Proceedings of 2015 Asian-Pacific Conference on Aerospace Technology and Science

May 20-23, 2015, Jeju Island, Korea

Damage assessment of composite structures using Particle Swarm Optimization

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Abstract

Composite materials are highly sensitive to the presence of manufacturing and service-related defects that can reach a critical size during service condition and thereby may affect the safety of the structure. When the structure undergoes some kind of damage, its stiffness reduces, in turn the dynamic responses change. In order to avoid safety issues early detection of damage is necessary. The knowledge of the vibration behavior of a structure is necessary and can be used to determine the existence as well as the location and the extent of damage.

Keywords: Composite structures, Damage assessment, Inverse technique, anisotropic damage, Particle Swarm Optimization, Finite Element Method

1. Introduction

Composite structures are widely being used in civil, mechanical, aircraft and spacecraft fields due the various advantages such as high strength to weight ratio, high stiffness to weight ratio, corrosion resistance etc. In spite of these major advantages, composite structures may undergo several types of damage such as delamination, fiber-matrix debonds and fiber breakage, etc. due to the defects in manufacturing process or fatigue loading during service which in turn affect the effective performance of the structure. These damages reduce the stiffness and other mechanical properties, and thus affect the response of the material. In order to avoid safety issues and to economize the costs of repair, early damage detection and assessment is necessary since careful design cannot prevent the development of damage in the structure. Santos et al. [1] developed a numerical technique for the identification of damage on laminated structures based on FSDT. The damage in the composite is anisotropic in nature whose extent is distributed in several orthogonal directions and the extent of damage in any orthogonal direction is independent of the other.

Different approaches are used to detect and assess damages in structures. Salawu [2] discussed the use of natural frequency as a diagnostic parameter in structural damage assessment. The vibration based damage detection is an effective method due to its simplicity of implementation and ability of acquiring both the global and the local damage information of the structure and these methods are increasingly used nowadays for the identification of damages in aerospace, civil and mechanical engineering structures. The location and severity of damage in composite structure are determined from changes in natural frequencies employing an inverse technique, Unified Particle Swarm Optimization (UPSO).

1.1. Damage Modelling Based On Stiffness Reduction

When damage occur in an element of a structure, the stiffness as well as the global frequency of the whole structure decreases. Generally, when some damage appears in a structure, stiffness matrix can offer more information than the mass matrix since the changes of mass matrix may be considered negligible. So it is logical to apply the changes in stiffness matrix to detect damage.

For anisotropic damage, the variable is tensorial in nature and hence the identification of the models is much more complicated. Reduction of in-plane and bending stiffness and re-distribution of membrane stresses occurs due to the presence of damages in the system which inturn affect the static and dynamic response characteristics of the system. So understanding vibration characteristics is essential in fail safe design. Due to the complexities involved in an anisotropic damage, the use of numerical methods such as the finite element method based on damage mechanics has been proved to be very effective.

For obtaining the frequency response, the forward method is used and to determine the location and severity of damage inverse technique is used.

2. THEORETICAL FORMULATION

2.1. Anisotropic damage

In a thin plate, anisotropic damage is parametrically incorporated into the formulation by Valliappan et al. [3] considering the damage parameter which is a representation of reduction in effective area and is given by:

$$\Gamma_i = \frac{A_i - A_i^*}{A_i} \tag{1}$$

Where A_i^* is the effective area (with unit normal) after damage

A_i is the area of damaged material with unit normal n_i

$i \in$ {1, 2, 3} are the three orthogonal directions

Assuming that the internal forces acting on any damaged section is the one before damage:

$$\sigma_{ij}\delta_{jk}A_k = \sigma_{ij}^*\delta_{jk}A_k^* \tag{2}$$

The damage model should not assume the damage tensor to be symmetric in order to define the damage effectively in composites. Therefore,

$$\sigma_{21}^* = \frac{1-\Gamma_2}{1-\Gamma_1}\sigma_{12}^* \tag{3}$$

2.2. Unified Particle Swarm Optimization

The particle swarm optimization (PSO) algorithms, first proposed by Kennedy and Eberhart [4], are inspired by the collective motion of insects and birds trying to reach an unknown destination, known as "swarm behavior". PSO algorithm has advantages lies with its simplicity in its architecture and convergence speed. Further, to improve its efficiency many alternations and variations are proposed to the original PSO algorithm, among which UPSO one that has the ability to harness both exploration and exploitation capacity simultaneously by balancing the influence of both global and local search directions simultaneously. Mathematically, for a swarm size of P number of particles, in an S-dimensional search space, let G_{ij}^{t+1} and L_{ij}^{t+1} denotes the velocity update of i^{th} particle in global and local variants of PSO respectively for the $(t+1)^{th}$ iteration as given by,

$$G_{ij}^{t+1} = \chi\left[v_{ij}^{t} + c_1 r_1\left(pbest_{ij} - x_{ij}^{t}\right) + c_2 r_2\left(gbest_{ij} - x_{ij}^{t}\right)\right] \tag{4}$$

and, $$L_{ij}^{t+1} = \chi\left[v_{ij}^{t} + c_1 r_3\left(pbest_{ij} - x_{ij}^{t}\right) + c_2 r_4\left(lbest_{ij} - x_{ij}^{t}\right)\right] \tag{5}$$

Where, $pbest, gbest$ and $lbest$ respectively denotes the best position explored by individual particle, any particle in the swarm and in the neighborhood of individual swarm respectively. χ denotes the constriction factor which is equals to 0.72984. c_1 and c_2 are two acceleration coefficients and is considered as 2.05 each in present study. Finally, all *r* terms denote random numbers between [0, 1] and independent of each other. Combining Equations (4) and (5), the aggregate velocity of the particles in the search directions is defined as,

$$V_{ij}^{t+1} = u.G_{ij}^{t+1} + (1-u).L_{ij}^{t+1}, \qquad u \in [0,1] \tag{6}$$

