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DECENTRALIZED DAMAGE DETECTION IN A PLANAR FRAME

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ABSTRACT

Smart sensors (those with computer capabilities onboard, as well as wireless communication) are new tools that can provide advantages when detecting damage in a structure. This paper, based on smart sensors, presents a modification of a Proper Orthogonal Decomposition (POD) algorithm for damage detection in a decentralized fashion. The methodology is applied to planar frames. Results shown that the methodology proposed can detect damage, whoever some limitations are encounter.

Introduction

Damage detection has been a major topic of research in the past decades. A fair number of techniques, including change in frequencies, mode shapes, content of energy, etc., can be studied (Scott et a. 1996). Most of these techniques employ a traditional instrumentation, in which there is always a central data acquisition where all the information is concentrated. Later, the data is processed, and finally results are presented.

In this never-ceasing development of new technology, the idea to have only one data acquisition system is getting left behind. New sensors with onboard computation capabilities are a reality, opening a new era for solving problems in a distributed fashion. Additionally, the use of radio frequencies to transmit data, eliminating the need for cables, could significantly reduce the costs involved with the instrumentation of a structure. The techniques for damage detection mentioned above need to evolve to take advantage of these new paradigms.

With new solutions come new obstacles. Synchronization was never a problem because only one device controlled all the sensors. Now, with distributed algorithms, it is necessary to verify that all the components of the network are recording at the same time, or at least known each one of the clock of the sensors. Other problems, such as the topology of the network, as well as how to send the information over the net, need to be addressed.

This paper presents a review of two damage detection algorithms. The first one is based on the change of modal shape energy (Carrasco et al 1997), and the last one concerns the Proper

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Orthogonal Decomposition (POD) algorithm (Galvanetto and Violaris 2007). These methods are studied to identify the damage in a planar frame. The energy method cannot always identify the damage, and the POD always shows the correct location of the damage. A modification of the POD method is presented and applied in a decentralized fashion. Results indicate that the decentralized algorithm identifies damage location, in a planar frame, with some limitations.

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Damage Methods Studied

There are several methods for damage detection. This paper presents the modal deformation energy method and the Proper Orthogonal Decomposition (POD) algorithm. Damage is defined herein as a diminishing of the stiffness of an element without changing its mass.

Modal Deformation Energy

Carrasco et al (1997) presented a modal deformation energy method for damage location. This method compares deformation energy of the original and damage stage of the structure. The equation to calculate the total energy deformation is:

$$U_j = \frac{1}{2}\{\phi_j\}^T[K]\{\phi_j\} \tag{1}$$

Where ϕ_j are the mode shapes associated to the bar j, and [K] is the stiffness matrix of the bar j. The total deformation energy can be visualized as the sum of the deformation energies of all the structural elements.

$$U_j = \sum_{i=1}^{N} U_{ij} \tag{2}$$

In equation (2) U_{ij} is the energy contribution of the element *i* in the *jth* mode, and *N* is the number of structural elements. Therefore, a change in the distribution between damaged (*d*) and undamaged (*u*) can be obtained with equation (3):

$$\Delta U_{ij} = Uu_{ij} - Ud_{ij} \tag{3}$$

Proper Orthogonal Decomposition

The POD is also known as Karhunen-Loève methodology. It provides a base for modal response of the data recorded in the elapsed time of an experiment. It can be used to identify the

response of dynamic systems with the help of sensors. The instrumentation of a structure gives information for modal analysis.

Galvanetto and Violaris (2007) used POD for damage detection in a cantilever beam. The damage was simulated reducing the stiffness and the mass of the structure. The Proper Orthogonal Modes (POMs) that captures the energy of each mode can be obtained from the PODs. The energy distribution between POMs is defined with the correspondent Proper Orthogonal Values (POV), and helps to identify the most important modes. Based on the POMs and POVs of damaged and undamaged stages, it is possible to determine the presence of damage.

