Damage assessment by Condensed Model Identification and Recovery with substructural approach

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**ABSTRACT:** This study aims to develop a system identification methodology for determining structural parameters of linear dynamic systems, taking into consideration of practical constraints such as large number of unknowns and insufficient sensors. The restrictions are relaxed in this study by a proposed method called the Condensed Model Identification and Recovery (CMIR) Method. Two substructural identification methods are formulated depending on whether the first-order state space model or second-order model is used. The proposed CMIR and substructural method are thus combined for the identification of stiffness values at substructural level with incomplete measurement. A fairly large structural system with 50 DOFs is identified with good results, taking into consideration the effects of noisy data. Lastly, an experimental study is carried out involving an eight-storey plane frame model. The identification results presented in terms of the stiffness integrity index show that the proposed method is able to locate and quantify damage with reasonable degree of accuracy.

1 **INTRODUCTION**

The need for quantitative global damage detection methods that can be applied to complex structures has led to research into Structural Health Monitoring methods that examine changes in the vibration characteristics of the structure. The general idea is that changes in the physical properties (i.e., stiffness, mass, and or damping) of the structure will, in turn, alter the dynamic characteristics (i.e., natural frequencies, modal damping and mode shapes) of the structure.

In practice, the number of sensors for measurement is often limited and thus makes the task of identifying system with many unknown parameters difficult, particularly when one attempts to identify the full system in one go. To resolve this problem and address the issue of incomplete measurement, Condensed Model Identification and Recovery (CMIR) method can be employed (Tee 2004). CMIR method is adopted to recover stiffness of individual storey from the identified condensed stiffness matrices in a numerically efficient way.

For the identification of complex structures, it is not practical to identify all of the parameters included in the structures because enormous computational time is required if convergence can be achieved at all. Hence, it may be necessary to adopt a substructural approach (Koh et al. 1991, 2003). Su and Juang (1994) presented the procedures for assembling substructural transfer function data, substructural Markov parameters and substructural state-space models. Tee et al. (2003) proposed two substructural identification methods on the basis whether substructural approach is used to obtain first-order or second-order model.

The main objective of this paper is to develop a numerical strategy for stiffness identification and structural damage assessment based on incomplete dynamic measurement and the substructural approach. Thus, the combination with the CMIR and substructural approach is developed. Formulation and special strategies to improve the identification performance for structural sys-
tems will be proposed and tested through numerical simulation studies and experimental verification.

2 THEORY

2.1 Basic formulation

The dynamic response of a N-DOF linear structural system can be represented by

\[ \mathbf{M}\ddot{\mathbf{q}}(t) + \mathbf{L}\dot{\mathbf{q}}(t) + \mathbf{K}\mathbf{q}(t) = \mathbf{f}(t) \]  

(1)

where \( \mathbf{M} \), \( \mathbf{L} \) and \( \mathbf{K} \) are the mass, damping, and stiffness matrices of the structure, respectively, \( \mathbf{q} \) is a displacement vector and the overdot denotes differentiation with respect to time \( t \). The equation of motion and measurement equations can be written in the first-order state space form as

\[ \mathbf{x}(k + 1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}\mathbf{u}(k) \]

\[ \mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{D}\mathbf{u}(k) \]  

(2)

where \( \mathbf{x}(k) \) is a state vector, \( \mathbf{y}(k) \) an output vector, and \( \mathbf{u}(k) \) an input vector. Matrices \( \mathbf{A} \), \( \mathbf{B} \), \( \mathbf{C} \) and \( \mathbf{D} \) represents time invariant system matrices.

Markov parameters \( \mathbf{Y} = [\mathbf{D} \hspace{1mm} \mathbf{CB} \hspace{1mm} \mathbf{CAB} \hspace{1mm} \ldots \hspace{1mm} \mathbf{CAB}^p \mathbf{B}] \) where \( p \) is an integer such that \( \mathbf{CAB}^p \mathbf{B} = 0 \) for \( k \geq p \), can be obtained using the Observer/Kalman filter Identification (OKID) (Juang et al. 1993). Once these parameters are identified, they can be used in the Eigensystem Realization Algorithm (ERA) for identification of dynamic structural characteristics (Juang and Pappa 1985). The mass, damping and stiffness matrices can be obtained from state space model (De Angelis et al. 2002). It is possible to compare the stiffness values of the undamaged and damaged models in order to locate and quantify the structural damage. A stiffness integrity index is defined such that the value is 1 for no loss in stiffness and 0 for complete loss of stiffness.

