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STRUCTRUAL DAMAGE DETECTION USING CHANGES IN STIFFNESS PROPERTIES WITH MODAL UPDATE TECHNOLOGY

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Abstract

All structures need to be periodically inspected to ensure that they are effective and safe for their intended use. Traditional evaluation methods have relied heavily on visual inspection; however, it is difficult to use visual inspection to detect internal damage or damage in inaccessible areas. One solution to this problem would be an evaluation method that uses global indices of the structure to determine local functionality.

Utilization of vibrational techniques for damage detection has been applied in the field of non-destructive evaluation in limited situations. Structural damage will cause changes in structural properties. These changes may be detected through structural health monitoring techniques. Because of the direct relationship between stiffness, mass, and damping of a multi-degree-of-freedom system to the natural frequencies, mode shapes, and modal damping values, many studies have focused on using these dynamic properties for the purpose of structural health monitoring.

In this paper, a new method of using changes in stiffness properties of a structure for damage identification and localization is introduced and an example of its application is provided. The representative comparison is presented using simulation data from the ASCE Benchmark steel structure at the University of British Columbia.

INTRODUCTION

Many in-service civil structures have exceeded their original intended service life. Continued interest among engineers has been focused on the utilization of vibrational techniques in the fields of nondestructive evaluation and damage detection for these structures. Most structural health monitoring techniques require experimental data recorded from in-situ structural response. If structural damage occurs, it leads to changes in the modal frequencies and mode shapes of a structure. Hence, the shifting of the natural frequencies can be used as an indication of damage. However, these modal changes do not typically provide sufficient information to locate or quantify the damage.

In this paper, a proposed damage detection approach is developed which uses modal update technology. This approach uses the system identification (SI) technique known as the Frequency Domain Decomposition (FDD). The structural characteristics, such as natural frequency and mode shapes, are extracted using this method. It is critical to correctly identify the system modal parameters for the proposed damage detection method, because the modal update process is dependent on the identified natural frequencies and mode shapes. If the identified natural frequencies (eigenvalues) and mode shapes (eigenvectors) are incorrect, the updated stiffness matrices would not accurately represent the actual structure.

PROPOSED METHODOLOGY

The proposed damage detection approach consists of two major parts: system identification (SI) and a modal updating process (Baruch 1982). System identification techniques are utilized to obtain the overall natural frequencies and mode shapes of the structure. The identified natural frequencies and mode shapes are then used to calibrate the initial structural model. Once the initial stiffness matrix is calibrated with modal parameters, subsequent structural damage, resulting in modal changes, can be used to locate and quantify the damage.

The objective of using the modal updating process is to obtain a model which can accurately represent the actual structure. The calibrated, undamaged, finite-element model (using measured structural response) is used as the baseline model. By repeating the same process with the subsequent damage data sets, the updated, damaged, finite-element model can be obtained. To validate the process, the eigen-solutions calculated from the updated models need to be similar to those obtained experimentally. To do so, the boundary conditions of the structure need to be correctly identified. The proposed methodology does assume that because changes in mass are typically negligible, the mass matrix will remain unchanged before and after damage.

SYSTEM IDENTIFICATION

As previously mentioned, using a system identification technique is the first major step in using the proposed methodology. The purpose of this step is to determine the structural modal parameters from the collected data. The general concepts of this system identification method are briefly discussed and summarized.

The Frequency Domain Decomposition (FDD) technique is an expansion of the traditional frequency domain approach (Brincker et al. 2001). Signal processing utilizing a discrete Fourier transform is the typical approach of domain decomposition. The Frequency Domain Decomposition (FDD) method identifies the power spectral density (PSD) matrix from the output signals by using auto spectral density functions and cross spectral density functions. As described in its name, FDD falls in the category of frequency domain analysis. The power spectral density matrix is decomposed at every discrete frequency line by Singular Value Decomposition (SVD). The diagonal singular value matrix is then plotted versus frequency, where the natural frequencies are represented by the peaks of this plot. One of the advantages of this approach is that the reference and input excitations can be unknown.

