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FEM modeling method of damage structures for structural damage detection

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Abstract

Many current methods on structural damage identification such as GA algorithms and neural networks technology are often implemented based on a few measured data and a large number of simulation data from structural vibration responses. Therefore, to establish an accurate and efficient dynamics model for a structure with different damage is an important precondition, so that plentiful simulation data of structural vibration response can be acquired using the dynamics model of the structure with damage. There are two problems when directly meshing small structural damage in FEM modeling, i.e., excessive gridding number and unavoidable errors from differently meshing for the same damaged structure. In order to solve these two problems, this paper presents an improved modeling method based on modifying element stiffness matrix at structural damage position using a modification coefficient. The first step of this improved modeling method is to determine modification coefficient of element stiffness matrix based on the coherence of natural frequencies for two kinds of models, and the second step is to verify the coherence of the frequency-response functions. This study also introduces algorithm and calculating results of damaged element stiffness matrix. Influence of structural damage position and constraint conditions on the modification coefficient for small structural damage are also discussed.

Keywords: Health monitoring; Damage detection; FEM dynamics model; Element stiffness matrix

1. Introduction

Online detection of position and severity of different damage occurring in many important engineering structures possesses great theoretical and applied significance for ensuring safety and reliability of in-service structures. One of the most feasible methods for realizing the above-mentioned objective is to identify structural damage status from online measured response data of structures during their usage.

The feasibility of structural health monitoring and damage detection based on structural vibration response has been proved by many published literatures [1,2], there are also many theories and technology, such as GA algorithms and neural networks [3–5], etc., which are used for diagnosing and detecting the severity and location of structural damage.

Generally, GA algorithms and neural networks are based on a few measured data and a large number of simulation data of structural vibration responses. Therefore, it is an important precondition to establish an accurate and efficient dynamics model for a structure with different damage, so that plentiful simulation data of structural vibration response can be acquired using the dynamics model of the structure with damage.

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However, in many currently used commercial software for structural dynamics analysis, if a structure with several small damage is directly meshed for establishing structural dynamics model, excessive gridding will be required, so that it is time-consuming for subsequent simulation calculations. Besides, different meshing required by different damage size will lead to numerical error, and this error may exceed the effect produced by small structural damage on structural dynamics characteristics, such as natural frequency.

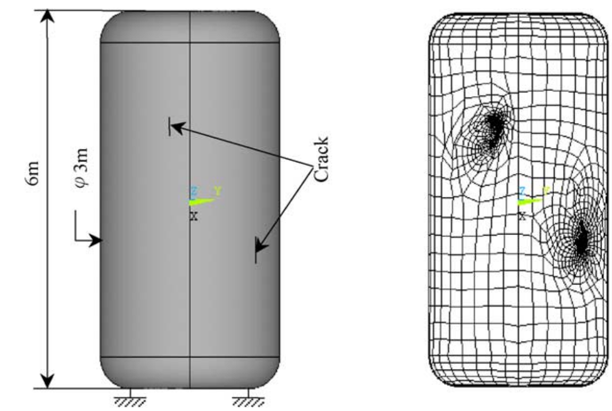
This paper presents an improved method for establishing dynamics model of a structure with small damage. This method is based on the variation of some element stiffness matrixes in damaged location to simulate the severity and location of small structural damage. The proposed method includes determination of modification coefficient of element stiffness matrix and verification of coherence of the frequency-response functions for two kinds models. The way of calculating simulated coefficient of element stiffness matrix in damage location is also discussed. The improved method can greatly decrease the number of required elements for modeling small structural damage, so that the efficiency of dynamics analysis for damaged structures can be increased.

2. Existing problems in meshing structure with small damage

For establishing dynamics model of structures with small damage, there are two existing problems in currently used commercial software.

