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A METHOD FOR IMPLEMENTATION OF DAMAGE DETECTION ALGORITHMS FOR CIVIL SHM SYSTEMS

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Abstract

A method for implementation of damage detection algorithms for ambient-vibration based structural health monitoring systems is presented. The method can be described in three parts: development of the damage detection methodology (DDM) for use in the system, development of a set of simulations of damaged data, and the optimization of the sensor locations. The DDM is developed by combining multiple damage detection algorithms. This is done to increase the robustness of the DDM. A set of calibrated damage simulations (CDS) for evaluation of the damage detection methodology is developed based on a finite element model and real data obtained from an ambient vibration test of the structure. Once the DDM is satisfactory, the implementation method can be iterated to find the optimal layout of the sensors. The DDM was initially developed using a 2D truss and a 3D frame example; the CDS was illustrated using real datasets from the 3D frame. Then the implementation method was applied to two building case studies.

INTRODUCTION

The future use of structural health monitoring (SHM) technology for civil structures is a topic of great interest to both the academic and industry communities. The link however between the present state of the technology and that of future use is not yet defined. The primary idea of a SHM system is to provide a means of evaluating the state of the structure remotely, without visual inspection. Such a system will do so using two components: a hardware system for the physical measurement and a software system for processing the measurements.

The current state of the hardware technology for monitoring is well established; there are many companies that provide monitoring systems, and there are many examples of structures that are currently monitored. On the other hand, a gap exists between the development of the software component and its application on real structures. The main field for the software component with respect to vibration-based SHM systems is usually referred to as damage detection. This implies that based on the vibration measurements, some sort of algorithm will process the data to identify if, where, and to what extent the structure has been damaged. Many of these algorithms that have been developed are very complex and have not yet been seen applied to real structures. The research project described in this paper focuses mainly on the software component of the SHM system. A method for the implementation of these algorithms is proposed. This method is based on the idea that the damage detection algorithms need to be properly evaluated for the specific structure of interest.

While this project focuses on the implementation of the damage detection algorithms, there are many other issues that have hindered the implementation of structural health monitoring in general. Some of these issues include variations of modal parameters due to temperature and other environmental effects; repeatability of the test measurements; automation of the systems; definition of the threshold of damage as indicated by changes in the modal parameters. Two other important practical issues deal with the interface between the system and the owner; and with the definition of damage that the system is intended to identify. Both of these issues affect the design of the SHM system, since they will dictate its final objective. The implementation method as it is presented here is focussed on the damage detection algorithms and uses two specific algorithms as an example. It can be expanded to address these other issues to become a complete implementation method for the SHM system..

CONCEPT OF THE IMPLEMENTATION METHOD

One of the difficulties with the implementation of vibration-based SHM systems is with the uncertainty in the performance of the damage detection component. There are many different vibration-based damage detection algorithms, but it is difficult to determine whether these algorithms will work with real structures. Since the primary obstacle for implementation is evaluating these algorithms and determining if they will work, then consequently the method must feature a way to evaluate the damage detection algorithms.

The implementation method can be described in three parts: first, the damage detection methodology that will be used in the system must be developed; second, a set of calibrated damaged simulations are created to evaluate the DDM; and third, the method is iterated until the DDM is satisfactory and the optimal sensor layout is found. The method is described in Figure 1.