2.2 Substructural First- and Second-Order Model Identification (sub-FOMI and sub-SOMI)

The sub-FOMI and sub-SOMI methods are adopted for identification of large structure in a divide-and-conquer manner (Tee et al. 2003). The sub-FOMI method is feasible for identification of small systems. However, it may have numerical difficulties when one needs to determine the second-order model from the global state space model of a large system. This is due to the need to solve large matrices, which reduces the solution accuracy and increases the computational effort. To resolve this problem, only the sub-SOMI method is recommended and employed in this paper. The important point to note here is that the sub-SOMI method increases the solution accuracy because the conversion from state space model to second-order model is done at the substructure level.

For the purpose of substructuring, the equations of motion for the entire structure can be written in partitioned form corresponding to internal (I) DOFs and interface (J) DOFs as follows:

\[
\begin{bmatrix} \mathbf{M}^I & \mathbf{M}^J \\ \mathbf{M}^J & \mathbf{M}^J \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}^I(t) \\ \dot{\mathbf{q}}^J(t) \end{bmatrix} + \begin{bmatrix} \mathbf{L}^I & \mathbf{L}^J \\ \mathbf{L}^J & \mathbf{L}^J \end{bmatrix} \begin{bmatrix} \dot{\mathbf{q}}^I(t) \\ \dot{\mathbf{q}}^J(t) \end{bmatrix} + \begin{bmatrix} \mathbf{K}^I & \mathbf{K}^J \\ \mathbf{K}^J & \mathbf{K}^J \end{bmatrix} \begin{bmatrix} \mathbf{q}^I(t) \\ \mathbf{q}^J(t) \end{bmatrix} = \begin{bmatrix} \mathbf{f}^I(t) \\ \mathbf{f}^J(t) \end{bmatrix}
\]  

(3)

From the identification point of view, two variations of the sub-SOMI methods are possible, depending on whether the absolute response or relative response is used, namely sub-SOMI with absolute response (sub-SOMI-AR) and sub-SOMI with relative response (sub-SOMI-RR).

In the sub-SOMI-AR method, velocities and displacements at some interface DOFs are measured by means of accelerometers. Though displacements and velocities can be obtained by numerical integration of the accelerations measured, numerical error would be introduced inevitably. In view of this, the sub-SOMI-RR method is developed here. The equations of motion for substructure \( s \) can be extracted and written as:

\[
\mathbf{M}_s\ddot{\mathbf{q}}_s + \mathbf{L}_s\dot{\mathbf{q}}_s + \mathbf{K}_s\mathbf{q}_s = \mathbf{f}_s - \mathbf{M}_s\ddot{\mathbf{q}}_s - \mathbf{Z}_s\mathbf{L}_s\dot{\mathbf{q}}_s - \mathbf{Z}_s\mathbf{K}_s\mathbf{q}_s
\]  

(4)
for \( s = 1, 2, 3, \ldots \). \( Z' \) is a connectivity matrix of which each element is either one or zero depending on whether the corresponding DOF is considered to account for interaction force. If a particular interface DOF is used to account for interaction forces, the element is equal to one; otherwise, the element is zero. Note that the response is defined in terms of the relative response where \( \mathbf{q} \) is the displacement relative to \( \mathbf{q} \).

The equation of motion for the first substructure can be formulated by assuming that the substructure behaves as a structure subjected to support excitation, i.e., acceleration at the interface storey. The sub-SOMI-RR method is formulated such that only accelerations (as opposed to displacements or velocities) at the interface storeys are required to compute the interface forces at the first substructure. For intermediate and the last substructures, stiffness and damping coefficients at the upper end interface storey and the corresponding displacement and velocity are obtained from the identification results of the previous substructure.