2.1. Excessive gridding number and extra large difference of gridding size

Fine mesh at damage position of structure with small damage is necessary in FEM calculation for an accurate description of structural damage. For example, in meshing a composite laminated vessel with two small cracks (Fig. 1), a large number of gridding in the damaged position is required. Obviously, it is very time-consuming to make dynamic analysis for structures with excessive degree-of-freedom. On the other hand, there may be great difference in gridding size in the whole structure due to the existence of small structural damage. Generally, it is required to get output data at any nodes, not only the nodes at damage location, because the location of structural damage is unknown in advance. It is often necessary to compute output data of coarse gridding on undamaged location for simulation of sensor output. Therefore, the required data for sensor output may not be accurate enough although a large number of elements have been adopted in the whole structure. The above-mentioned problem is caused because the design objective of the currently available commercial software for structural analysis generally emphasizes on the depiction of the local mutation of structural stress or strain in known position. However, for structural damage detection it may not be necessary or impossible to use dynamics responses at nodes of structural damage location. In vibration-based damage detection, the main objective is to determine the severity and location of structural damage using dynamic response at the selected several nodes, while the detailed variations of stress or strain in structural damage location may not be very important.



(a) Vessel model with two cracks **(b) Direct meshing crack damage**

Fig. 1. Model of laminated composite vessel.

2.2. Difficulties for expressing different structural damage size using directly meshing structure

This problem seems not understandable. This phenomenon can be explained using a practical example. For the model of composite laminated vessel shown in Fig. 1, meshing methods of using smart grade 6 in ANSYS 7.0 software are adopted, and modal analyses are carried out. The natural frequencies for three cases are computed using the same meshing grade, and the three cases include the undamaged vessel, the vessels with single crack length of 0.5% and 1% of the vessel length, respectively. The obtained natural frequencies for the first 20 orders are listed in Table 1. Results in Table 1 show that most of the natural frequencies for model with 0.5%L crack length are higher than those of undamaged model. Obviously, this result is suspectable. Generally, natural frequency of structural vibration should decrease when its mass is unaltered and its stiffness weakens is reduced due to structural damage. A comparison of natural frequencies between vessels with crack lengths of 0.5%L and 1%L (data in the last column of Table 1), most of $(f_2 - f_1)/f_1$ is negative, and this indicates that the natural frequency decreases with increase of structural damage. It can be noticed that some frequencies are nearly invariable with increase of crack length, and this can be explained as that the

Table 1
Natural frequency of the intact and damaged vessels

	Intact	Crack length = 0.5%L		Crack length = 1%L		
	f_0 (Hz)	f_1 (Hz)	$(f_1-f_0)/f_0$%	f_2 (Hz)	$(f_2-f_0)/f_0$%	$(f_2-f_1)/f_1$%
1	3.4361	3.4356	−0.02	3.4362	0.00	0.02
2	3.4369	3.4387	0.05	3.4379	0.03	−0.02
3	8.5989	8.5993	0.01	8.5992	0.00	0.00
4	11.9047	11.9047	0.00	11.9047	0.00	0.00
5	12.4169	12.7138	2.39	12.7389	2.59	0.20
6	12.4266	12.8049	3.04	12.7592	2.68	−0.36
7	13.6337	13.9890	2.61	13.9492	2.31	−0.28
8	13.6343	14.1636	3.88	14.1661	3.90	0.02
9	15.8754	15.8909	0.10	15.8882	0.08	−0.02
10	16.8402	17.2118	2.21	17.2407	2.38	0.17
11	16.8406	17.9590	6.64	17.8521	6.01	−0.60
12	17.8716	18.3120	2.46	18.2778	2.27	−0.19
13	17.8828	18.4943	3.42	18.4535	3.19	−0.22
14	18.8865	18.8866	0.00	18.8867	0.00	0.00
15	19.2177	19.2179	0.00	19.2177	0.00	0.00
16	23.7822	24.3686	2.47	24.3397	2.34	−0.12
17	23.7838	24.4494	2.80	24.4347	2.74	−0.06
18	26.0017	26.0017	0.00	26.0017	0.00	0.00
19	26.1966	26.1966	0.00	26.1966	0.00	0.00
20	27.1810	27.5908	1.51	27.5421	1.33	−0.18

L = vessel length.

mechanical distortion in crack location for these modes is very little.

