite plate.

TABLE 1 SPECIFICATION OF FIBRE AND MATRIX USED IN PRESENT STUDY.

Property type	Elastic modulus (GPa)	Poisson ratio ν	Tensile strength (MPa)	Density (g/cm ³)
E-Glass	72.52	0.33	3448	2.56
Polyester	3.5	0.2	34.5-102.5	1.2

TABLE 2 MECHANICAL PROPERTIES OF THE COMPOSITE PLATE.

Properties	Experimental	Mixture rule
Longitudinal modulus E_{11} (GPa)	44.4	44.88
Transverse modulus E_{22} (GPa)	8.6	8.85
Shear modulus G_{12} (GPa)	4.085	4.057
Poisson's ratio ν_{12}	0.3	0.303
Volume fraction ν_f	0.50	—
Longitudinal strength X^L (MPa)	618.9	—
Transverse strength X^T (MPa)	14	—
Shear strength τ_o (MPa)	28	—

III. MODAL ANALYSIS USING FINITE ELEMENT METHOD

A typical laminated composite plate of dimensions (150×150×5)mm with ten symmetric layer, are modeled using the finite element method (F.E.M) with four nodes plate element, each node has three degree of freedom: lateral displacement and rotation about x and y axes. A mesh of (10 × 10) elements, four node brick elements, is utilized in the analysis and F.E model shown in Fig. 2.

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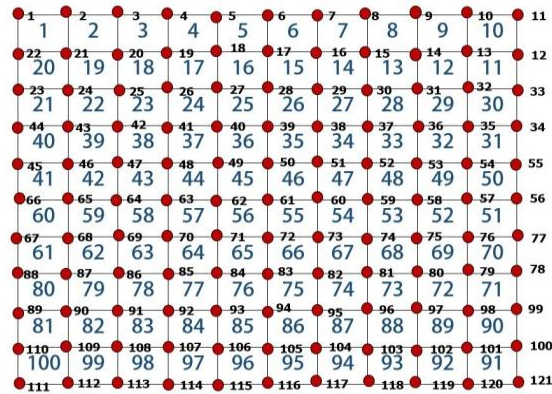


Fig.2 Finite element model of free-free composite laminate plate

The stiffness matrix of the element can be then formulated as:

$$[K_e] = \int_0^b \int_0^a [S]^T [D] [S] dx dy (1)$$

Where, [S] is the strain matrix and [D] is the elasticity matrix of the composite plate, *a* and *b* are the length and width of plate element respectively, which can be computed according to “Ref. [22]”.

Consequently, the mass matrix of element can be formulated as $[M_e]$:

$$[M_e] = \rho_c t \int_0^b \int_0^a \{N\}^T \{N\} dx dy (2)$$

Where, ρ_c is the density of the equivalent laminated composite plate and $\{N\}$ is the matrix of shape function.

The Eigen-frequency can be then evaluated from the solution of the characteristic equation for composite plate

The initially, the plates were modeled in order to get a first estimation of the un-damped natural frequencies and mode shapes utilizing finite element type solid65.

The material properties were then entered in the program, and the constraint imposed to simulate a type of fixation. The numerical results using F.E.M were computed for five specimen types and boundary fixations.

IV. THEORY OF STRUCTURAL DAMAGE DETECTION BY DAMAGE LOCATION VECTOR (DLV)

The main idea of damage location vector theory is to find load cases that give symmetrical zero strain field over the damaged elements in both states damaged and undamaged. These vectors can be shown to be included in the null space of the difference in flexibility matrix from damaged to undamaged condition, which is found by applying a singular value decomposition (SVD) analysis of the matrix. The identified vectors are then applied on the undamaged model of the structure and noted the stress in the members. To obtain Weighted Stress Index the stress were normalized by a series of operations. If the Weighted Stress Index is lower than one for a member, indicates that the member is probably damaged.

The damage location vector is usable for both determinate and indeterminate structures. Data from the damaged portion is not required for detection of the damage in indeterminate structures. While for determinate structures, since no force redistribution happen, it requires the information from damaged portion also [23]. Since most structures are indeterminate, this method is suited for most practical applications [24]. The mechanical and damage parameters of composite laminates plates identification was developed in [25]. we can represent the equation of motion of a multi-degree of freedom (MDOF) structure as:

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$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\} \quad (3)$$

Where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrix respectively. $\{x\}$ is the nodal displacement vector and $\{F\}$ is the nodal force vector.