The new position of the particles for $(t+1)^{th}$ iteration is,

$$x_{ij}^{t+1} = x_{ij}^{t} + V_{ij}^{t+1}, \qquad \forall i \in P \ and \ \forall j \in S \tag{7}$$

The parameter, *u* in Equation (6) is called unification factor and its value is modified throughout the iterations according to the equation,

$$u(t) = \exp\left(\frac{t.\log(2.0)}{t_{\max}}\right) - 1.0 \tag{8}$$

3. Results and Discussion

3.1. Damage assessment results

The current study deals with damage at the macro level that can be described using anisotropic parameters and its influence on free vibration has been observed. Moreover identification of damage and its severity has been done using the present formulation with the help of PSO.

The dimension and material properties of the composite beam considered for the demonstration of the developed algorithm is given:

Table 1. Material properties considered for the numerical composite beam

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	υ_{12}	ρ (kg/m^3)
9.5	6.8	1.4	0.14	1761

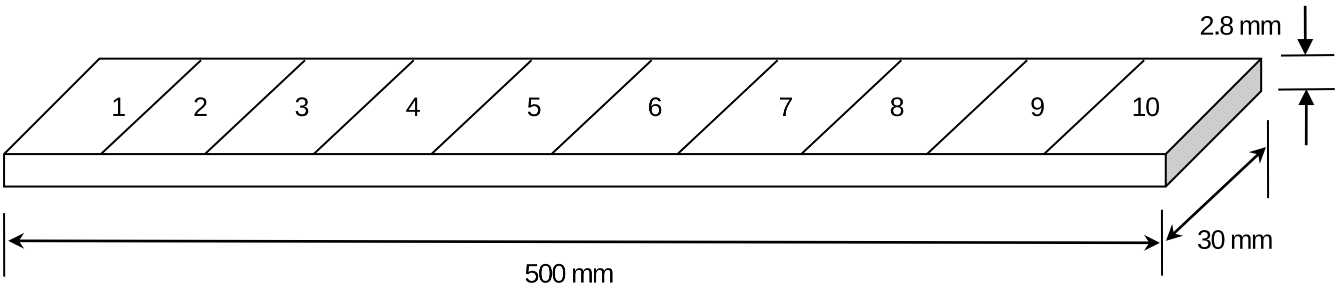

Fig. 1. Composite Beam model

The algorithm is verified for both single and multiple element damage cases. For finite element simulation the beams are modeled with 10 orthotropic elements as shown in Figure 1. First six numerically evaluated natural frequencies (Table 2) are used for constructing the objective function. It can be observed from Table 2 that the fundamental natural frequency decreases with the increase in damage ratio. Up to 1.0% noise is added to the numerical natural frequency to simulate the experimental condition. UPSO algorithm is employed to search the actual damaged element and damage amount. For optimization purpose, 50 swarms are considered for the study. Maximum number of iteration allowed is 300. The damage conditions considered for the study and the results of damage assessment for various noise levels are evaluated and produced in Table 3.

Table 2. Damage cases selected for simulation studies in fixed beam structure and the corresponding natural frequencies

Damage Id	Damage Conditions $[\text{Element No.} (\Gamma_1, \Gamma_2)]$	Natural Frequencies					
		1st	2nd	3rd	4th	5th	6th
Undamaged		26.57	73.24	143.76	170.11	238.52	271.29
D1	4 (0.60, 0.00)	23.92	62.08	137.31	162.80	209.29	245.05
D2	4 (0.00, 0.50)	26.58	73.29	143.77	165.99	238.66	270.41
D3	3 (0.50, 0.00)	25.36	60.14	128.21	157.19	214.74	258.05
	7 (0.35, 0.00)						
D4	3 (0.00, 0.40)	26.58	73.35	143.81	156.25	238.78	267.94
	7 (0.00, 0.65)						

Table 3. Damage assessment results

Damage Case	Damage Id	Actual	Damage Assessment Results [Element No., (Γ_1, Γ_2)]		
			0.00 % Noise	0.50 % Noise	1 % Noise
Single element damage	D1	4 (0.60, 0.00)	7* (0.60, 0.00)	4 (0.60, 0.06)	7* (0.60, 0.00)
	D2	4 (0.00, 0.50)	4 (0.00, 0.50)	4 (0.00, 0.50)	4 (0.00, 0.49)
Two element damage	D3	3 (0.50, 0.00)	3 (0.50, 0.00)	3 (0.50, 0.00)	3 (0.50, 0.00)
		7 (0.35, 0.00)	7 (0.35, 0.00)	7 (0.35, 0.00)	7 (0.35, 0.09)
	D4	3 (0.00, 0.40)	3 (0.00, 0.40)	3 (0.00, 0.40)	8* (0.00, 0.33)
		7 (0.00, 0.65)	7 (0.00, 0.65)	7 (0.00, 0.63)	4* (0.00, 0.68)

*since frequency is used as the diagnostic parameter to identify the location of damage and the support condition of the beam is symmetric, the present results produce the symmetric location corresponding to the actual damaged element of the beam

Conclusions

A numerical procedure is presented to detect and quantify damage in a composite structure based on changes in natural frequency data using UPSO technique. The proposed methodology is demonstrated using a numerically simulated composite beam and plate structure containing single and single and multiple damages. As indicated by the simulation results, the proposed method is able to detect and quantify the damage accurately using first six natural frequencies for considered damage cases.

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