The above-mentioned example shows that errors due to different meshing may be greater than variations of structural dynamic characteristics caused by small structural damage. Moreover, it is difficult to adopt the current meshing method for intact and damaged structures. Therefore, some improved method for meshing structures with damage are suggested in the next section.

3. Improved modeling method for structures with damage

Local damage in a structure always causes reduction of local structural stiffness, so that these variations can be denoted using change of material elastic coefficients of the local structure [6]. Dynamics model of a damaged structure can be established using the modified material elastic coefficients in local damage position of the structures, and it may not be necessary to depict the geometry of small damage. Thus, it is possible to avoid troubles caused by direct meshing structures using current commercial software in modeling damaged structures. The method proposed in this study has two steps: (1) directly meshing structure and ignoring existence of structural damage, (2) for those elements in position of structural damage, their element stiffness matrixes are adjusted to simulate structural damage, i.e.,

$$\mathbf{K}_d^e = (1-\alpha)\mathbf{K}_0^e \quad (0 < \alpha \leqslant 1) \tag{1}$$

where $\mathbf{K}_d^e$ is the stiffness matrix of element with some damage, and $\mathbf{K}_0^e$ is the one for elements without damage. α is a modification coefficient for stiffness matrix of elements with structural damage. In this study, Eq. (1) is the simplest scalar factor because only one element stiffness matrix is considered and influence on all elements of this matrix is considered to be the same. In fact, it is unknown in modeling damaged structures that a special damage will influence how many elements in structural FEM model, and the influenced degree on every element also is not known in advance. Therefore, multiple and alterable scalar parameter α should be adopted for better description to a given structural damage in FEN modeling. Improved meshing model for structure with damage will contain less gridding number and well-proportioned gridding size, so that two problems mentioned in Section 2 of this paper can be well solved.

For this improved modeling method, the key issue is how to determine the modification coefficient α according to structural damage status, such as the severity and position of structural damage. Of course, variations of mechanical character for damaged element can be analyzed based on theoretical formulae of structural damage mechanics [7]. However, these theoretical formulae are only suitable for few patterns of structural damage because the required data are based on some standard material samples.

This study attempts to obtain the modification coefficient α in Eq. (1) using optimal equivalent principle of structural dynamics. For example, when establishing dynamics model of a structure with crack damage, different values of coefficient α are tried until the smallest statistical error of several natural frequencies between two kinds of models is reached, one is directly meshing structural crack in geometry, and the other is to simulate crack damage using modification coefficient α for several element stiffness matrixes. Thus, dynamics model of structure with crack damage can be established using less FEM grids and the obtained optimal α value.

Of course, for these two kinds of dynamics models, i.e., directly meshing crack damage, and simulating variations of element stiffness in meshing, local stress and strain in damaged position are different. However, this difference should not produce too much influence on measurement output of sensors, because when vibration-based structural damage detection is adopted, it is generally not feasible to install sensors at damage position, which is unknown in advance.

It is necessary to analyze the size of structural damage to be detected by vibration-based method, when modeling and determining the modification coefficient α for stiffness of damaged element. Generally, the size of structural damage can be approximately divided into three levels: (1) micro-damage, i.e., damage size is smaller than 0.1% of structural size; (2) small-damage, i.e., damage size is about 1% of structural size; (3) macro-damage, i.e., damage size is greater than 10% of structural size. For structural micro-damage, vibration-based detection method is generally not successful, and it should be detected using instruments with high precision, such as C-scan, ultrasonic wave, etc., but these methods are not suitable for structural online detection. Besides, structural micro-damage may produce very little influence on structural safety life. However, structural small-damage generally tends to develop into macro-damage, therefore, structural small-damage possesses the potential harm to in-service structures. Hence, it is necessary to monitor structural health or to detect structural small-damage during their usages. For structure with macro-damage, they often have been destroyed, so macro-damage can be found using naked eye or other simple method. Therefore, more attention should be paid to online detection for structural small-damage.