To implement the POD methodology, it is necessary to acquire displacements di at N points of the system, sample until the M stop time. The collected values of displacements are normalized subtracting the mean value (equation 4)

$$a_i = d_i - \bar{d}_i 1 \tag{4}$$

where 1 is a vector of dimension M with all the components equal to the unity. The vectors a_i are used to obtain the matrix A of dimension M x N (equation 5):

$$A = \begin{bmatrix} a_1(t_1) & a_2(t_1) & \cdots & a_N(t_1) \\ a_1(t_2) & a_2(t_2) & \cdots & a_N(t_2) \\ \vdots & \vdots & \vdots & \vdots \\ a_1(t_M) & a_2(t_M) & \cdots & a_N(t_M) \end{bmatrix} \tag{5}$$

With the matrix A can be constructed the correlation matrix R.

$$R = (1/M)A^T A \tag{6}$$

The R matrix is symmetrical and real of order NxN; therefore the eigenvectors form an orthogonal base. The POMs can be easily obtained from the PODs, which capture the energy of every mode. The energy distribution between POMs is defined by the POVs, which provide a participation index of the corresponding mode.

The eigenvectors of R are the POMs, and eigenvalues are the POV of the system. Comparing the two stages (with and without damage) can localize the damage.

Numerical examples

Modal Deformation Energy

The modal deformation energy method is applied in 2D truss and in a planar frame. Damage is simulated with reductions of stiffness in the elements.

2D Truss single damage

A 2D truss with 11 bars and 7 nodes is constructed with the following properties. Elasticity Modulus (E) of 2038.9019 kg/cm2, area of 66.45 cm2, longitude of horizontal bars 300 cm and incline bars 424.26 cm (Fig. 1).
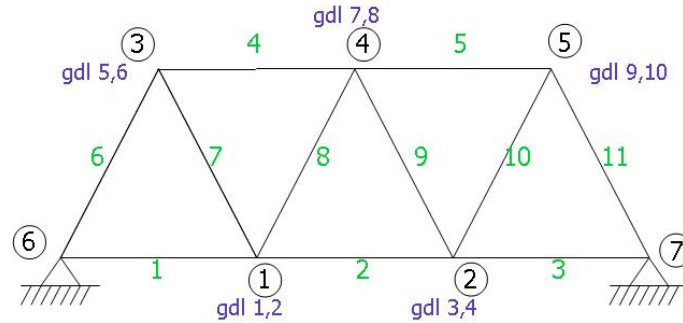

Figure 1.   Two dimensional truss.

In the first case, the element number 2 is subject to a reduction of 20% of stiffness. The numerical values of the modal shapes of the truss with and without damage are calculated. The modal deformation energy is calculated with equation (1).

The difference of energy between these states, of each mode, is calculated with equation (2). The numeric values are shown in Table 1.

Table 1.   Energy difference of each bar with respect to every mode.

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode
bar 1	-0.0531	0.0000	-0.0000	67.1302	-71.5300	-0.0122	-0.0000	-0.5130	6.5769	-0.0000
bar 2	-0.2124	0.0000	-0.0000	-59.4114	41.8124	-0.0489	-0.0000	-2.0520	26.3075	0.0000
bar 3	-0.0531	0.0000	0.0000	67.1302	-71.5300	-0.0122	0.0000	-0.5130	6.5769	0.0000
bar 4	0.0458	-0.0000	0.0000	-10.6997	11.9896	-0.8352	-0.0000	0.3970	-0.9482	0
bar 5	0.0458	0	-0.0000	-10.6997	11.9896	-0.8352	0.0000	0.3970	-0.9482	-0.0000
bar 6	0.0629	0.0000	-0.0000	-8.7178	8.6625	0.7536	0	0.8022	-1.9317	-0.0000
bar 7	0.0306	-0.0000	0.0000	-17.4133	20.9906	0.0023	0.0000	7.5504	-12.3205	0.0000
bar 8	0.0018	-0.0000	0.0000	12.2502	-5.5365	0.1378	0.0000	-8.9166	1.3183	-0.0000
bar 9	0.0018	-0.0000	0.0000	12.2502	-5.5365	0.1378	-0.0000	-8.9166	1.3183	-0.0000
bar 10	0.0306	0	-0.0000	-17.4133	20.9906	0.0023	-0.0000	7.5504	-12.3205	-0.0000
bar 11	0.0629	0.0000	0.0000	-8.7178	8.6625	0.7536	0.0000	0.8022	-1.9317	0.0000