In contrast to the sub-SOMI-RR method which is a self-start approach, the sub-SOMI-AR method needs a start-up approach and the least-squares method is used. For identification of lower end stiffness interface in each substructure for the sub-SOMI-AR method, the least-squares method is employed. In addition, the least-squares method is used in damage detection with either the sub-SOMI-AR or sub-SOMI-RR methods, where one particular portion of structure, which is suspected to have damage, is identified. Detailed explanation of the formulation is presented in Tee (2004).

### 2.3 Condensed Model Identification and Recovery (CMIR) Method

Full measurement is often impractical due to limited sensors and other practical constraints in instrumentation. As such, a condensed model based on incomplete measurement yields only the condensed stiffness matrices. The challenge is to determine individual stiffness parameters of the full system indirectly from the identified condensed stiffness matrix. The proposed method is thus called CMIR Method. Three different CMIR methods, namely CMIR with Static Condensation (CMIR-SC), CMIR with Dynamic Condensation (CMIR-DC) and CMIR with System Equivalent Reduction Expansion Process (CMIR-SEREP), are employed (Tee 2004). Only CMIR-SEREP is recommended and employed in this paper because it has the best performance among the three versions of CMIR. This is due to the fact that the CMIR-SEREP method preserves the eigenvalues and vectors during the condensation process.

Suppose the total DOF of the model are divided into primary DOFs (\( \psi \)), which will be retained in the reduced models, and the secondary DOF (\( s \)), which will be deleted from the model. The matrices \( \mathbf{M} \) and \( \mathbf{K} \) can be partitioned as

\[
\mathbf{M} = \begin{bmatrix}
\mathbf{M}_{pp} & \mathbf{M}_{ps} \\
\mathbf{M}_{sp} & \mathbf{M}_{ss}
\end{bmatrix}, \quad
\mathbf{K} = \begin{bmatrix}
\mathbf{K}_{pp} & \mathbf{K}_{ps} \\
\mathbf{K}_{sp} & \mathbf{K}_{ss}
\end{bmatrix}
\]

Using the condensed substructural model, the \( n \times n \) mass and stiffness matrices can be obtained by OKID/ERA as well as conversion from state space model to second-order model with \( n \) sensors. An eigen-analysis on these condensed matrices yields the identified natural frequencies and mode shapes denoted as

\[
\Lambda = \text{diag}(\Omega_1^2, \Omega_2^2, \ldots, \Omega_n^2), \quad \Phi_{\psi} = [\Phi_{\psi_1}, \Phi_{\psi_2}, \ldots, \Phi_{\psi_p}]
\]

The eigen-matrix in Equation 6 is then expanded to include secondary DOFs using

\[
\Phi_{\psi} = - (\mathbf{K}_{ss} - \Omega_i^2 \mathbf{M}_{ss})^{-1} (\mathbf{K}_{sp} - \Omega_i^2 \mathbf{M}_{sp}) \Phi_{\psi}, \quad i = 1, \ldots, n
\]

The SEREP transformation matrix \( \mathbf{P} \) is then computed from the expanded mass-normalized eigen-matrix (Papadopoulos and Garcia 1996). The stiffness and mass matrices of the condensed substructural model refined by SEREP method are

\[
\mathbf{K}_{SE} = \mathbf{P}^T \mathbf{K} \mathbf{P}, \quad \mathbf{M}_{SE} = \mathbf{P}^T \mathbf{M} \mathbf{P}
\]

The procedure for recovering the storey stiffness values from the condensed substructural stiffness matrices is highly nonlinear and Genetic Algorithm (GA) is found to be suitable in this
study. Note that the eigenvalues and eigenvectors obtained from Equation 8, for simplicity termed as the analytically condensed values should theoretically be identical to Equation 6. Hence the procedure to obtain $K$ and $M$ is to assume an initial set of values for $K_{sp}$, $K_{ss}$, $M_{sp}$ and $M_{ss}$ to be used with Equation 7 and compute Equation 8. The latter is then used to compute the eigenvalues and eigenvectors and check whether they match Equation 6.