Now, a practical method to determine coefficient α in Eq. (1) will be depicted. Suppose that the structural natural frequency obtained using dynamics FEM model with direct meshing at structural damage position is f_{i0}, and the natural frequency obtained using dynamics FEM model with uniform grid and different simulating coefficient α is $f_i(\alpha)$. Let

$$E(\alpha) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[f_i(\alpha) - f_{i0}]^2}, \tag{2}$$

$E(\alpha)$ is the statistical error of the natural frequency between these two kinds of models, and N is the number of natural frequency to be considered. Obviously, $E(\alpha)$ varies with α. When $E(\alpha)$ reaches the minimum value, the corresponding α value can be taken as the required coefficient α for simulating damage in the improved modeling method. Theoretically, the required α value can be determined using partial $\partial E(\alpha)/\partial\alpha = 0$. However, it is easier to compute α value using graphical method.

However, the usable data for structural damage detection is generally dynamic response at some nodes of structure, but is not the natural frequency. This is because that structural natural frequency is very not sensitive to small structural damage. If only natural frequencies are alike for the above-mentioned two kinds of models, the dynamics equivalence is not accurate enough to structural damage detection. These two kinds of models should also have the same dynamic response. Therefore, improved modeling method proposed in this study also includes verifying the established model based on the frequency-response of FEM model of directly meshing structure.

4. Examples

A hollow cylindrical composite vessel (shown in Fig. 1) is modeled by ANSYS software. Its thickness is 8 mm. It is made of wound resin glass fibre with orthogonal layer $(-45°/45°)_{10}$. Material parameters of the example model are $E_1 = 47.518$ GPa, $E_2 = 4.588$ GPa, $G_{12} = 2.10$ GPa, $\mu_{12} = 0.4495$, $\mu_{21} = 0.0434$, and $\rho = 1860$ kg/m^3. For the case with one crack, FEM dynamics model shown in Fig. 2(a) is established with 2249 elements using direct meshing in crack position I by Smart grade 4 in ANSYS software, so that the reference of structural natural frequency is obtained. Then, the dynamics model shown in Fig. 2(b) is established with 1212 elements using Smart grade 4 in ANSYS software ignoring the existence of the crack, but the stiffness matrix of the element in position I is modified by different α value. When N in Eq. (2) equals 20 and the crack length is 0.4% of the vessel length, the curve of $E(\alpha)$ versus α is shown in Fig. 3. The result indicates that for the

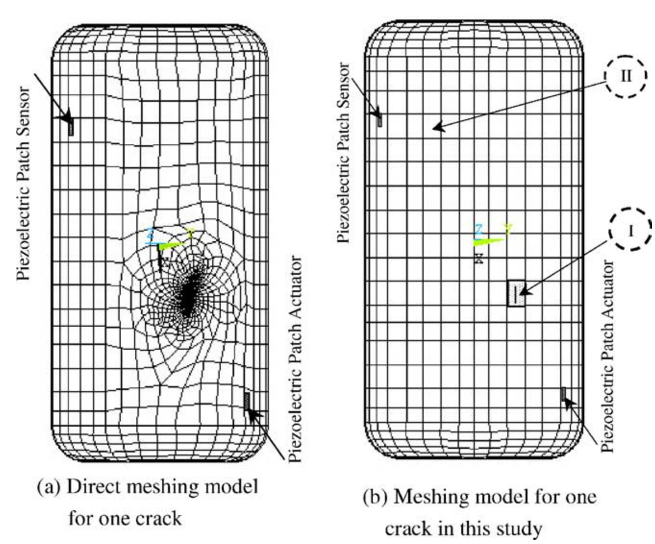


Fig. 2. Two kinds of ways for meshing structure.