For a laminated composite plate with and without damage, of negligible damping, the spatial model of the plate needs to consist only of $[K]$ and $[M]$. The assumption of negligible damping is justified for the case of homogeneous metallic structures, the equation of motion in the case of free vibration then becomes:

$$[M]_{UD}\{\ddot{x}\} + [K]_{UD}\{x\} = 0 \quad (4)$$

$$[M]_D\{\ddot{x}\} + [K]_D\{x\} = 0 \quad (5)$$

The subscripts UD , D are used to indicate the undamaged and damaged structure respectively. Damage will be considered to result in a reduction in stiffness only, hence $[M]_{UD} = [M]_D$.

Let $[Z(\Omega)]$ be the dynamic stiffness matrix,

$[\alpha(\Omega)]$ be the receptance frequency response function (RFRF) matrix at a particular frequency Ω and the k^{th} column of this matrix be denoted by $\{\alpha(\Omega)\}_k$, where:

$$[Z(\Omega)] = [k - \Omega^2[M]] \text{ and } [\alpha(\Omega)] = [[K] - \Omega^2[M]]^{-1}$$

Then it follows from the orthogonality of the dynamic stiffness matrix:

$$[Z(\Omega)]_{UD} \{\alpha_{UD}(\Omega)\}_k = \{\delta\}_k = [Z(\Omega)]_D \{\alpha_D(\Omega)\}_k \quad (6)$$

Where $\{\delta\}_k$ is a vector, the elements of which are zero except the k^{th} element which is equal to 1.

The dynamic stiffness matrix before and after damage can be related as follows:

$$[Z(\Omega)]_D = [Z(\Omega)]_{UD} - [\Delta Z(\Omega)] \quad (7)$$

Where $[\Delta Z(X)]$ represents the difference in dynamic stiffness matrix between the damaged and undamaged structure.

“(6)” can be rewritten as:

$$[Z(\Omega)]_{UD} (\{\alpha_D(\Omega)\}_k - \{\alpha_{UD}(\Omega)\}_k) = [\Delta Z(\Omega)] \{\alpha_D(\Omega)\}_k \quad (8)$$

$$\{d(\Omega)\} = [\Delta Z(\Omega)] \{\alpha_D(\Omega)\}_k \quad (9)$$

And let $\{\Delta\alpha(\Omega)\}_k = (\{\alpha_D(\Omega)\}_k - \{\alpha_{UD}(\Omega)\}_k)$ be the difference of the k^{th} column vectors of the response frequency function matrix of the damaged structure and undamaged or virgin structure, then Eq. (8) can be rewritten as:

$$\{d(\Omega)\} = [Z(\Omega)]_{UD} \{\Delta\alpha(\Omega)\}_k \quad (10)$$

From “(9)” It can be seen that the j^{th} element of $\{d(X)\}$ would be non-zero if the j th row of $[DZ(X)]$ is non-zero as a consequence caused by structural damage. A non-zero element of DLV refers to the DOF associated with damage and a zero value would point to no associated damage. DLV reflects the change in the response brought about by structural damage, it also points to the $DOFs$ that have been affected by the damage that's why the name damage location vector. DLV can be evaluated by “(10)”. This offers a choice to examine damage at different frequencies.

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In summary *DLV* requires:

- The structure when it is free of damage can be described by a spatial model in the form of mass matrix $[M]$ and stiffness matrix $[K]$. These matrices are usually provided by an *FEM* model of the undamaged structure.
- A column of measured FRF data from vibration test denoted as $\{\alpha_D(\Omega)\}^R$.

Here "R" stands for reduced since the measured *FRF* data in the vector $\{\alpha_D(\Omega)\}^R$ would come from a delimited number of *DOFs* which are merely a subset of the *DOFs* used by the *FEM* model. Some mathematical techniques have been used to expand the *DOF* of the experimental model to reconcile with the *DOF* of the *FEM* model to overcome this incompatibility. This technique is called Dynamic Expansion Method *a* [9] as described here: first the full set of *DOFs* is partitioned into the measured (master *DOFs*) and the unmeasured (slave *DOFs*). The slave *DOFs* are mostly rotational *DOFs* but can be linear *DOFs* which may not be suitable measured due to some reasons, for example inaccessibility. The structural stiffness and mass matrices $[K]$ and $[M]$ are then partitioned accordingly to K_{mm} , K_{ms} , K_{sm} , K_{ss} and M_{mm} , M_{ms} , M_{sm} , M_{ss} , in a similar fashion as carried out in Guyana reduction technique of *FEM*, where subscript m stands for master *DOF* and s for slave *DOF*.

