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Damage localisation in beam-like structures using high-order mode shape

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ABSTRACT

This paper investigates the application and reliability of using mode shape in damage detection and localisation of beam-like structures. This is based on the fact that mode shape is function of the physical properties of the structure. Therefore, changes in the physical properties will cause detectable changes in the mode shape [1]. Numerical study has been carried out for low and high-order mode shapes of cantilever steel beam models. This is done using modal analysis in Ansys, a FEA commercial software, by introducing a single damage in the form of localised cross section reduction. The ANSYS model is validated using the comparison of numerical naturel frequencies with experimental frequencies of cantilever beam. The results demonstrate that high-order mode shapes are more likely to indicate damage location than either low-order mode shapes of beam even for a small amount of damage.

1. Introduction

The occurrence of fault during the operation of structures is often inevitable. Natural events or incorrect usage of a structure can be a cause of fault in the structure [1]. Therefore, the use of Non-Destructive Testing methods to detect the fault is important to increase of safety and reliability and decrease of maintenance and repairing cost.

NDT Methods such as acoustic or ultrasonic methods, magnetic field methods, dye penetrant, radiography, eddy current methods include difficulties which made them impractical, infeasible and expensive in large scale structures [2]. The problems of these methods are that the place of fault is not indicated either the location of fault has to be determined or the tests have to be given periodically in sensitive points in the structure to introduce the fault of the structure. In this case, regardless of being cost-increasing, the fault may occur at unpredicted locations. Another problem is that the location of the

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fault maybe at invisible and/or unavailable locations for the tests [3, 4].

The global damage identification method has been expanded during the last years and the main cause is that these methods don't include the problem mentioned for NDT methods. Moreover, nondestructive evaluation using dynamic response has been considered a lot [4]

The basic idea of these methods is that fault will alter the stiffness, mass, or energy dissipation properties of a system, which in turn change the measured dynamic response of the system [5]. In order to detect structural damage from structural dynamic response signals, the relationship between fault (i.e., stiffness loss) and resonant frequency changes is used.

Frequency change is low sensitive to small change in the elements stiffness and it depends on the environmental conditions such as moisture content and temperature 1.

To overcome these disadvantages, some researchers have focused on using mode shape measures to evaluate the damage [6-7]. And they demonstrate that, the mode shape-based methods are sensitive to change in the elements stiffness of structure which has made this methods one of the most practical tool for fault identification.

2. Modal analysis using ANSYS

The frequency extraction procedure in ANSYS is a linear procedure which performs Eigen value extraction to calculate the natural frequencies and the corresponding mode shapes of a structure. The Eigen value problem for the natural frequencies of an undamped finite element model is given by :

$$\left(-\omega^2 M + K\right)\phi = 0 \tag{1}$$

Where, M is the mass matrix (which is symmetric and positive definite) ; K is the stiffness matrix ; ϕ is the eigenvector ; ω is the natural frequency of the structure.

Ansys provides three eigenvalue extraction methods such as Lanczos ; Automatic Multilevel Substructuring and Subspace iteration. The Lanczos solver with the traditional architecture is the default eigenvalue extraction method because it has the most general capabilities. For the Lanczos method, the maximum frequency of interest or the number of eigenvalues required has to be provided [1].

Output variables such as displacement are available for each Eigen value, and represent the mode shapes.

3. Experimental test and specimen

An experimental program was conducted on cantilever beam specimen subjected to reductions in the depth dimension to determine natural frequencies and the mode shapes changes. Modal analysis is performed on the beams with different single crack scenario. The tested specimen is the prismatic beam of $0.7m$ length with square cross section 0.016×0.016 and the crack is at $150mm$. A saw-cut was used to introduce the crack at the corresponding point across the beam. The beam parameter was smaller ratio that could to approximate the Bernoulli-Euler beam, although the correction to reduce the effect of shear is only necessary at higher frequencies.

To measure the mode shapes of intact and damaged beam in test, the accelerometer (B&K 4384) was moved from one point to another to pick up a total of response signals along the length of the beam. The transfer function FRF was acquired through a signal analyzer (B&K 2032). The measurements were made using a block size of 400 lines thus giving a resolution of $0.25Hz$ per spectral line (Fig. 1). The obtained FRF for the intact beam is illustrating in the Fig. 2.

Fig. 1. Set-up Schematic of the modal testing.

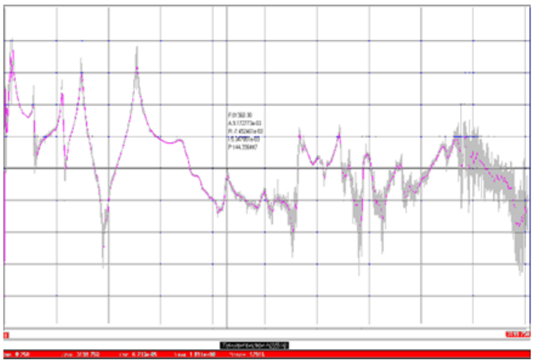

Fig. 2. Experimental FRF function for intact beam.