The principal difference is encountered in the element number 2 in the modes 1 and 9. This difference is large compared with the other bars. The modes 4, 5 and 6 show a great participation in the first three bars. The modes 2, 3, 7 and 10 have almost no participation in the change of energy deformation. It is assumed that bar number 2 is the damage element; therefore, this method can detect damage. Other elements were tested with similar results.

2D Truss multiple damage

The same truss was then subject to a multiple damage case scenario. The damage elements were 7 and 10, with a reduction of 20% of their stiffness. Modal deformation energy was calculated as well as their differences. Results are presented in Table 2.

Table 2.   Energy difference of each bar with respect to every mode.

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10
bar 1	0.0112	1.0817	-0.9143	73.0927	-72.9730	0.0034	1.0466	-1.0462	-1.5963	-0.0914
bar 2	0.0448	0.0000	0.0000	-35.5615	41.8124	0.0135	-0.0000	-4.1848	-6.3853	0.0000
bar 3	0.0112	1.0817	-0.9143	73.0927	-72.9730	0.0034	1.0466	-1.0462	-1.5963	-0.0914
bar 4	0.3803	-0.0031	0.1520	-13.4319	11.9376	-0.0284	9.1081	0.5849	0.9707	-10.5966
bar 5	0.3803	-0.0031	0.1520	-13.4319	11.9376	-0.0284	9.1081	0.5849	0.9707	-10.5966
bar 6	0.5221	0.1440	2.5264	-10.9020	9.7016	0.0035	-0.8466	0.3878	1.7982	-2.4400
bar 7	-1.1181	-2.2019	-1.2450	-29.4685	20.2770	-0.0009	-6.1986	-11.1508	22.2803	11.7787
bar 8	0.0369	0.8720	-1.0004	14.7006	-4.6716	0.0233	-2.0610	11.4398	-23.2378	1.2592
bar 9	0.0369	0.8720	-1.0004	14.7006	-4.6716	0.0233	-2.0610	11.4398	-23.2378	1.2592
bar 10	-1.1181	-2.2019	-1.2450	-29.4685	20.2770	-0.0009	-6.1986	-11.1508	22.2803	11.7787
bar 11	0.5221	0.1440	2.5264	-10.9020	9.7016	0.0035	-0.8466	0.3878	1.7982	-2.4400

The principal difference is encountered in elements numbers 2 and 7 in the modes 1, 2, 8, 9 and 10. These differences are large compared with the other bars. The modes 4 and 5 show a great participation in the first 3 bars. The mode 6 almost has no participation in the change of energy deformation. It is assumed that bars numbers 2 and 7 are the damage elements. Other elements were tested with similar results. This method is extrapolated to a planar frame, and it is shown in the following section.

Planar frame single damage

A simple planar frame with two stories and one bay was used with the following properties. Elasticity Modulus (E) of 2038.9019 kg/cm2, area of beams and columns 66.45 cm2, moment of inertia of columns 21227.803 cm4. Elements 6 and 5 are considered with infinity stiffness (i.e. I very large). See Figure 2.
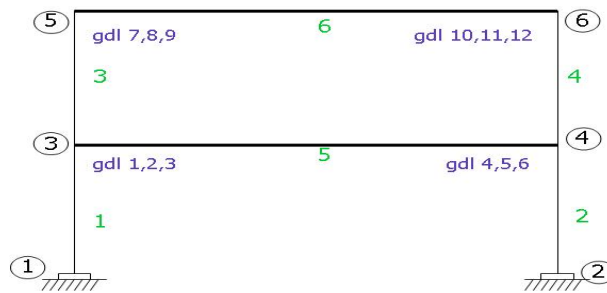

Figure 2.   Planar frame.