The unmeasured set of *FRF* is obtained from the following formula:

$$\{\Delta\alpha_s\}_k = -\{[K_{ss}] - \omega^2[M_{ss}]\}^{-1}\{[K_{sm}] - \omega^2[M_{sm}]\} \times \{\Delta\alpha_m\} \quad (11)$$

To obtain a comparable complete set this set is then adjoined to the measured set, that's why the term "Dynamic Expansion". The partitioning of matrices are needed for dynamic expansion, but also the location of damage requires easy identification of elements by relating *DOF* to elements, thus the algorithm requires reordering of *DOF* forward and backward.

In this paper it is aimed to achieve the evaluation of *DLV* over a range of frequency, and plotting *DLV* in a three-dimensional plot, in which the first axis represents frequency values corresponding to the frequency range over which the damage location algorithm is applied to, the second axis is the numbered *DOFs* of the structure and the third axis represents the absolute value of the of elements of *DLV*, each corresponds to one *DOF*. This three-dimensional plot is called Damage Location Vector Plot (*DLVP*).

“(10)And(11)” involve considerable computing and the algorithm is best handled by utilized *MATLAB* software (R2013).

There is another way to show damage by compressing the data into a two-dimensional plot by adding data corresponding to a particular *DOF* at all frequencies together, that is the first axis is still the numbered *DOFs*, the second axis is the values of *DLV* obtained at all frequency sampling points added together to indicate cumulative damage over the frequency range. This two-dimensional plot is called cumulative damage location plot (*CDLP*).

DLV is now applied to a plate structure. First the damage and noise are simulated in a plate structure to analyze the performance of *DLV*, second damage is physically introduced in a cantilever plate, and finally *FRF* data are measured and used in *DLV* to detect damage.

V. CASE STUDY OF DAMAGE DETECTED IN LAMINATED COMPOSITE PLATE STRUCTURE

A three-dimensional of finite element model can be used to calculate the stiffness and mass matrices of laminated composite plate .The application of *DLV* to a composite plate structure using numerically simulated damage and noise has been presented inReference.[10]. In the present analysis, damage is physically induced into the plate and actual frequency response function measurements with real noise and coordinate incompatibility are employed in the assessment of damage detection by *DLV*.

V. I. MASS AND STIFFNESS MATRICES OF PLATE ELEMENT

The composite plate use in the present analysis is a square of $150*150mm$, and $5 mm$ thick. The mechanical properties are computed and presented in Table 2. The plate is fixed in one edge and free in the other edges as shown in Fig.3. A mesh of 100 elements, each of $15mm$ square was used. It was shown that the element of four *DOFs* per node is

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adequate for *DLV*. The structural mass and stiffness matrices of the plate structure using finite element models were assembled using an algorithm written in MATLAB, readily available for further mathematical manipulations required by damage location vector. The *FEM* model of the plate is shown in Fig. 3.

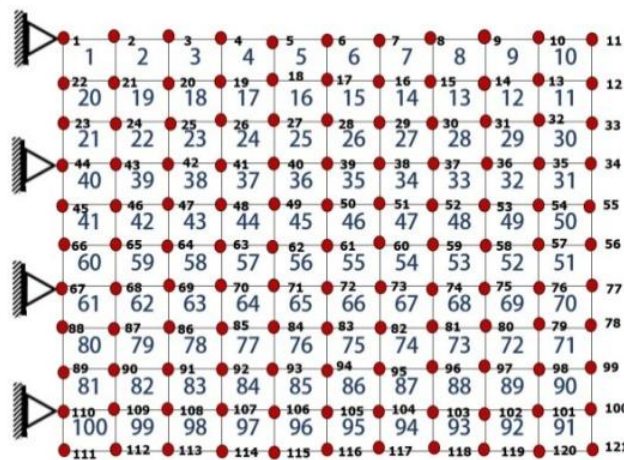


Fig.3 Finite element model of the fixed-free composite laminate plate

V.II. DAMAGE LOCATION VECTOR USING EXPERIMENTAL FRF FROM VIBRATION TESTS

The test specimens are manufactured in the form of laminated composite plate with dimensions 150×150×5 mm. five types of specimens with various fiber orientations are manufactured using the hand layout technique. The mechanical properties of fiber and polyester (matrix) are listed in Table 1. The fiber volume fraction is 0.50%. The orientation of the ten plies are $[0/0/0/0/0/0/0/0/0/0]$, $[0/30/0/30/0/30/0/30/0/30]$, $[0/45/0/45/0/45/0/45/0/45]$, $[0/60/0/60/0/60/0/60/0/60]$ and $[0/90/0/90/0/90/0/90/0/90]$ with 0.5 mm thickness of each ply. Vibration tests were investigated on five laminated composite plates' specimens of the same dimensions as the finite element model. Damage was induced in each case using diamond saw cuts into the plates. Two cases were studied; case *A* without damage in plate as shown in Fig. 2 and Case *B* where damage is applied in elements 44, 45, 46, 47, 54, 55, 56, 57 in the central as shown in Fig. 4.