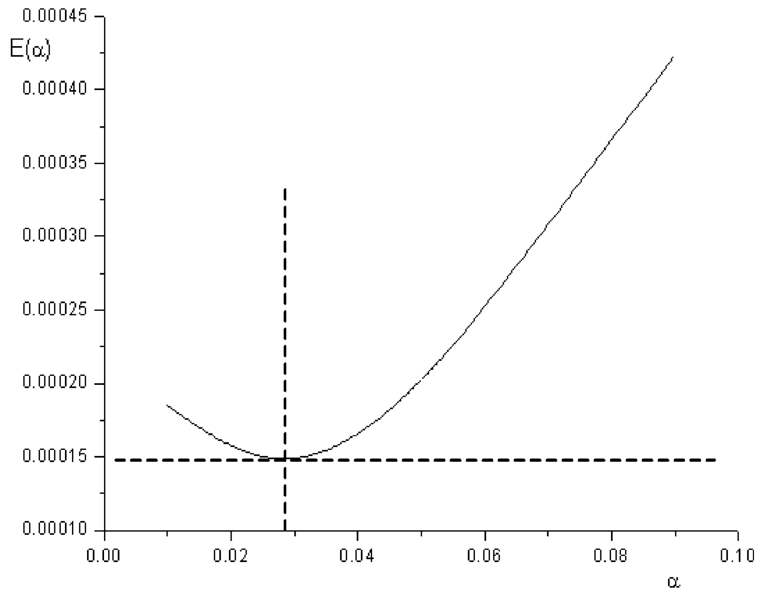


Fig. 3. Optimal α value for one crack in position I.

given crack damage, when α equals to 0.028, the $E(\alpha)$ will be minimal. In order to compare frequency-response characteristics of FEM model using modification coefficient of element stiffness matrix with that of the FEM model using directly meshing structure, their frequency-response functions at the same node are calculated, and is shown in Fig. 4. Result shows that there exists such a good coherence between two frequency-response functions at a wide frequency range that is up to the first 30 orders of the structural natural frequency.

Relationship between the single crack length and the required α value is shown in Fig. 5. Result indicates that the required α value increases with crack development, and this means that the modification coefficient α for a single element stiffness matrix can denote the severity of structural crack damage. Fig. 6 shows that the required α value for damage position II and the same crack length 0.4%L should approximately equals to 0.039, but α equals 0.028 when a crack with the same length is in position I. This result demonstrates that the position of structural damage can also be indicated.

It is necessary to analyze effect of the modification coefficient α. Although direct action of the α is the local element, its effect on structural dynamics is not only on local structure or few frequencies and modes. Otherwise, it cannot be explained that there exists such a good coherence of frequency-response functions for two models with great difference of element number (2249 and 1212). In

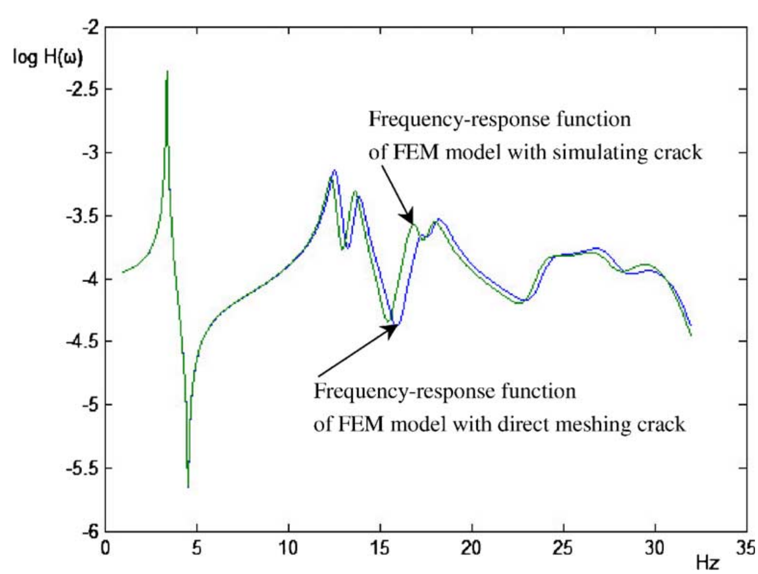


Fig. 4. Frequency-response functions of two kinds of models.