Damage of 70% in element number 4 is simulated by reducing its inertia. Modal deformation energy was calculated as well as their differences. Results are presented in Table 3.

Table 3.   Energy difference of each bar with respect to every mode.

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12
element 1	-0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000
element 2	0.0000	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	-0.0000	-0.0000	0.0000	0.0000	0.0000
element 3	-0.1034	-3.3962	-0.0276	3.2920	0.1385	0.1231	-0.0125	-0.0139	-0.0006	0.0010	-0.0003	-0.0001
element 4	-0.0000	-0.0000	-0.0000	0.0000	-0.0000	-0.0000	-0.0000	-0.0000	0.0000	0.0000	0.0000	0.0000
element 5	-0.0000	0.0000	-0.0000	-0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000	0.0000	-0.0000	-0.0000
element 6	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	0.0000	-0.0000	-0.0000	0.0000	-0.0004	0.0000	0.0004

It can be observed in Table 3 that the main difference of deformation energy is present in element 3, which is incorrect. Other cases were tested with incorrect results; therefore, this method cannot be used for damage detection in planar frames.

Proper Orthogonal Decomposition

The POD is applied to the planar frame described in figure 2. The POD can be used to identify the response of dynamic systems with the help of sensors. At first, sensors are placed at the middle points of the structure (see Figure 3). To avoid confusion, the locations i of the sensors are presented in darkened circles, while the nodes describing the frame will be represented with white circles.
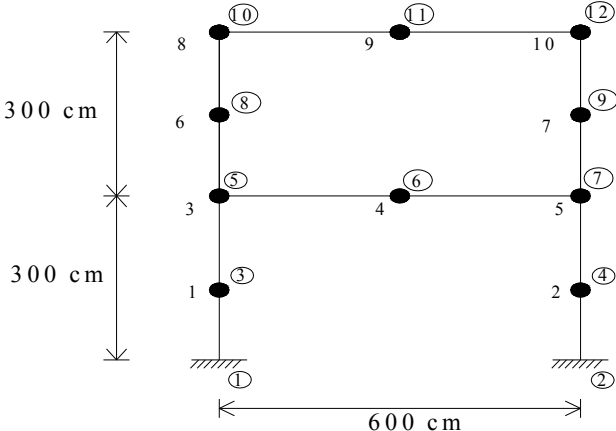

Figure 3.   Nodes and sensor locations

Damage is simulated by reducing 20% of the inertia of the column between nodes 5, 8 an 10. A white noise signal is applied to the base of the structure. For a structure with damage and without damage, the following methodology was used: displacements of every point are obtained and later normalized (equation 4). The matrix A and R is constructed (equation 5 and 6). From R, the POMs and POVs (eigenvectors and eigenvalues) are calculated. Table 4 and 5 shown the ratio between POMs and POV without damage and damage.

Table 4.   (POMs w/o damage)/(POMs with damage).

					N = 10					
i	1	2	3	4	5	6	7	8	9	10
1	0.8603	0.9917	0.9729	0.0287	0.5544	0.0090	0.9248	0.6948	0.7469	0.6747
2	0.8813	0.9497	0.9861	0.8182	0.9686	0.0114	0.7118	0.8508	0.7115	0.9432
3	0.8610	0.9243	0.8053	0.4752	0.1930	0.0264	0.3512	0.6649	0.6529	0.3842
4	0.8711	0.9504	0.7868	0.4703	0.4488	0.1493	0.0043	0.0046	0.0232	0.0053
5	0.8818	0.9681	0.6939	0.1945	0.0123	0.0060	0.8878	0.9531	0.7979	0.1411
6	1.0000	0.5788	0.3526	0.6625	0.2677	0.4196	0.0995	0.0242	0.1623	0.3373
7	0.9848	0.6012	0.7659	0.4336	0.2977	0.7901	0.4638	0.8988	0.6077	0.5410
8	0.9394	0.9426	0.6592	0.8554	0.1217	0.1688	0.9025	0.4795	0.5207	0.0621
9	0.9462	0.9026	0.7423	0.2777	0.2747	0.1012	0.0403	0.0641	0.0545	0.0052
10	0.9516	0.8794	0.7630	0.7484	0.2425	0.6303	0.5322	0.9556	0.2412	0.1814