In the cantilever and free-free boundary conditions, a combination of both cases (A and B). The plates were tested using B&K shaker with vibration exciter type (4828) to obtain FRF curves. Also Frequency Spectrum Analyzer type (3160-A-042) was used. In these tests, a B&K (4507B) accelerometer sensor was mounted on the plate at the fixed point to measure the response of the plate. Make excitation of the plate at all nodes in turn. At each node we have recorded the average of five readings. Also, the PULSE Lab Shop v.15. 1. Software is utilized for the data processing as shown in Fig.5.

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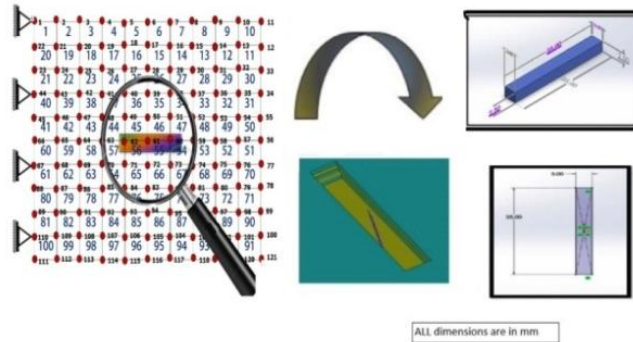


Fig.4 the composite plate with damage applied in elements.

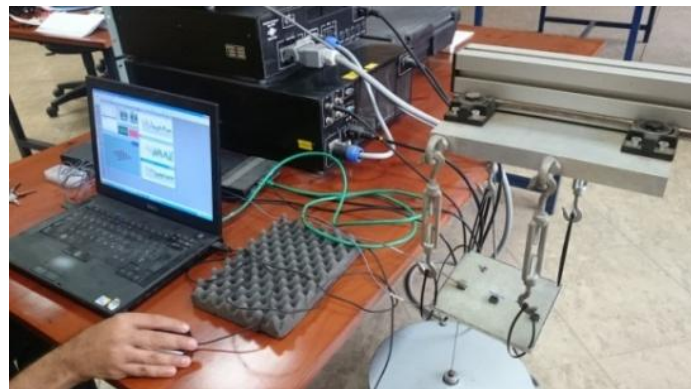


Fig.5.Modal test for composite plates

A typical experimental set up of the system is shown in Fig. 6.

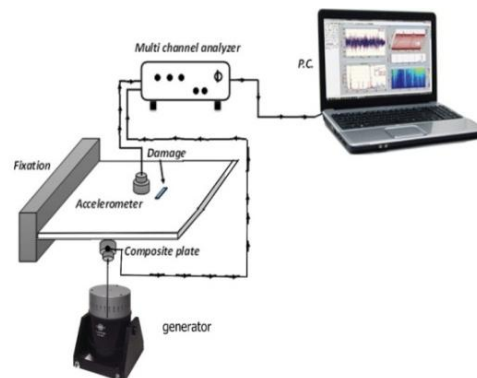


Fig.6 Experimental apparatus set up for vibration testing for composite plate specimen.

In the tests, the specimens were fixed in the test rig such that one edge is fixed and the others are free. The depth and location of crack were checked directly by measurement at each test. Fig.7 shows the frequency response function recorded in specimen [0/90/0/90/0/90/0/90/0/900] orientations at case A and B.

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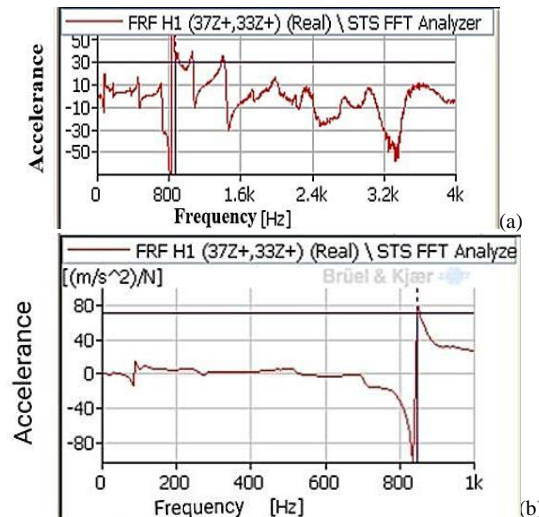


Fig.7 Frequency response spectrum for FFT analyzer at (a) undamaged and (b) damaged.