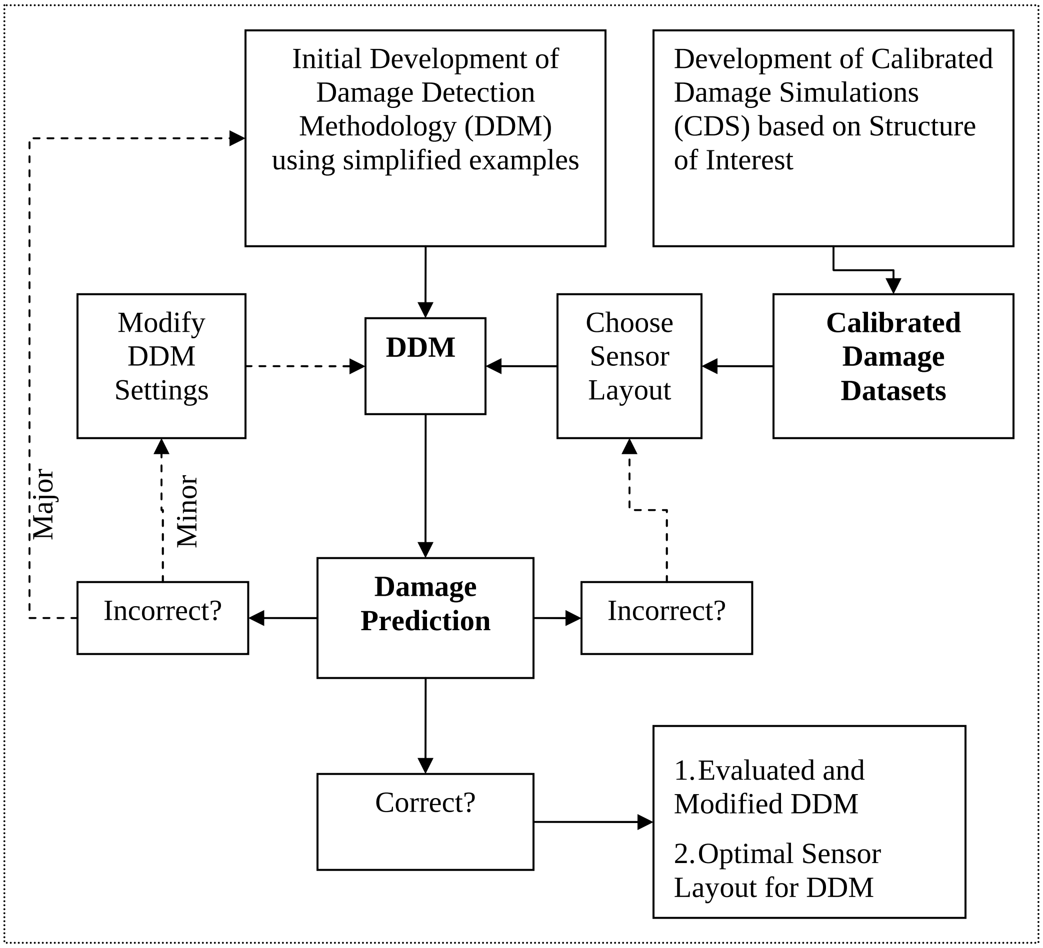

Figure 1. Implementation Method

Once the CDS and the DDM have been created, the next step is to choose the initial sensor layout for the structure. Then, the simulated datasets from those points in the FEM are extracted, and processed with the DDM. If the results are not satisfactory, the process is iterated in one of two ways. If the results are incorrect but reasonable, then the sensor layout can be iterated. This is considered the optimization process of the method; the optimal layout of the sensors (ie. minimal number to find the damage) can be determined. If the results are incorrect and not satisfactory, iterations of the DDM can be made. A minor iteration is considered to be modification of the settings within the DDM, while a major iteration is one that may require addition or removal of a damage detection algorithm. Full details are presented in [Turek, 2007]. The goals of the implementation method are first to provide a DDM that can be used in the SHM system. The DDM has been evaluated and modified according to the process described. Secondly, the optimal layout of the sensors according to what is required by the DDM can be found. There may be additional influences on the sensor layout other than what is found in the implementation method.

CALIBRATED DAMAGE SIMULATIONS

The development of the calibrated damage simulations (CDS) is the first key concept of the implementation method. One of the main ideas behind this project is that the DDM must be properly evaluated; the best way to do this would be to damage the building of interest and obtain real datasets. Since this is not feasible for a real structure, a simulation must be performed. The idea of the calibrated simulations is that they will reproduce as closely as possible the actual vibrations of the structure, should it be damaged. They are calibrated using the results of an ambient vibration test on the undamaged operating state of the structure. Then, a FEM of the structure is constructed, and ambient vibration simulations are performed with the model using various aspects of the AVT to calibrate the results.

