INFLUENCE OF ROTATIONAL DEGREES OF FREEDOM IN MODEL UPDATING OF A SIMPLE 3-D STEEL STRUCTURE

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ABSTRACT

When a building suffers damage under moderate to severe environmental loadings, its physical properties such as damping and stiffness parameters are changed. There are different practical methods besides various numerical procedures that could be successful to detect a range of these changes. Almost all proposed model updating methods have been used translational components of mode shapes, because only these components are identified from vibration tests. This paper focused on considering importance of using some rotational/translational components of the mode shapes to detect beam/column damages in a 3-D structure. Objective functions are defined based on combination of two criteria of these four ones: comparison between frequencies and/or mode shapes of two situations, the modal assurance criteria (MAC), and the modal flexibility matrix. Four measured components are examined: 3-components of master joint, all translational/ or rotational components, and all components of mode shapes. In order to evaluate effectiveness of the assumptions, three damage scenarios are considered: damage is occurred in a column, in a beam, and in both of them. In order to analysis, an automatic iterative model updating method has been developed in MATLAB software that uses OpenSees as its finite element analysis engine. Extensive analysis shows that for model updating procedure employing rotational components is vital to detect beam damages. In addition, using the modal flexibility matrix based objective function besides measuring the rotational components of mode shape vectors can result in a very precise prediction of the damage locations and their intensities for both beams and columns elements.

Keywords: Model Updating Method; Iterative Optimization Method; Damage Detection Method; Rotational DOFs; Translational DOFs

1. INTRODUCTION

Structural damage assessment and health monitoring have been developed in the last few decades. Detecting damages in a structure due to operational loads, impact load, earthquake, corrosion or other events in the structure, can provide vital information about the structural and its operational state. Traditional methods of damage identification, either visual or localized experimental methods, require the vicinity of the damage be known and accessible, that is somehow impossible in complicated structures. So there is a need for providing more applicable techniques for damage detection in complicated structures.

It is obvious that damage in a structure changes the structural characteristics, such as stiffness, and mass which effect on dynamic properties, therefore plentiful of vibration-based damage detection methods have been developed in the literature. Vibration-based damage detection methods are promising because they can detect structural damage quickly and cost-effectively. Some of these damage detection methods minimize an objective or error function, which is defined in terms of the

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discrepancies between the vibration data identified by modal testing and those computed from the analytical model. Research on the use of vibration and modal data to detect, locate and quantify damage in civil structures has vastly increased in the past two decades.

Different detection methods in order to define their objective functions have been used different modal parameters. Some of them completely rely on changes in natural frequencies (H.Y. Wang et al. 1997, Z. Ismail et al. 2012 and M.M. Fayyadh et al. 2011),while some others need information of mode shapes, modal damping, etc. (A.G.A. Rahman et all 2011 & 2013 and Z. Ismail et all 2012 & 2006). Methods based on measuring modal assurance criteria (MAC) (C. Fox 1992), modal strain energy (N. Stubbs 1995), modal strain energy decomposition (H.Z. Yang et al. 2003 & 2004) and dynamically measured flexibility matrix are few examples. Among those, the dynamically measured modal flexibility matrix method is based on the fact that a damaged member alters the flexibility of its related degrees of freedom. Pandey and Biswas (A.K. Pandey et al. 1964) presented a detection and localization method based on changes in the measured modal flexibility of the structure. The results of the numerical and experimental examples of their method showed that damage locations by using only the first few modes can be detected. These examples demonstrated that the modal flexibility method which employs mixed form of both natural frequencies and mode shapes is more sensitive to damage than other methods based on natural frequencies or mode shapes alone (A. Yan et al. 2005 and B. Jaishia et al. 2006).

This paper focused on considering importance of using model updating procedure employed some rotational/translational components of the mode shapes of a 3-D damaged structure to detect beam/column damages. Three combined criteria are used as objective functions such that comparison of the 1st few frequencies of the measured and analytical values is common between all of them, so the added function to each criterion is: (1) comparing discrepancies between mode shapes of two situations, (2) the modal assurance criteria (MAC), and (3) the modal flexibility matrix. Four measured components are examined: (a) 3-components of master joint, (b) all translational components, (c) all rotational components, and (d) all components of mode shapes. In order to evaluate effectiveness of the assumptions, three damage scenarios are considered: (i) damage is occurred in a column element, (ii) in a beam element, and (iii) in both of them. Extensive analysis is carried out on a 3-D steel moment frame.