To estimate the accuracy of eigenvectors, a correlated coefficient for modal vector (CCFMV) value is used:

$$CCFMV(e_i^c, e_i^l) = \frac{\left| e_i^c \cdot e_i^l \right|}{\sqrt{\left( e_i^c \cdot e_i^c \right) \left( e_i^l \cdot e_i^l \right)}}$$  \hspace{1cm} (9)

where superscripts ‘c’ and ‘l’ are the analytical and identified eigenvectors, respectively. A CCFMV value close to 1 suggests that the two modes or vectors are well correlated and a value close to 0 indicates uncorrelated modes. Therefore, the error function is defined as

$$\varepsilon = \sum_{i=1}^{n} \left[ (1 - \frac{\Lambda_i^c}{\Lambda_i^l})^2 + (1 - CCFMV(e_i^c, e_i^l))^2 \right] \hspace{1cm} (10)$$

The problem of recovering the stiffness values is transformed into minimization of Equation 10. The GA approach is used in this sense to provide an optimal solution for the set of unknown parameters of the substructural system to be identified.

By the proposed CMIR method, all stiffness parameters in the entire system can be recovered by extracting sufficient information using two different approaches, namely the “repositioned sensor” approach and “fixed sensor” approach (Tee 2004). In some cases, it is possible to shift the sensors to maximize the information available for structural identification and this approach is called the repositioned sensor approach. If it is not possible to shift the sensors, a novel way is to apply the fixed sensor approach and to deliberately ignore some sensors so as to obtain more information for the purpose of matrix recovery.

The proposed CMIR method and substructural method address different aspects of large-scale structural identification. The former allows the use of incomplete measurement and the latter represents a divide-and-conquer approach to reduce the size of system identification. In this paper, these two methods are thus combined for the identification of stiffness values and damage assessment at substructural level with incomplete measurement. The focus is on estimating all stiffness values from the condensed stiffness matrices by the CMIR-SEREP method at the substructure level.

3 NUMERICAL RESULTS AND DISCUSSIONS

A 50-storey shear building is considered to demonstrate the ability of the proposed methodology to tackle a large problem that is typical of real structures. The exact stiffness value for each level is 1100 kN/m for the first ten storeys and 900 kN/m for the other storeys.

The objective of this study is to demonstrate the convenience of identifying a portion of a large structure without any response measurement in the rest of the system. For verification purpose, the numerical simulation study is only carried out to identify one particular portion which is suspected to have damage. In this section, damage is assumed to take place at the 20th, 25th and 26th DOFs with stiffness integrity index of 0.80, 0.85 and 0.75 (i.e. 20%, 15% and 25% damage), respectively. Therefore a substructure, $S = \{19-30\}$, i.e. 19th to 30th DOF inclusive is identified independently using the sub-SOMI-RR method.

As mentioned before, in the sub-SOMI-RR method, there is no need to use the start-up least-squares approach to identify the stiffness and damping which are used to form the interface force. However, the start-up least-squares approach is performed here to identify stiffness and damping at the 31st DOF because the substructure is identified independently. Six acceleration sensors are placed at the DOFs 19, 20, 23, 26, 29 and 30. Also, one force acts on the 30th DOF of this substructure. The fixed sensor approach is presented in this study because it is more practical. In this study, one sensor is ignored in this substructure that is at the 20th DOF. Note that for the identifi-
cation of each substructure, responses of DOFs outside itself are not needed. This means that we can identify a small part of a large system without the measurements outside the perimeter of the substructure.

The actual stiffness values compared with the estimated or identified values are shown in Table 1. The mean absolute error and maximum absolute error are 6.15% and 9.2%. The numerical study is repeated with 5% I/O noise. Not surprisingly the results are less accurate but they are still reasonable with mean and maximum absolute error of 8.04% and 10.6% respectively. The results are encouraging with the computational time of 105 minutes. Compared to the whole structural identification, the saving in computational time is 91% (Tee 2004). It illustrated that the method is useful when only a small part of a large system needs to be identified. The method is used again to test its ability to identify damage in a part of a large structure, which is shown in Figure 1. The mean and maximum errors are 4.77% and 9.6% based on the sub-SOMI-RR method with 0% I/O data. The identification is repeated with an introduction of 5% random noise in all measured accelerations and excitation. In the presence of 5% I/O noise, the mean and maximum errors are 6.32% and 11.8%, respectively. It is noted that the damage extent can be quantified with reasonable accuracy for different size of damages.

