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Vibration based Structural Health Monitoring of a composite T-beam

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ABSTRACT

A vibration based damage identification method is investigated experimentally for a 2.5-dimensional composite structure. The dynamic response of an intact and a locally delaminated 16-layer unidirectional carbon fibre PEKK reinforced T-beam is considered. A force–vibration set-up, including a laser vibrometer system, is employed to measure the dynamic behaviour of the T-beam. The Modal Strain Energy Damage Index algorithm is applied using the bending and torsion modes. Special attention is paid to the effect of the number of measurement points required to detect and localize the delamination accurately.

1. Introduction

Development of Structural Health Monitoring technologies for composite based structural components for aircrafts is one of the objectives of the European research program Clean Sky/Eco-Design. An increase of the part's service life reduces its cost and long term ecological impact.

One of the key issues in composite structures is the early detection and localization of damage. Often service induced damage do not involve visible plastic deformation, but internal matrix related damage, like transverse cracks and delaminations. Their detection impose costly maintenance techniques. Vibration based damage identification methods are promising as an alternative for the time consuming and costly Non Destructive Testing methods currently available. These methods also offer the potential to be used as a real-time health monitoring system. The change of the dynamic properties is employed to identify damage such as delaminations.

Grouve et al. [1] used a vibration based Structural Health Monitoring technique by monitoring shifts in natural frequencies to detect a delamination in a simple composite beam structure. However, it is often complicated to localize damage uniquely. Stubbs et al. [2] proposed a technique which shows to be capable to detect and localize damage in beam-like one-dimensional structures. They were the first who introduced a damage identification method based on the observation that local changes in the modal strain energy of the vibration modes of a structure are a sensitive indicator of damage. Cornwell et al. [3] extended the method for plate-like, hence two-dimensional, structures. Only recently, the step to three-dimensional frame structures was made [4,5].

Until now, the Modal Strain Energy Damage Index algorithm is hardly used on anisotropic, composite structures. Moreover this methodology is mainly applied to one-dimensional beam and two-dimensional plate-like structures with only flexural vibrations. The question is whether the methodology is applicable for more complex and larger structures with a minimum amount of sensors. A step in this direction is to consider a 2.5-dimensional composite beam structure with a more general deformation pattern, including bending and torsion, in order to extract a maximum of damage related information from the measured vibration modes. Duffey et al. [6] are the only ones who included torsion modes and vibrations in their research. Torsion vibrations can become rather complex and tend to be more difficult to measure. However, beside bending modes, torsion modes could also provide damage related information. This could become advantageous, in particular for larger structures, if the number of measurable vibration modes is limited and the number of sensors is to be reduced. Therefore it is also important to investigate the effect of the number of measurement points on the damage identification results.

This paper mainly presents the experimental work performed at the University of Twente. It reports on the application of the Modal Strain Energy Damage Index algorithm, applied to a 2.5-dimensional composite structure vibrating under bending and torsion modes, in order to detect and localize a delamination. An experimental set-up around an intact and delaminated T-beam is used for this purpose. Use is made of an external measurement device for the characterisation of the dynamic behaviour, in order to easily vary the amount of measurement point. The results obtained in this study will set requirements to the methods and the instrumentation necessary to apply the method in a Structural Health Monitoring environment.

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2. The Modal Strain Energy Damage Index algorithm

The strain energy of a vibration mode is referred to as the modal strain energy of that mode. Consequently, the total modal strain energy is the sum of the modal strain energy contributions of all modes considered. The modal strain energy is calculated by linking the deformation of a structure to the strain. A distinction must be made between axial, flexural and torsional deformation–strain relations. Only the bending and the torsion strains are analysed, since the T-joint is a slender structure. The mechanical relations read (see Fig. 1 for the coordinate system used):

$$\frac{\partial^2 u_{x/y}}{\partial z^2} = \frac{M_{y/x}}{EI_{xx/yy}}; \quad \frac{\partial \theta_{xy}}{\partial z} = \frac{T_z}{GJ_{xy}} \tag{1}$$

with u the displacement, θ the rotation, M the bending moment, T the torque, EI and GJ, respectively, the bending and torsion rigidity of the beam. The subscript '(x/y)' refers either to x or y. The strain energy is found by integrating the squared strains over the length l of the structure [6]:

$$U_B = \frac{1}{2}\int_0^l EI\left(\frac{\partial^2 u_{x/y}}{\partial z^2}\right)^2 dz; \quad U_T = \frac{1}{2}\int_0^l GJ\left(\frac{\partial \theta_{xy}}{\partial z}\right)^2 dz \tag{2}$$

Consider the structure to be vibrating in the nth bending mode. The displacement amplitude for the mode shape is $u_{x/y}^{(n)}(z)$. As a result, the modal strain energy of the nth mode is written as:

$$U_B^{(n)} = \frac{1}{2}\int_0^l EI\left(\frac{\partial^2 u_{x/y}^{(n)}(z)}{\partial z^2}\right)^2 dz \tag{3}$$

Subsequently, the structure is discretised in N elements in axial (z) direction. The strain energy $U_{B,i}^{(n)}$, due to the nth mode and associated with the ith element is then given by:

$$U_{B,i}^{(n)} = \frac{1}{2}\int_{z_{i-1}}^{z_i} (EI)_i\left(\frac{\partial^2 u_{x/y}^{(n)}(z)}{\partial z^2}\right)^2 dz \quad \text{with}: \quad U_B^{(n)} = \sum_{i=1}^{N} U_{B,i}^{(n)} \tag{4}$$