4. Numerical study

A numerical study using finite element model of cantilever beam structures is conducted. The finite element model of the beam has been created in ANSYS 12. The validated FEM model consists of several Solid 186 elements types (Fig. 3).The material considered to be linear isotropic with Modulus of elasticity $E = 2.9GPa$; $Poisson's\ ratio = 0.3$; $mass\ density = 7800kg/m3$.

Using modal analysis, first height natural frequencies and corresponding flexural mode shapes were obtained for the intact beam. Modal analysis is repeated for each damage location and first height natural frequencies and corresponding mode shapes are obtained for the damaged beam.

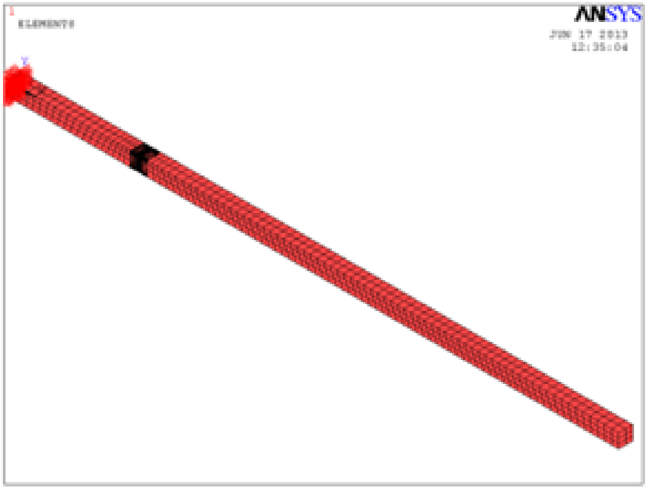

Fig. 3. FEM Model of cantilever beam (16021 nodes and 7989 elements).

5. Results and discussion

In this paper, damage identification methods using mode shape from the numerical modal analysis is studied and investigated to detect damage. In numerical modal analysis, the corresponding mode shapes of the beam with crack location $c/L = 0,214$ and relative crack depth varying from $a/h = 0\%$ to 62.5% with $\Delta a/h = 6.25\%$ are shown in Figs. 4, 5, 6 and 7.

The change of mode shape 1 provides only the location of the crack at $a/h = 65\%$, it has a high accuracy but it's less sensitive to the presence of crack, the mode shape 2 is completely insensitive to the crack, the changes in the second mode shapes can't be observed clearly, they are nearly invariant in these modes shapes even for large a/h (Fig. 4). The mode three locates better the crack position for crack depth rapport a/h more than 25%. The mode shape 4 is best localizer than the mode shape 6 ; its sensitivity is around 25%.

For lower order mode shapes, there is a slight change in the mode shapes of beam which is manifested as a small relative shifting in the response at the region of crack location specially for the early stages of crack.

While the changes in the higher order mode shapes provide a better indication of the presence of a crack for shallow crack. The mode shape 7 is more sensitive (12.5%) but their variation appears in a length which extends from 0 to $200mm$ (Fig. 6). The mode shape 8 locates well the crack ; their sensitivity is less than 12.5% (Fig. 7). This can be explained by the relationship between the position of the crack and the anti-node of the corresponding mode, this position allows the crack to be more openness and therefore makes the properties dynamic more sensitive (Figs. 8 and 9).

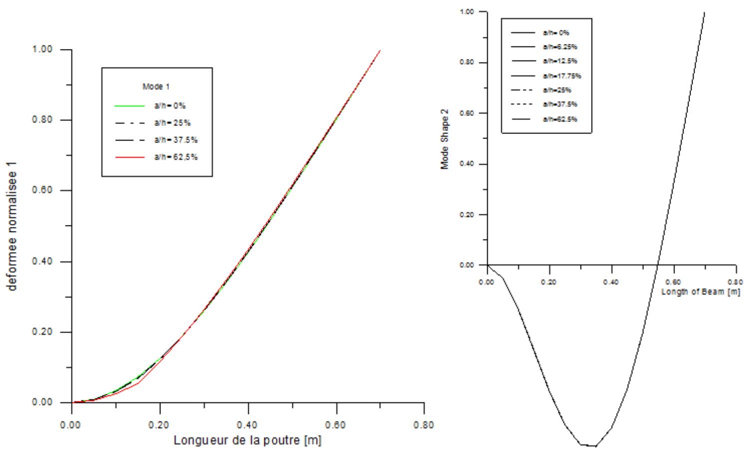

Fig. 4. FEM Mode Shape 1 and 2 : Comparison for intact and damaged beam.