The study then takes a step forward by removing two sensors, to test the limits and to use as fewer sensors as possible. The results are shown in Figure 1. Both mean and maximum absolute errors increase to 7.58% and 14.0% respectively when two less sensors are used under 5% noise. Correspondingly the mean and maximum absolute errors are 5.73% and 10.2% respectively under 0% noise. Referring to Figure 1, we see that results improve with the number of sensors used.

Table 1. Identified storey stiffness values with the sub-SOMI-RR method using 6 sensors

<table>
<thead>
<tr>
<th>Storey</th>
<th>Exact Stiffness (x 10^6 N/m)</th>
<th>Identified Stiffness (x 10^6 N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0% Noise</td>
<td>5% Noise</td>
</tr>
<tr>
<td>19</td>
<td>900</td>
<td>966 (7.3%)</td>
</tr>
<tr>
<td>20</td>
<td>900</td>
<td>947 (5.2%)</td>
</tr>
<tr>
<td>21</td>
<td>900</td>
<td>823 (-8.6%)</td>
</tr>
<tr>
<td>22</td>
<td>900</td>
<td>952 (5.8%)</td>
</tr>
<tr>
<td>23</td>
<td>900</td>
<td>842 (-6.4%)</td>
</tr>
<tr>
<td>24</td>
<td>900</td>
<td>982 (9.1%)</td>
</tr>
<tr>
<td>25</td>
<td>900</td>
<td>935 (3.9%)</td>
</tr>
<tr>
<td>26</td>
<td>900</td>
<td>836 (-7.1%)</td>
</tr>
<tr>
<td>27</td>
<td>900</td>
<td>871 (-3.2%)</td>
</tr>
<tr>
<td>28</td>
<td>900</td>
<td>983 (9.2%)</td>
</tr>
<tr>
<td>29</td>
<td>900</td>
<td>887 (-1.4%)</td>
</tr>
<tr>
<td>30</td>
<td>900</td>
<td>842 (-6.4%)</td>
</tr>
</tbody>
</table>

| Mean Absolute Error | 6.15% | 8.04% |
| Max. Absolute Error | 9.2%  | 10.6% |

<table>
<thead>
<tr>
<th>Storey</th>
<th>Integrity Index</th>
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<tbody>
<tr>
<td></td>
<td>Exact</td>
</tr>
<tr>
<td>19</td>
<td></td>
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<tr>
<td>20</td>
<td></td>
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<td>29</td>
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<td>30</td>
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</table>
4 EXPERIMENTAL VERIFICATION

A small-scale laboratory model of an eight-storey steel frame was fabricated and tested to validate the applicability of the proposed method. The steel frame had a total height of 1.2 m and a plan of approximately 400 mm × 500 mm. At each storey, there were six columns, three longitudinal beams in the x-direction and four transverse beams in the y-direction. All elements had cross section of 25 × 5 mm. In addition, steel bars of 5 mm diameter diagonally brace the beams to simulate floor rigidity. All connections were done by welding. The steel used for all members was grade 43 with density of 7850 kg/m³ and Young’s modulus of 205 GPa approximately.

Figure 2 shows the experimental set-up of dynamic testing for the steel frame. The model was welded at the base to a 20-mm thick steel plate, which was bolted to a rigid supporting frame using M25 bolts. The model was erected horizontally to facilitate ease of hanging weights along the model using hooks for static experiments (which were conducted to determine the actual stiffness, Tee 2004). For vibration-based identification, a shaker was used to dynamically excite the frame, and accelerometers were used to measure the dynamic response.

4.1 Simulated column damage of laboratory model

Damage of the steel frame was created by decreasing the storey stiffness values at selected storeys. For experimental damage detection of the laboratory model, structural damages were artificially created in progression. The aim was to demonstrate whether the proposed identification strategy could detect storey stiffness changes in terms of location and severity. As illustrated in Figure 3, one or more undamaged columns (25 × 5 mm) at certain storeys were cut by a saw. Each saw-cut of column represented a reduction of approximately 16.7% of storey stiffness value at that storey. In this way, the damage created can be quantified by computing the decrease in stiffness value for verifying the proposed strategy. However, due to Vierendeel effect, cutting one column at a storey will affect the storey stiffness of adjacent storeys. To account for this effect, the actual stiffness integrity indices were determined by simple static experiment, the results of which served as the benchmark for validating the proposed numerical strategy. Six damage scenarios were created in the following sequence:
- Scenario 1: One center column on the top side of the steel frame in the third storey.
- Scenario 2: Case 1 plus the center column on the bottom side in the third storey.
- Scenario 3: Case 2 plus the center column on the top side in the seventh storey.
- Scenario 4: Case 3 plus the center column on the bottom side in the seventh storey.
- Scenario 5: Case 4 plus the center column on the top side in the fourth storey.
- Scenario 6: Case 5 plus the center column on the bottom side in the fourth storey.