2. MODEL UPDATING PROGRAM

In order to analysis, an automatic iterative model updating method has been developed in MATLAB software that uses OpenSees as its finite element analysis engine. This program using a kind of sensitivity analysis, update some items iteratively during the analysis process.

As mentioned above, in this paper three damage scenarios are considered: (i) one damage is only in a column element, say element No. 2, (ii) one damage is in a beam element, say element No. 6, and finally (iii) two damages are in a column element and a beam element, say elements No. 2 & 6. The damaged elements are assumed as elements with reduced stiffness values, which are defined by percentage of stiffness reduction with respect to the undamaged values. The finite element model of the 3-D steel moment resisting frame structure is formed in the OpenSees software. Since in this research there is no experimental data, it is assumed that the modal information of each real damaged structural model is the measured information. Damage detection procedure starts by using the intact undamaged FE model. In each step by determining damage parameters and correcting the stiffness coefficient of the concern elements into the last previous model, the instant corrected model is determined. This iterative procedure is continued until the optimization criteria are completely fulfilled. For this purpose, an optimization procedure is designed in MATLAB software, and various objective functions are defined such that in each set of analysis some of them are used. In order to minimize these objective functions nonlinear least square method that is the most efficient algorithm is implemented. It shall be mentioned that, in this program by changing stiffness coefficient in each steps, MATLAB automatically defines a new model in OpenSees by modified members' stiffness. After doing finite element analysis by OpenSees, modal data of modified structure will be used to evaluate objective functions.

2.1 Objective Functions

Objective functions are a measure of residual between the experimental data and the predicted response that is extracted from a finite element analysis. Several kinds of objective functions have been used in the literature. In this paper, four error functions are defined such that in each analysis two of them are used as an objective function that should be minimized. Structural responses, which are used in the model updating process, are modal frequencies and mode shape vectors of the 3-D frame model. Four error functions are defined as below:
The 1st error function. This function has already been the most practical function that is used in almost always cases of identification or damage detection procedures. This error function compares the progressive analytical modal frequencies with the concern measured modal data which is extracted from an experiment. If Λ_A and Λ_E represent the analytical and experimental eigenvalues, the 1st error function is estimated as follows:

$$EF1 = \frac{([\Lambda_A] - [\Lambda_E])}{[\Lambda_E]} \tag{1}$$

The 2nd error function. Difference between experimental and analytical elements of the mode shape vectors has been widely used before as an error function. It is given by:

$$EF2 = [\emptyset_A] - [\emptyset_E] \tag{2}$$

The 3rd error function. The Modal Assurance Criterion (MAC) is one of the common objective functions, and has been widely used by many researchers. This function provides a measure of consistency between experimental and analytical mode shape vectors and is defined as follow:

$$MAC\left(\emptyset_{A\,i}, \emptyset_{E\,j}\right) = \frac{\left|\emptyset_{A\,i}^{\,T}\emptyset_{E\,j}\right|^2}{(\emptyset_{A\,i}^{\,T}\emptyset_{A\,i})(\emptyset_{E\,j}^{\,T}\emptyset_{E\,j})} \tag{3}$$

Where, $\emptyset_A$ and $\emptyset_E$ represent the analytical and experimental mode shape vectors, respectively. The error function 3 is based on MAC and is given by:

$$EF3 = [\mathrm{I}] - MAC\left(\emptyset_{A\,i}, \emptyset_{E\,j}\right) \tag{4}$$

The 4th error function. The last error function is defined as the difference between the measured and analytical modal flexibility matrices that is calculated based on modal information as follows:

$$EF4 = \|[\emptyset_A][\Lambda_A]^{-1}[\emptyset_A]^T - [\emptyset_E][\Lambda_E]^{-1}[\emptyset_E]^T\| \tag{5}$$

As mentioned above, based on these error functions, three combined objective functions are formed. These are as follows: (1) employing EF1 and EF2, as a routine criterion, (2) employing EF1 and EF3, and finally (3) employing EF4. Performance of these objective functions is examined in the following parts of the paper.

3. FINITE ELEMENT MODEL

A simple three dimensional steel moment frame is modeled in OpenSees software, Figure 1. The columns and beams sections are selected from the European standard profiles: IPB160 and IPE180, respectively. This simple 3-D structure is modeled as a one bay one story frame. Length of each bay in the X and Y directions are the same as four meters, and its height is five meters. It should be mentioned that the roof is considered as an integrated diaphragm.