V.II. I. EXPERIMENTAL STUDY OF (CASE A) INTACT STRUCTURE

The undamaged structure was tested first in order to study the effect of real noise on the DLV algorithm. The experimental frequency response function data are fed into the DLV algorithm which shows a zero DLV.

The corresponding cumulative damage location plot is shown in Fig. 8, which depicts that the effect of noise is widely but randomly distributed over the frequency range and DOFs. From this CDLP, the maximum magnitude of elements of DLV is indicated in Fig. 8.

V.II.II. EXPERIMENTAL STUDY OF DAMAGE STSTE (CASE B)

As stated above, the damage case B is called the central damage was introduced through a surface by saw cut in elements 44,45,46,47,54,55,56 and 57 as shown in Fig. 9. Damage location vector technique was used to experimental FRF data, from which the CDLP is obtained as shown in Fig. 10. Consider the specimen $[0/0/0/0/0/0/0/0^0]$, the CDLP shows six prominent peaks associated with DOFs 93,102,105, 107,108.and 110 pointing to nodes 49, 61, 71, 74, 75 and 82, which correctly identified elements 44,45,46,47,54,55,56 and 57 as containing the damage. There are also nine peaks of less prominence which point to nodes 51, 59, 62, 86, 71, 72, 63, 70, and 50 as shown in Fig.10. It can be noted that these nodes (60, 61, and 62) are in the instant neighborhood of previous elements, indication that these neighboring nodes are affected by damage also, albeit the effect is of order of 20% of that inflicted on nodes that constitute the damaged element; and that the effect decays very quickly with distance from the damage.

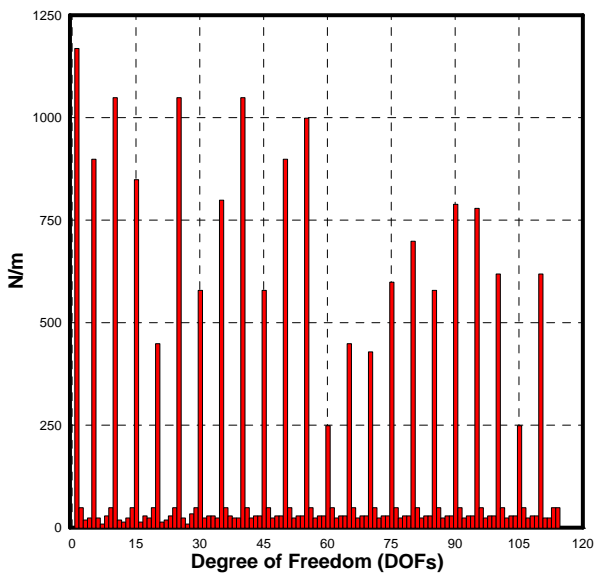
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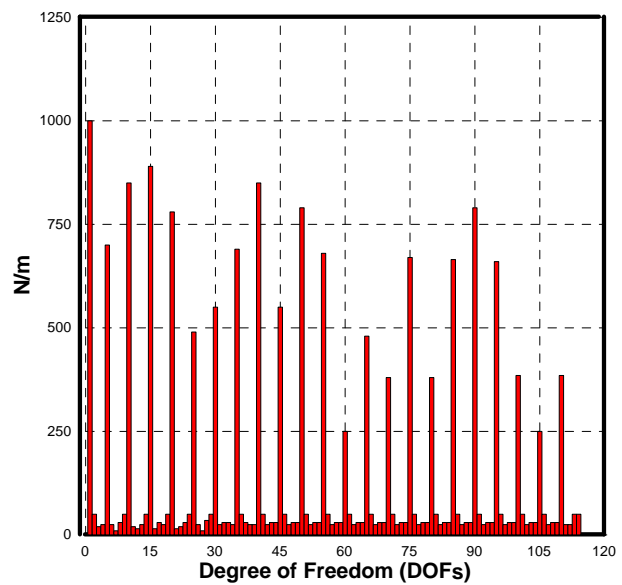
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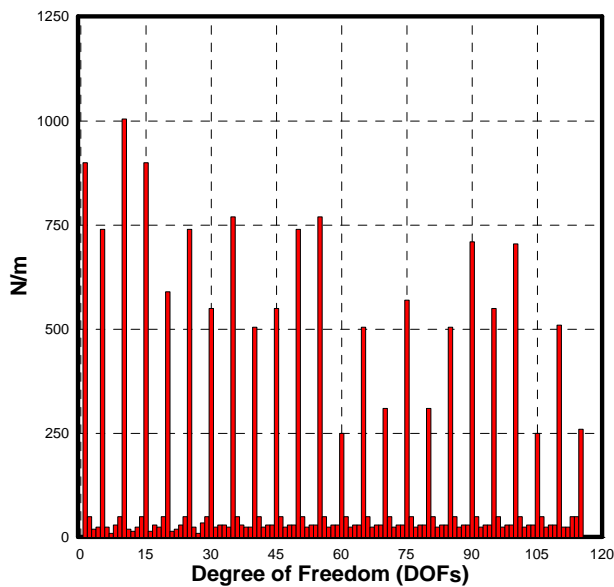
2D Cumulative Damage Location Vector Plot for [0/0/0/0/0/0/0/0]