CASE STUDY

In this section, the damage detection approach presented is applied to the computer generated simulation data provided by the ASCE benchmark problem. The ASCE benchmark steel building is a four-story, two by two bay, steel frame building (Figure 1) that is located at the University of British Columbia (UBC Building). There is one undamaged and three damage condition states in this study. The undamaged state is used as the baseline model. Other damaged states are explained and compared with the baseline model to determine the location and magnitude of the damage. Since the global structure stiffness is a function of the local element stiffness information, the local damaged elements will result in stiffness changes in the global stiffness matrix. If damage has occurred, the severity and location of the damage can be identified by comparing the changes in global stiffness matrices. By comparing the changes in stiffness at the location of each DOF, the proposed procedure can quantify the location and the extent of the damage.

Each bay width is 1.25 meters which give the building a square footprint of 2.5 meters. All story heights are 0.9 meters. The finite-element model used in this study has 120 degrees-of-freedom (DOF), which allows out-of-plane motion and rotation. The in-plane motion is restrained. A more detailed description of this building can be found at Johnson et al. (2004).

There are four simulated condition states for the ASCE benchmark study. The initial, undamaged condition state is used as the baseline model (U-1). There are three other damage scenarios studied for this study. The second condition state (U-2), is created by removing brace element number 22 at the first story. The third condition state (U-3), is created by removing two braces on the north face in the first story. The braces removed are elements 22 and 23 (figure 2). The fourth condition state (U-4), is created by removing four brace elements in the X direction (two braces on the south face and two braces on the north face) in the first story. These damage states are summarized in Table 1 and the orientation of the damaged brace elements are shown in Figure 2.

By applying the previously mentioned system identification method, Frequency Domain Decomposition (FDD), the identified natural frequencies (first eight modes) for the four condition states were obtained and are summarized in Table 2. The "diff2" listed on Table 2 signifies the difference (between U-1 and U-2) divided by U-1 reported as a percentage. The negative sign signifies U-2 is less than U-1. Similar procedures were used to obtain "diff3" and "diff4."

Table 2 shows that the first eight modes of this structure are affected differently by the removal of one, two, and four braces at the first story. Mode one represents the first mode in the X direction for the structure. The first mode has the largest percent reduction for the identified natural frequencies. This is an expected result since all the braces removed provided stiffness in the X direction. By contrast, modes 2 through 8 generally exhibited softening behavior to a lesser degree than mode one. The exception is mode three, which exhibited a slight increase in natural frequency which cannot be easily explained. Because decreases in identified natural frequencies are indicators of structural damage, the percent shift is an indication that this structure has been damaged. However, using natural frequencies alone, the details of the damage are obscure.

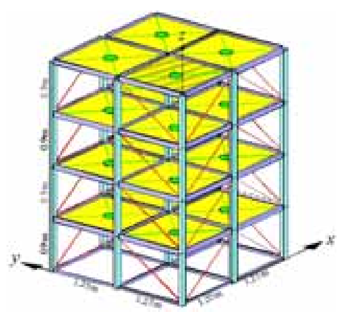

Figure 1. ASCE benchmark steel building (Ventura et al, 1997).

Table 1. Descriptions of damage states

Damage State	Damage Description.
U-1	Baseline model.
U-2	Brace element 22 is removed.
U-3	Brace elements 22 and 23 are removed.
U-4	Brace elements 22,23,26, and 27 removed

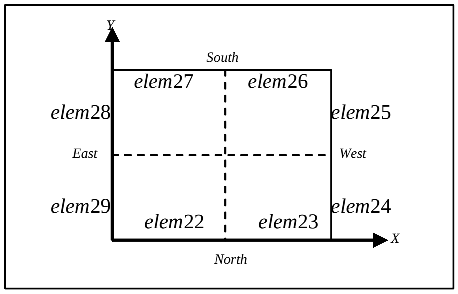

Figure 2. Orientation of the brace elements at the first story.