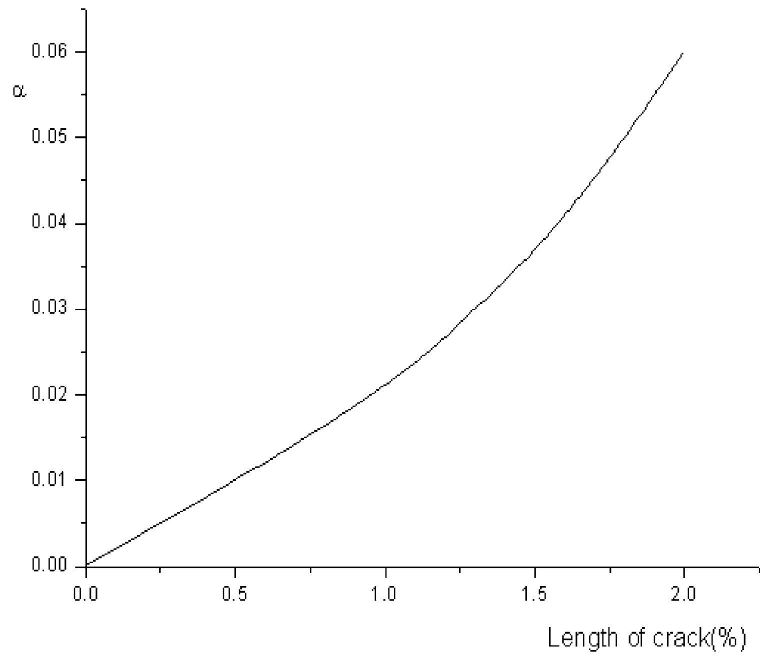
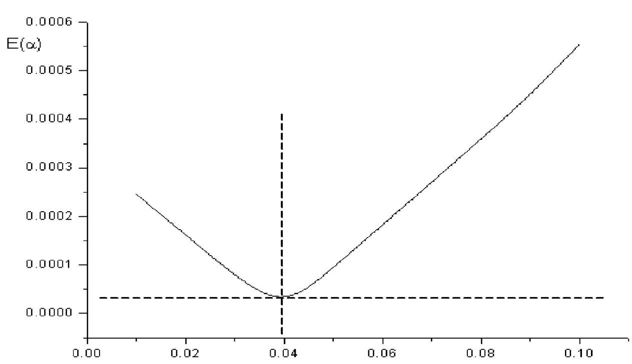


Fig. 5. Crack length versus α.



Crack length=0.4% L in position II

Fig. 6. $E(\alpha)$ versus α.

fact, the function of α is not only to simulate local structural damage, but also to improve difference between two kinds of models with different mesh. Perhaps, this is because simulating changes to few elements stiffness matrix leads to improvement of the global stiffness matrix.

It is known that accurate detection for the position and severity of structural damage will depend on the integrality of the acquired sample data in advance for dynamics characteristics of all damage status of the detected structures. However, the obtained damage sample data from real structures often are very few because structural damage in real structures does not frequently occur. On the other hand, it is not completely feasible to acquire a large numbers of structural damage sample data using experimental measure due to many samples of damaged structures must be manufactured. Therefore, it is more usable to obtain a large numbers of structural damage sample data using numerical simulation by the established structural dynamics model. Modeling method for damaged structure proposed in this study can provide reliable and convenient method for acquirement of structural damage sample data using numerical simulation.

5. Conclusions

Based on the analysis for existing problems in modeling engineering structures with small damage using current commercial structural analysis software, an improved modeling method is proposed in this study. In this method small structural damage is expressed using variations of stiffness matrix of several elements. Since superfluous FEM gridding is avoided, the improved method can be used to establish FEM model for structures with small damage. It is more efficient to use this new model to obtain structural dynamic response, which will be used for structural damage detection.

Results from the given example show that there exists such a good coherence between two frequency-response functions at a wide frequency range that is up to the first 30 orders of the structural natural frequency. At the same time, severity and position of structural damage can be indicated using a modification coefficient for element stiffness matrix in damaged location. Although the obtained results are based on a special example, the modeling method proposed in this study can still be able to be adopted for establishing dynamics model for different structures with multiple damage status and different constraint conditions.

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