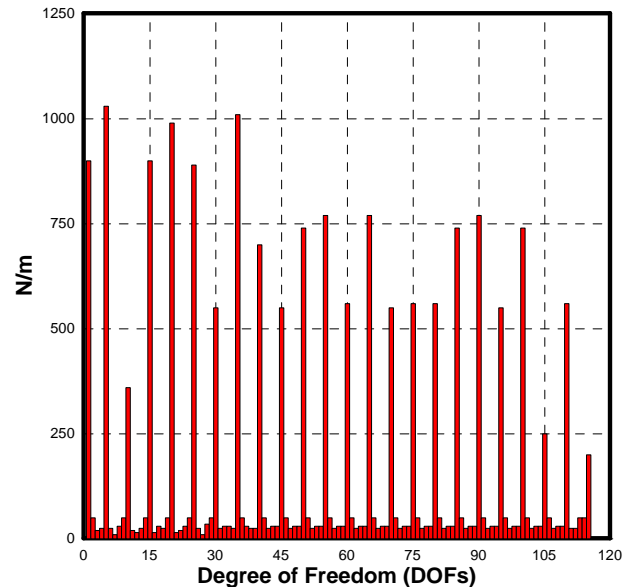
2D Cumulative Damage Location Vector Plot for [0/30/0/30/0/30/0/30]



2D Cumulative Damage Location Vector Plot for [0/45/0/45/0/45/0/45]



2D Cumulative Damage Location Vector Plot for [0/60/0/60/0/60/0/60]



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2D Cumulative Damage Location Vector Plot for [0/90/0/90/0/90/0/90/0/90]

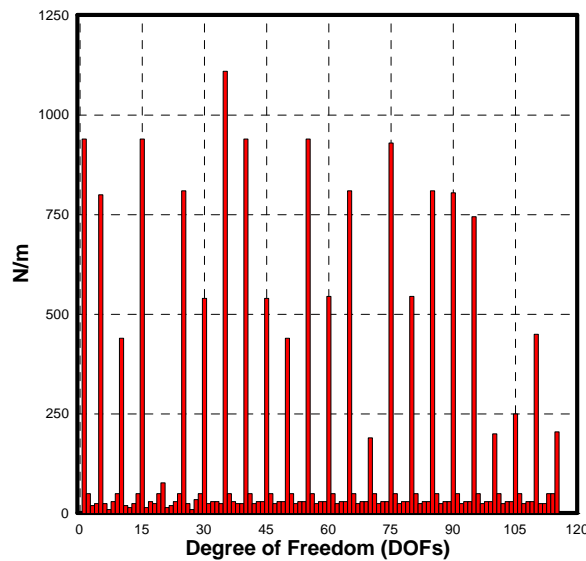


Fig.8 Lateral cumulative damage location plot using experimental FRF data for undamaged plate (case A) for various types of staking sequences.