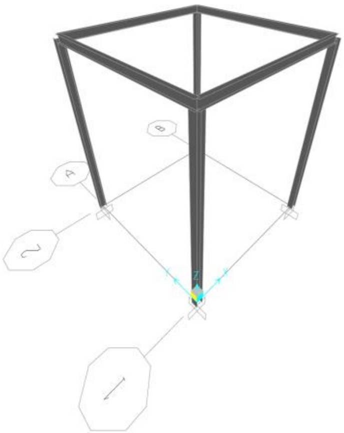

Figure 1. Simple three dimensional steel moment frame

3.1 Damage Scenarios

In this paper, damage is defined as a reduction in the element stiffness value as a percentage of the undamaged value. Three damage scenarios are considered: (i) the column element No. 2, (ii) the beam element No. 6, and (iii) the column element No. 2 and the beam element No. 6. Table 1 shows the amount of stiffness reduction in elements in all scenarios. In this table element's name is based on axes name on Figure 1.

Table 1. The damage scenarios

Scenario (i)		**Scenario (ii)**		**Scenario (iii)**	
Element	Damage Ratio	Element	Damage Ratio	Element	Damage Ratio
Column B1	30%	Beam A2-B2	40%	Column B1	30%
Element No. 2		Element No. 6		Beam A2-B2	40%

3.2 Measurement Methods

In order to detect damaged elements in a structure via model updating methods, some experimental tests should be designed and performed on that structure. Several type of data could be gathered and compared with analytical ones. But, the most practical data is the modal information such as frequencies and mode shape vectors. In this paper, all objective functions use the 1st four modal information of the structure.

Four measured components based on the 3 dimensional mode shape vectors of the model structure are examined: (a) 3-components of master joint, (b) all translational components, (c) all rotational components, and (d) all components of the mode shapes.

4. RESULTS AND DISCUSSION

The damage estimation for the three damage scenarios employing the three different objective functions as well as four measurement methods is examined. Since there is no experimental data in this project, all obtained or measured data determined from analysis of models in different situations. By using iterative optimization process all damaged elements are determined. Results of different sets of analysis has been classified based on their objective functions, and are presented in the following parts.

4.1 The objective function 1

This objective function by using EF1 and EF2 compares the first four frequencies and mode shape vectors obtained from two situations: measured from the damaged structure and determined from the analytical model in each iterative step. Different damage scenarios: *i.e.* (*i*), to (*iii*), as well as various measurement methods, *i.e.* (a) to (d), have been investigated by this function. Results show that in none of situations, this objective function couldn't correctly detect location or intensity of damages. In other words, this objective function is not so powerful to be employed for damage detection of 3-D structures.

4.2 The objective function 2

This objective function by employing EF1 and EF3, is examined the first four frequencies and the rule constructed based on the MAC criteria. Different damage scenarios: *i.e.* (*i*), to (*iii*), as well as various measurement methods, *i.e.* (a) to (d), have been investigated by this function. Results demonstrate that some sort of data is not so rich to correctly detect damages. For example measurement method (a) that consists of master joints' displacements and rotation data, could not predict damage location in none of the scenarios. It seems in this situation, there are very limited damage equations that the correct answer could be determined. But on the other hand, there is another measurement method, say (d), that it could accurately estimate damage locations and their concern intensities for almost all scenarios.
There are some noticing items: as it can be seen in Figure 2, for damage scenario (*i*), measuring only displacements of joints can result in prediction of the damage precisely. Also when all degrees of freedom including rotations and displacements are used, damage is detected very carefully. In other words, by employing this objective function, for correctly detection of columns' damages using translational measurement data is necessary.