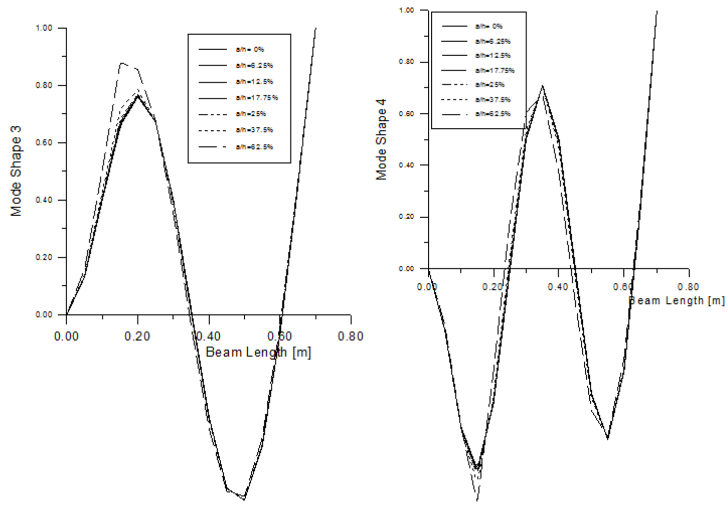

Fig. 5. FEM Mode Shape 3 and 4 : Comparison for intact and damaged beam.

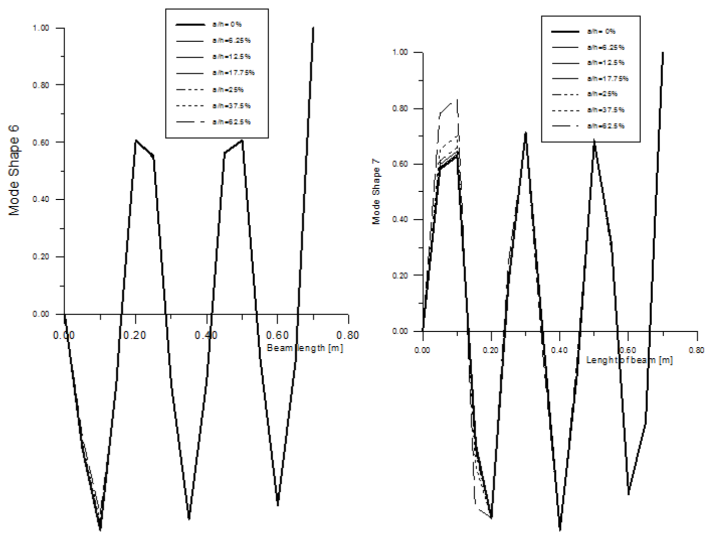

Fig. 6. FEM Mode Shape 6 (left) and 7 (right) : Comparison for intact and damaged beam.

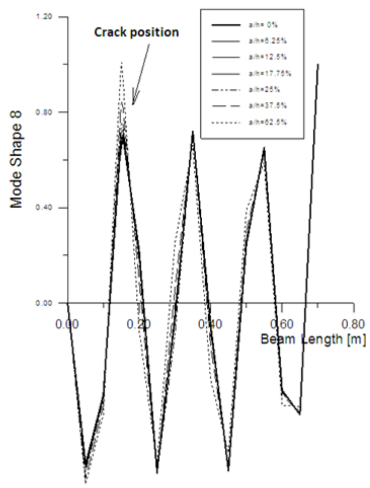

Fig. 7. FEM Mode Shape 8 : Comparison for intact and damaged beam.

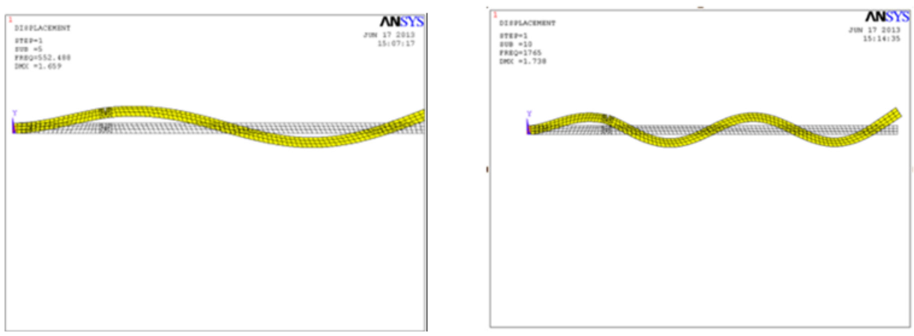

Fig. 8. FEM Mode Shape 3 and 5

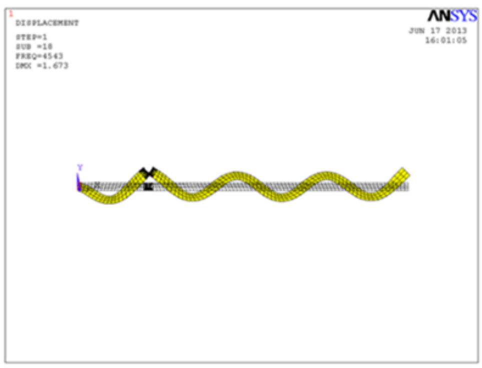

Fig. 9. FEM Mode Shape 8.

6. Conclusion

A method for using the mode shape change technique in the analysis of the vibratory response of a cracked beam is presented. The main objective is to use the changes in the mode shapes to detect and to locate the damage. A numerical study was conducted using a cantilever beam to demonstrate the feasibility of the method.

Results obtained indicate that the method can be used successfully in identifying the location of the damage. The experimental FRF function was used to validate the FEM model and the numerical low and high order mode shapes changes was discussed. Better results were obtained when using the high order mode in the location of the fault.

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