The CDS method is divided into several steps, described as follows:

1. An ambient vibration test of the building is performed.
2. An FEM is designed and updated by correlation with the frequencies and mode shapes from the AVT.
3. The FEM is used for the simulations. Several things can be incorporated into the simulations from the AVT:
   i. The modal damping estimates;
   ii. The simulation input; created by using the actual measured ground level vibrations in combination with a random white noise signal.
4. Damage cases must be chosen as to best represent the likely damage scenarios expected.
5. Once the datasets have been created, noise is added to the signals. The noise is applied as a coloured noise added to the simulated time signals.
6. The sensor locations must be chosen.
7. The final datasets are created by extracting time history records from the chosen sensor set locations.

Details of the development of the CDS are presented in [Turek and Ventura, 2007]. It is illustrated using the IASC/ASCE Benchmark Frame [Ventura et al., 2003], due to the fact that there are real damaged datasets available from the benchmark study. It was shown that the CDS can provide a good representation of the real datasets.

DAMAGE DETECTION METHODOLOGY

The development of the DDM is the second key concept of the implementation method. The main concept of the damage detection methodology is that in order to achieve a robust and accurate methodology, two or more damage detection algorithms must be combined. The methodology uses two damage detection algorithms as the primary ‘core’ of the methodology, then the predictions are processed statistically, and lastly, filtered through a third damage detection technique in an attempt to eliminate false predictions.

In the DDM example that was developed in this project, the Damage Locating Vector (DLV) technique [Bernal and Gunes, 2004] was chosen as the primary damage detection algorithm. The DLV technique is a flexibility-based technique; a flexibility matrix can be assembled from the measured mode shapes and natural frequencies. To apply the technique, a flexibility matrix from the undamaged state and a damaged state are required, and the change in flexibility is obtained. From that change in flexibility, a series of ‘damage locating vectors’ (DLV’s) are obtained. These DLV’s are applied to a model of the structure as static loads; in the resulting structural response, those elements that have zero stresses are considered to be damaged.

One of the requirements of the DLV technique is that scaled mode shapes are required to get the exact flexibility matrix. In ambient vibration, or output-only testing, the scaled mode shapes are not available. Therefore, approximate or equivalent flexibilities are obtained instead. Two techniques to obtain those equivalent matrices are used: the Stocastic Damage Locating Vector (SDLV) [Bernal, 2006] and the Proportional Flexibility Matrix (PFM) [Duan et al., 2005] techniques.

It is typical practice to begin the development of a DDA using simple examples. In this project, the DDM was initially developed in the same way. Then, the methodology is ‘evolved’ to adapt to more complex examples. First the methodology was developed for a 2D truss example. The simplicity of the truss example allows for a clear development of the DDM. Then, the DDM was applied to the IASC/ASCE Benchmark frame, as a three-dimensional example. This frame is a useful example because real datasets are available for the damage cases. The results were presented in [Turek and Ventura, 2007b], and indicated that the combined methodology had the most consistent and successful results.

APPLICATION OF METHOD TO CASE STUDIES

To demonstrate the implementation method, it was applied to real building case studies. Initially there was only one building, but due to difficulties at several stages of the method, and due the fact that the first building was very large and complex, a second case study was added. The first case study was the Melville, a 44 story reinforced concrete building. The second case study was the Heritage Court Tower (HCT), a fifteen a story reinforced concrete building. Both are located in downtown Vancouver, Canada. Photos of the two buildings are shown in Figure 2.

Figure 2. Heritage Court Tower and the Melville Buildings

MODEL UPDATING AND SIMULATIONS

For the model updating part of the CDS method, it was found that the finite element model of the Melville was very complex and due to time constraints an automated model updating was not performed. The results of the manual updating on the Melville were deemed satisfactory for the next phase of the simulation. For the model updating of

the HCT building, a previous work on the subject had been performed using automated updating [Ventura et al., 2003]. The model was updated within a reasonable correlation of the real data.
For the simulations, only the measured ground input and the obtained damping values were used. It was found that the addition of noise did not contribute to the realism of the simulations; therefore no noise was added.

DAMAGE DETECTION

For the application of the DDM, it was first applied only to the Melville. The initial results were inconclusive. It was observed that one of the difficulties in applying the DLV approach to such a building was due to the complexity of the finite element model to which the load vectors were applied. A proposed solution was to create a simpler 'equivalent' model for the damage detection phase. This is theoretically correct provided that the new model shares the natural frequencies and mode shapes of the original model. Consequently, an equivalent frame model that shared the geometry of the Melville at the measured points was created. Then the computed DLV's were applied to the frame model to determine the region of damage in the structure. It was found that the results were better than when using the full FEM, however they were generally inconsistent.