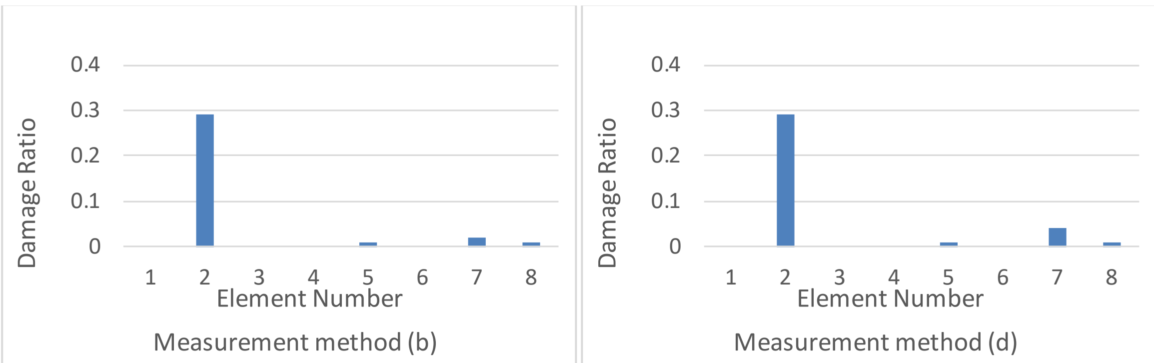

Figure 2. Results of the objective function 2, in scenario *(i)*

Figure 3 illustrates the damage detection results for the scenario (*ii*). In this scenario a beam element is damaged. Two measurement method (c) and (d) are successful to correctly detect location and intensity of damage. Both of these methods use rotational degrees of freedom in model updating process. In other words, for correctly detection of beams' damages it seems using rotational measurement data is necessary. Though, measuring rotational DOFs are a little weird!
There are some noticing items: Although, both methods could accurately detect location, but method (c) inaccurately detect 5% damages for elements 1 and 2. And also the method (c) estimates the intensity of real damages of element 6 a little smaller than (about 38%) the real value (40%). On the other hand, the method (d) was very good at detection of both location and intensity. There is a small point here that, maybe better estimation of method (d) with respect to (c) is for greater number of measurement data. This should be examined in the future.

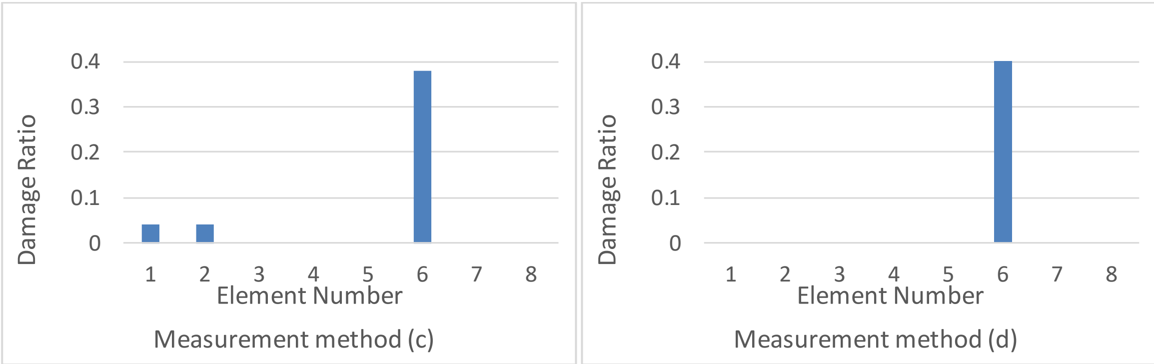

Figure 3. Results of the objective function 2, in scenario *(ii)*

At last, Figure 4 shows the results for scenario (*iii*) that contains damage in the two elements; the column No. 2 and the beam No. 6. In this scenario, with objective function that consists of MAC and modal frequencies, only measurement method (d) that uses all degree of freedoms data could predicts the damaged elements and their related intensities. It seems by increasing the number of damaged elements of the structure, model updating procedure needs more measured information from the real structure, to be able to correctly detect location and intensities of damages.