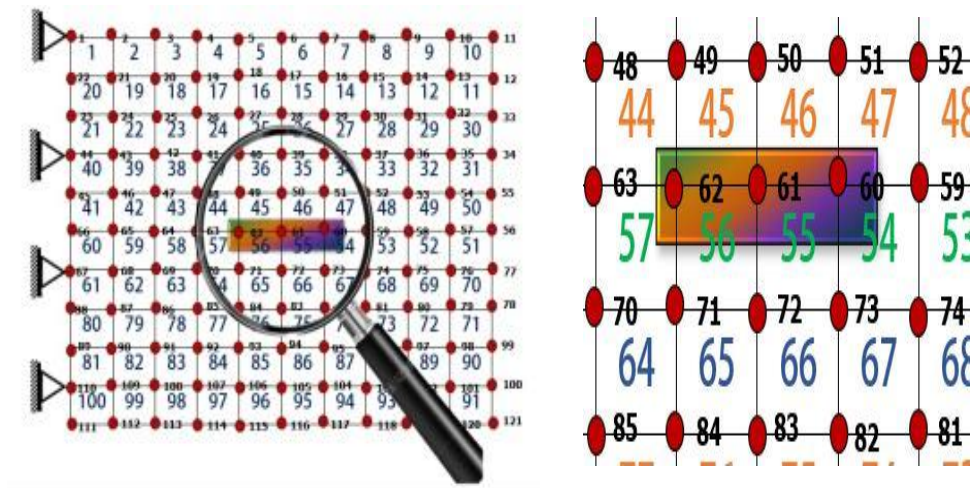


Fig.9 damaged elements and nodes

The resulting cumulative damage location plot in Fig.10 from which it can be seen the effect of noise is again random and negligible but there are now peaks of various magnitudes. These peaks of CDLP are ranked in order and illustrated (in Table.3).

Table.3 illustrates the corresponding node numbers in relation to this lateral degree of freedoms. As a closer inspection of Table 3 shows that its three DOFs at nodes 60, 61, 62, can be seen to be ranked only as 9th, 10th and 11th respectively. So it indeed contained damage then the magnitude of its DOF at node 23 would have been larger, and the

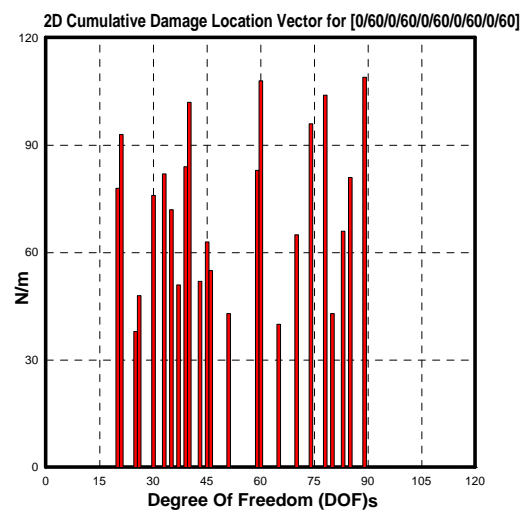
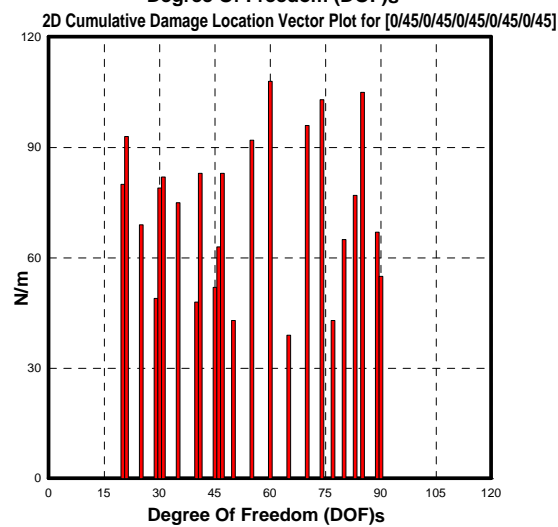
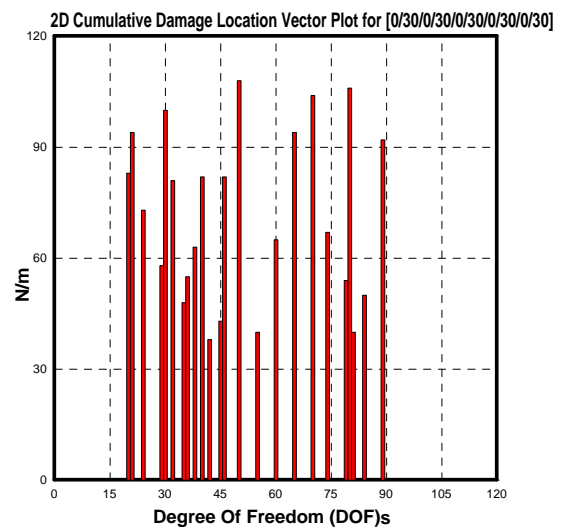
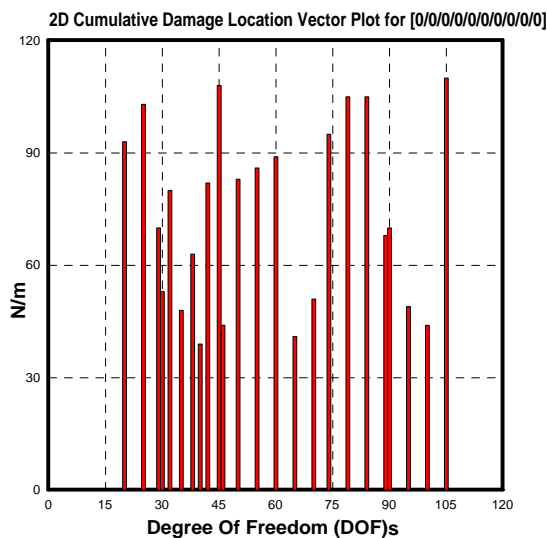
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DOFs at nodes 62 and 61 that are shared with element no. 44,45,46,47 and elements no 57,56,55,54 respectively would have even been far much larger. Thus it can be seen that DOFs in the immediate neighborhood of an element containing damage are also slightly affected.