The equivalent frame model approach was then applied to the HCT building, which was a simpler building, both in size and floor plan geometry. However it was found that the results still were inconsistent. An attempt at improving the results was made by adding more sensors to the system. It was found that the damage could be better localized, however there was still inconsistency, and now an apparent bias appears in the results. The bias came from the fact that depending on where the sensors were located, certain elements were loaded more than others. This is an obvious effect of static loading; depending on the layout of the loads, certain elements may not be loaded, such as zero force members. One possible way to deal with this is to apply a weighting factor to the resulting forces in the frame; however, if certain members are not loaded than they can not provide information on their condition.

As a result, more sensors would be needed for the successful application of the DLV technique. There is a basis for this requirement in structural theory: for each 'mode' of deformation of an element that is damaged, one additional sensor is needed to find that damage. For example, in a truss element that has one deformation mode (axial), two sensors are needed. For a beam element with three deformation modes (axial and two bending), four sensors are needed. For a shell element with six deformation modes, seven sensors are needed. Likewise if two shell elements are damaged, 14 sensors are needed to locate the damage. This confirms the idea that the use of an equivalent frame model is useful, since more damage can be localized with fewer sensors required.

In addition to the theoretical limits in the technique, the main fundamental issue with flexibility-based methods is in the approximate formation of the flexibility matrix. Since they are formed with unscaled modes, the approximations may be poor. From the results in this project, it may be concluded that the flexibility-based methods are not the best choice when only the output data is available; however, the method does work, although more sensors would be required. Based on the statics of the problem an optimization scheme can be developed to find the sensor locations.

The optimization scheme can be stated as follows:

1. The optimal sensor layout can be found such that when unit loads are applied at the sensor locations, equal forces in each element result.
2. Those forces must not be zero (ie. there must be at least one sensor).

An example of this would be that in the case of a building, where only every 3rd or 4th floor is measured, it may be found that in certain parts of the building the element forces are already almost zero when unit loads are applied. Then, for those floors only, more sensors are added, rather than simply adding sensors to every floor. This improves the efficiency of the system by only adding sensors that will improve the results.

CONCLUSIONS

This paper presented the concept of a method for implementation of SHM systems for civil structures. The implementation method had three parts: create a damage detection methodology for use in the system; create a set of calibrated damage simulations to evaluate the DDM; and optimize the location of sensors in the system.

Using the IASC/ASCE benchmark frame as an example, a framework for a damage detection methodology and a set of calibrated damage simulations was created. For the DDM, the Stochastic Damage Locating Vector and Proportional Flexibility Matrix techniques were used in combination with a model-updating technique. It was found that the combined methodology provided better and more consistent results than the individual techniques. For the calibrated damage simulations, it was shown that by using the results of an ambient vibration test of the undamaged structure, simulations that better represented the real data could be obtained.

The implementation method was then applied to real structures. The first case study was of the Melville building, a 44-storey concrete tower. The second case study was of the Heritage Court Tower (HCT), a 15-storey concrete tower. Both buildings were located in downtown Vancouver, Canada. For the simulations of the Melville, the automated model updating step was passed because of the complexity of the model. The manual updating of the model was deemed satisfactory to move on to the next step. It was found in the simulations that only the real ground motion and damping estimate were needed to create satisfactory data sets.

For the application of the DDM, it was found that the SDLV and PFM methods, which are both flexibility-based damage detection methods, were not consistent in their predictions. It was concluded that the flexibility-based methods are not the best choice for use in ambient-vibration based SHM systems. It can be shown however, that they will work with more sensors; and in addition, that an optimization scheme can be developed to find the best sensor locations.

From these examples, it was shown that the implementation method was successful in evaluating the performance of the DDM for real building cases. It was also shown that the method can find ways to better use the damage detection algorithms; this is important since most of the algorithms will have limitations such as was shown with the flexibility-based approach. As it was noted in the introduction, the implementation method can be expanded to create other issues relating to the practical implementation of SHM technology, such as temperature effects and automation.

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