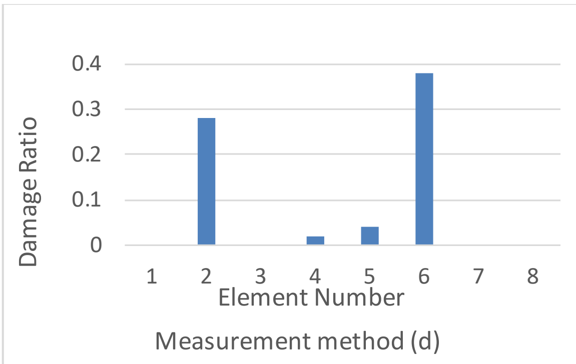

Figure 4. Results of the objective function 2, in scenario *(iii)*

4.3 The objective function 3

This objective function by employing EF4 compares the modal flexibility matrices for the first four mode information between the damaged structure and the analytical model. Different damage scenarios: *i.e.* (*i*), to (*iii*), as well as various measurement methods, *i.e.* (a) to (d), have been investigated by this function. The results are a bit stunning, because in all scenarios, the measurement method (c), which consists of the only rotational data, presented the best prediction for the both damage locations and their concern intensities. Figures 5, 6 and 7 show the estimated damages in the three assumed scenarios. It is clear that except some minor deviation in the results of scenario (*ii*), the damaged elements are correctly detected and the amount of the damage is precisely estimated.
There are some noticing items: It seems that detection of beam damages when there is no any damaged column is more difficult than detection of damaged columns. By using the flexibility method, even measuring only the rotational values of DOFs may result in a correct detection of both location and intensity of beams and/or columns damages.

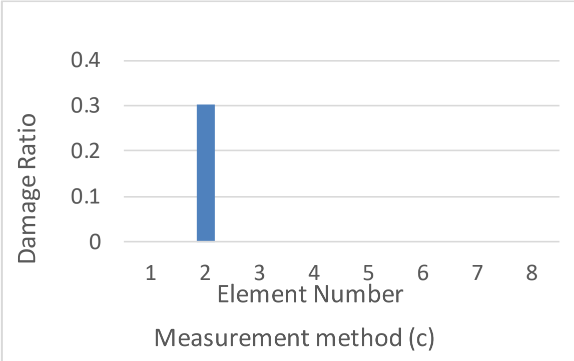

Figure 5. Results of the objective function 3, in scenario *(i)*

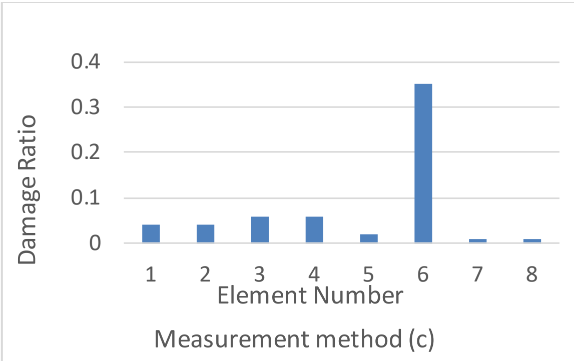

Figure 6. Results of the objective function 3, in scenario *(ii)*

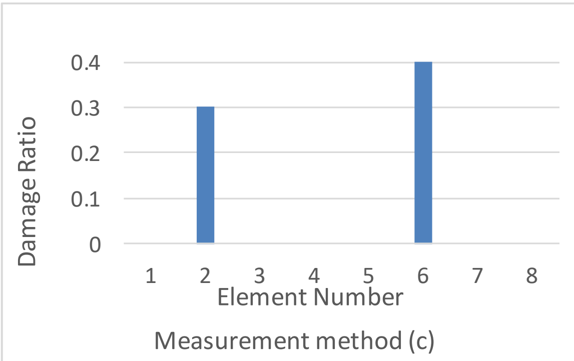

Figure 7. Results of the objective function 3, in scenario *(iii)*

5. CONCLUSIONS

Almost all proposed model updating methods have been already proposed employed translational components of mode shapes, because only these components are identified from vibration tests. This paper focused on considering importance of using some rotational/translational components of the mode shapes in damage detection of a 3-D steel moment resisting frame structure. Different objective functions as well as various measured methods are examined for detection of damages occurred in a beam, a column, and both together. Three objective functions are defined based on combinations of the modal information, MAC, and the modal flexibility matrix. Four measured components are examined: 3-components of master joint, all translational components, all rotational components, and all components of mode shapes. In order to analysis, an automatic iterative model updating method has been developed in MATLAB software that uses OpenSees as its finite element analysis engine. Extensive analysis shows that using some simple objective functions like mode shape difference are not able to update a 3-D structural model. But, some other combinations between the measurement method and the objective function are very successful to detect not only location of damages but also their intensities. For instance, using the modal flexibility matrix based objective function besides measuring the rotational components of mode shape vectors can result in a very precisely predicting of the damage locations and their intensities for both beams and columns of a 3-D structure. On the other hand, employing MAC as an objective function leads to discussing results. By measuring all degrees of freedom data, detection results are perfect. But, it is noticed that when using MAC criteria for detection of column damages, measuring displacement data are very suitable but for beam damages, measuring rotational data are more appropriated.

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