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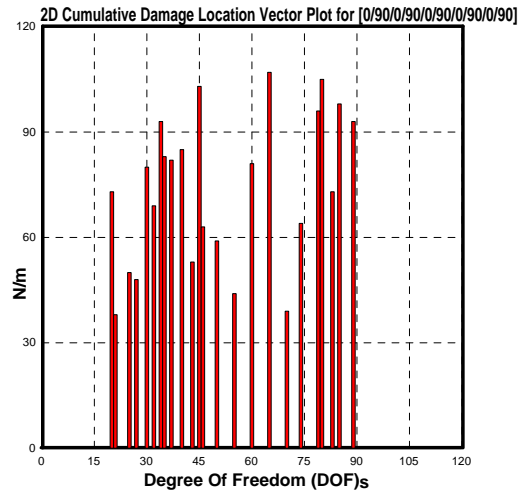


Fig.10 Lateral cumulative damage location plot using experimental FRF data for plate damage case B for various types of staking sequences.

Table 3 Ranking of DOFs from 2D CDLP for plate damage cases A and B

Rank no.	DOFs no.					Corresponding node no.
	[0/0/0/0/0/0/0/0/0]	[0/30/0/30/0/30/0/30/0/30]	[0/45/0/45/0/45/0/45/0/45]	[0/60/0/60/0/60/0/60/0/60]	[0/90/0/90/0/90/0/90/0/90]	
1	93	83	80	78	73	48
2	103	94	93	93	38	49
3	70	73	69	38	50	50
4	53	58	49	48	48	51
5	80	100	79	76	80	52
6	48	81	82	82	69	53
7	63	48	75	72	93	58
8	39	55	48	51	83	59
9	82	63	83	84	82	60
10	108	82	52	102	85	61
11	44	38	63	52	53	62
12	83	43	38	63	103	63
13	86	82	43	55	63	70
14	89	108	92	43	59	71
15	41	40	108	83	44	72
16	51	65	39	108	81	73
17	95	94	96	40	107	74
18	105	104	103	65	39	75
19	105	67	43	96	64	71
20	68	54	65	104	96	47
21	70	106	77	43	105	64
22	49	40	105	66	73	69
23	44	50	67	81	98	86
24	110	92	54	109	93	82

International Journal of Innovative Research in Science, Engineering and Technology

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VI. CONCLUSIONS

This paper aims to assess both theoretically and experimentally, damage detection using DLV's. The method is first studied theoretically on a thin plate structure using simulated damage. The method is then tested experimentally on a free-free plate provided with several damage cases using Mechanical exciter tests. The method is improved through the use of FRFs of the intact structure obtained both numerically and experimentally in an attempt to overcome difficulties imposed by initial damage and noise. Based on the analytical and experimental assessment that was performed using the DLV algorithm, the following can be concluded:

- 1- The DLV method could detect damage location successfully both theoretically and experimentally.
- 2- The DLV can identify single cracks damage locations.
- 3- Damage identification based on DLV can accurately determine the extent of the damage from natural frequency and mode vector line drive.
- 4- Frequency response function (FRF) of the intact structure obtained numerically and experimentally, the DLV method could overcome difficulties imposed by initial damage and noise to detect and localize the damage experimentally.
- 5- The position of nodes and antinodes are shifted for cracked composite plates compared with plain ones.

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ISSN(Online): 2319-8753
ISSN (Print): 2347-6710

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

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