Similar quantities can be defined for a damaged structure, using the mode shapes $\tilde{u}^{(n)}$ of the damaged structure. The derivation for the torsion modal strain energy components follows the same route. The rotation angle θ_{xy} is defined as:

$$\theta_{xy} = \frac{\partial u_y}{\partial x} \tag{5}$$

The strain energy of the nth torsional mode associated with the ith element hence reads:

$$U_{T,i}^{(n)} = \frac{1}{2}\int_{z_{i-1}}^{z_i} (GJ)_i\left(\frac{\partial^2 u_y^{(n)}(x,z)}{\partial x \partial z}\right)^2 dz \tag{6}$$

Note that the mode shape must be defined as a function of x and z, in contrast to the bending mode, which is constant in x– and y-direction.

The local fractional strain energies, as defined by Cornwell et al. [3], are:

$$F_{B/T,i}^{(n)} = \frac{U_{B/T,i}^{(n)}}{U_{B/T}^{(n)}}; \quad \widetilde{F}_{B/T,i}^{(n)} = \frac{\widetilde{U}_{B/T,i}^{(n)}}{\widetilde{U}_{B/T}^{(n)}} \tag{7}$$

for the intact and damaged structure, respectively. The fractional strain energy remains relatively constant in the intact element, under the assumption that the damage is primarily located at a single element. Given the damage is located at element j, it can be derived that:

$$(EI)_j \int_{z_{j-1}}^{z_j}\left(\frac{\partial^2 u_{x/y}^{(n)}(z)}{\partial z^2}\right)^2 dz / U_B^{(n)} = (\widetilde{EI})_j \int_{z_{j-1}}^{z_j}\left(\frac{\partial^2 \tilde{u}_{x/y}^{(n)}(z)}{\partial z^2}\right)^2 dz / \widetilde{U}_B^{(n)} \tag{8}$$

$$(GJ)_j \int_{z_{j-1}}^{z_j}\left(\frac{\partial^2 u_y^{(n)}(x,z)}{\partial x \partial z}\right)^2 dz / U_T^{(n)} = (\widetilde{GJ})_j \int_{z_{j-1}}^{z_j}\left(\frac{\partial^2 \tilde{u}_y^{(n)}(x,z)}{\partial x \partial z}\right)^2 dz / \widetilde{U}_T^{(n)} \tag{9}$$

These equations are rearranged to obtain the quotient of the flexural and torsional stiffnesses, using the assumptions in [3,7]:

$$\frac{(EI)_j}{(\widetilde{EI})_j} \equiv \frac{\tilde{f}_{B,j}^{(n)}}{f_{B,j}^{(n)}}; \quad \frac{(GJ)_j}{(\widetilde{GJ})_j} \equiv \frac{\tilde{f}_{T,j}^{(n)}}{f_{T,j}^{(n)}} \tag{10}$$

The local damage index β for the jth element can be obtained by using the definition proposed by Stubbs et al. [2], which is a summation of the fractions $f_j^{(n)}$ over the number of modes considered:

$$\beta_{B/T,j} = \sum_{n=1}^{N_{freq}} \tilde{f}_{B/T,j}^{(n)} \Bigg/ \sum_{n=1}^{N_{freq}} f_{B/T,j}^{(n)} \tag{11}$$

3. T-joint stiffener

The structure investigated here is a composite T-shaped stiffener section. This type of stiffener is frequently used in aerospace components to increase the bending stiffness of the component without a severe weight penalty. Recently, a new type of stiffener, depicted in Fig. 1, was developed by Fokker Aerostructures, in collaboration with the Dutch National Aerospace Laboratories (NLR).

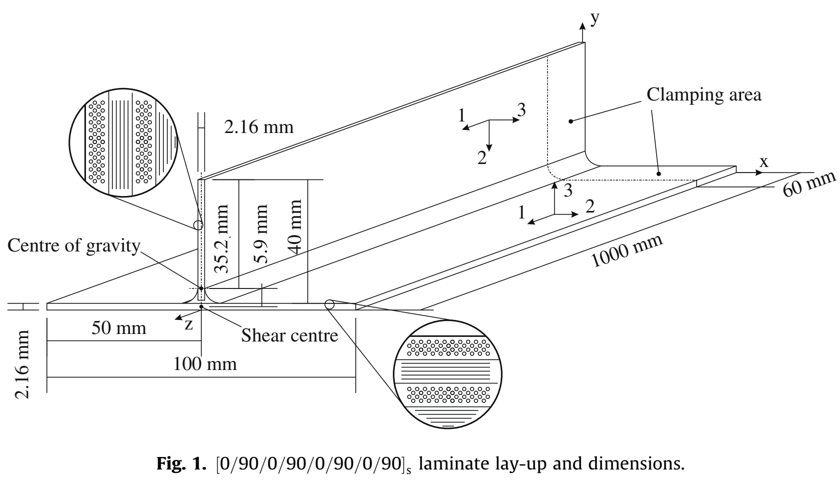

Fig. 1. $[0/90/0/90/0/90/0/90]_s$ laminate lay-up and dimensions.