Accelerometer
Base plate
Supporting strong frame
Steel
Shaker
4.2 Dynamic tests and identification of damaged frame

The model is divided into two substructures: $S_1 = [3-8]$, i.e. 3rd to 8th storeys inclusive and $S_2 = [1-4]$. The displacement values used to form the interface force are computed either directly from the measurement through displacement transducer or from the integration of acceleration measured by accelerometer. Even though the displacement values obtained from the integration of accelerations are more practical than that obtained from displacement transducers, displacement transducers are used in this study.

The same laboratory model is used for the verification of the proposed sub-SOMI-RR method based on complete measurement (8 sensors) and the combined sub-SOMI-RR and CMIR-SEREP method based on incomplete measurement (4 and 6 sensors). The fixed sensor approach is used to extract sufficient information for incomplete measurement with 6 sensors whereas the repositioned sensor approach is used with 4 sensors. In the case of 4 sensors, the sensors are located at storeys 3, 4, 5, and 8 when identifying substructure 1. The sensor at 8th storey is then shifted to 1st storey when identifying substructure 2. In the case of 6 sensors, the sensors are located at storeys 1, 3, 4, 5, 7 and 8.

Six damage scenarios were created but only two damage scenarios (Scenarios 3 and 6) are discussed due to page constraint. The discussion of the other damage scenarios can be found in Tee (2004). The identified results for Damage Scenario 3 presented in Figure 4 show encouraging results for the proposed method as far as accuracy is concerned. The mean absolute error for the stiffness values is 9.1% while the maximum error is 14.0% for incomplete measurement with 4 sensors. The identified stiffness integrity index of second and fourth undamaged storeys are both 0.89 (-9.1% error) because the second and fourth undamaged storeys are just adjacent to the third damaged storey. In view of the noisy environment in which the experiment is conducted and measurement errors that may have been involved, the results are considered good.

Next, the results for Damage Scenario 6 with complete and incomplete measurement are presented in Figure 5. The identification results obtained with complete measurement are satisfactory; the mean error is 5.06% and maximum absolute error is 8.8%. Using 4 sensors, the results are acceptable with mean error of 8.14% and maximum absolute error of 11.8%. Using 6 sensors, the combined CMIR-SEREP and sub-SOMI-RR method improves the results slightly to give mean error of 7.77% and maximum absolute error of 10.1%. The results show that the stiffness integrity indices are identified with accuracy using substructural approach based on incomplete measurement for Damage Scenario 6.
5 CONCLUSIONS

The purpose of vibration-based identification is to provide a quantitative and non-destructive way of damage assessment. To this end, a divide-and-conquer strategy has been developed in this paper by performing system identification at the substructure level in first- and second-order model. A new methodology for identification of stiffness and damage using incomplete measurements is also presented. The main research significance is that with the proposed CMIR method, it is possible to recover stiffness and stiffness integrity index of each storey from identified condensed stiffness matrices in a particular substructure by extracting sufficient information with either fixed or repositioned sensor approach. The results indicate that the proposed method can be quite successfully used for damage estimation of structures with fairly large number of DOFs. Due to inevitable experimental noise and modeling error, a small leakage to an adjacent undamaged element took place. It was shown that the identification results reflected accurately the various degrees of structural damages introduced in stages for the structural laboratory model. By and large, the identified stiffness integrity index, in particular, is found to reveal the location and extent of damage in the numerical and experimental study accounting for effects of incomplete and noisy measurements. Nevertheless, the structure considered may still be simple from the practical point of view. Further work is required to improve the proposed strategy using more complex structure and identifying damage of lesser severity than what has been considered.

REFERENCES