Table 2. Identified natural frequencies in Hz

	U-1	**U-2**	Diff2	**U-3**	Diff3	**U-4**	Diff4
1	8.27	8.21	*-0.73*	7.30	*-11.73*	6.80	*-17.78*
2	8.31	8.31	*0.00*	8.31	*0.00*	8.31	*0.00*
3	13.47	13.65	*1.34*	13.65	*1.34*	14.65	*8.76*
4	22.91	23.31	*1.75*	22.91	*0.00*	20.49	*-10.56*
5	23.41	23.41	*0.00*	23.01	*-1.71*	22.91	*-2.14*
6	34.69	37.11	*6.98*	34.69	*0.00*	34.69	*0.00*
7	39.02	38.12	*-2.31*	37.11	*-4.89*	37.11	*-4.89*
8	40.53	40.63	*0.25*	38.62	*-4.71*	38.12	*-5.95*

In order to confirm that the modes investigated are similar from one condition state to the next, the Modal Assurance Criterion (MAC) (Lieven and Ewins 1988) numbers are calculated to compare the modal shapes. These MAC numbers are summarized in Table 3. A MAC number above 0.95 indicates that the modes are very similar. The very high MAC numbers in table 3 indicate that the mode shapes are consistent through the various condition states. The proposed damage detection methodology utilizes the changes in natural frequencies, as well as any detectable changes in mode shapes to calibrate the stiffness matrix of the structural model. In this way the calibrated global stiffness matrices from each condition state can be compared to the stiffness matrix from the baseline model and changes in stiffness can be detected. These stiffness matrix changes can be utilized to identify both the location and the extent of the identified damage. Table 4 summarizes the story stiffness for the four different condition states in the X direction. Note the percent difference (e.g. diff3) is defined as the difference between U-3 and U-1 divided by U-1.

Based on the results presented in Table 4, it is observed that the first story stiffness has decreased significantly. For example, the story 1 percent stiffness reduction in the X direction for "Diff4" is approximately two times larger than 'Diff3' and four times larger than 'Diff2'.

This large reduction in stiffness indicates that the damage occurred on the first story. Other small story stiffness variations listed in Table 4 are believed to have resulted from the calculation of the modal update process and small variations in the identified natural frequencies and mode shapes. By observation, damage state 4 (U-4) is larger than damage states 2 and 3. Overall, the results from Table 4 match the assumption made in the problem statement. The relationship between the number of removed brace elements and the percent stiffness reduction in the X direction and in rotation is presented in Figure 3.

Removing two braces results in 26 percent reduction and removing four braces in the X direction causes nearly a 60 percent reduction. Figure 3 shows that for this building, the relationship between the stiffness reduction and the number of removed braces is nearly linear.

Table 3. MAC numbers for four damage cases

Mode	U-1	U-2	U-3	U-4
1	1.000	0.9989	0.9981	0.9988
2	1.000	0.9990	0.9936	0.9978
3	1.000	0.9977	0.9828	0.9946
4	1.000	0.9894	0.9983	0.9927

Table 4. Comparison of identified story stiffness parameters (X direction)

Story	U-1 (N/m)	U-2 (N/m)	Diff2	U-3 (N/m)	Diff3	U-4 (N/m)	Diff4
1	1.07E8	9.45E7	-11.68	7.88E7	-26.36	4.35E7	-59.35
2	1.08E8	1.09E8	0.93	1.06E8	-1.85	1.06E8	-1.85
3	1.08E8	1.08E8	0.00	1.06E8	-1.85	1.06E8	-1.85
4	7.82E7	7.72E7	-1. 28	7.70E7	-1.53	7.80E7	-0.26

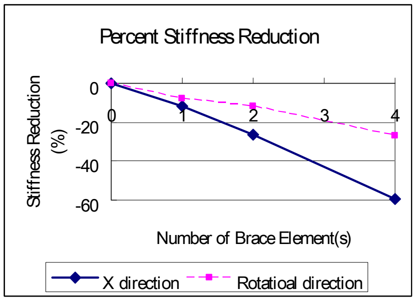

Figure 3. Stiffness reduction (%) in the X and rotational directions due to removing brace(s).

CONCLUSIONS

The proposed damage detection approach, based on the comparison of updated stiffness matrices obtained using the before and after damage state, has been shown to successfully identify the location and severity of damage for the UBC steel building. A statistically significant reduction in the modal frequencies of a structure is a reliable indicator of damage. It is believed that the proposed damage detection methodology can be extended and applied to structural health monitoring of general civil structures.

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