modo	1	2	3	4	5	6	7	8	9	10
1	0.8349	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.2455	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.2770	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.0113	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.0478	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.0048	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.2187	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0645	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0421	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0763

The most important mode change can be identified using the POVs. The lowest relationship is encountered in mode number 6. Later, using the POMs at mode 6, it can be observed that the greater difference is present at points i = 1, 2 y 5 (nodes 3, 4, and 7, respectively). With this information, it can be concluded that the element damage is at nodes 2, 4 and 7, which is incorrect. The methodology POD proposed by Galvanetto and Violaris does not seem to work well for this planar frame.

However, the POMs and POVs do not give the correct damage detection, using the ratio of the R matrices damage can be detected (see Table 6).

Table 6.   (R w/o damage)/(R with damage)

i	1	2	3	4	5	6	7	8	9	10
1	0.8901	0.9115	0.8906	0.9010	0.9118	0.9699	0.9850	0.9126	0.9192	0.9244
2	0.9115	0.9335	0.9120	0.9227	0.9338	0.9469	0.9615	0.8908	0.8972	0.9023
3	0.8906	0.9120	0.8910	0.9014	0.9123	0.9692	0.9842	0.9119	0.9184	0.9237
4	0.9010	0.9227	0.9014	0.9120	0.9230	0.9579	0.9728	0.9012	0.9077	0.9129
5	0.9118	0.9338	0.9123	0.9230	0.9341	0.9464	0.9610	0.8902	0.8967	0.9018
6	0.9699	0.9469	0.9692	0.9579	0.9464	0.8348	0.8477	0.7843	0.7900	0.7945
7	0.9850	0.9615	0.9842	0.9728	0.9610	0.8477	0.8608	0.7965	0.8022	0.8068
8	0.9126	0.8908	0.9119	0.9012	0.8902	0.7843	0.7965	0.7365	0.7418	0.746
9	0.9192	0.8972	0.9184	0.9077	0.8967	0.7900	0.8022	0.7418	0.7472	0.7515
10	0.9244	0.9023	0.9237	0.9129	0.9018	0.7945	0.8068	0.7461	0.7515	0.7558

According to the data in Table 6, the major differences are present at points i = 1, 3 y 8 (node 3, 5, and 10). Also, from modes 5 to 10, sensor location number 8 always has the lower R ration. It can be concluded that this relationship detects the damage element at node 8 corresponded to element 3, 6 and 8, which is correct.

The next step in using this methodology is to extrapolate its actual use in a decentralized fashion.

Decentralized Damage Methodology

In the above example of damage detection, there were sensors placed at middle points of beams and columns. Other combinations of sensors were also investigated; however, they did not necessarily give better results. An optimal compromise between the number of sensors and the accuracy of the methodology was investigated resulting in the presented middle points. The frame shown in Figure 4 was used with the same material properties as the frame previously shown.

Sensors are located at beam-column intersections as well as middle points. Damage detection is implemented in a decentralized fashion; that is, sensors are able to collect and process the information. After processing the information, middle point sensors will forward the results to the intersection sensors. Figure 4 shows the processing of the information recorder over the structure. Sensor i = 1, 5, 6 and 12 pass along their information to sensor 5; sensors 2, 6, 7, 7, and 13 to sensor 7, and so forth. Finally, only information from sensors 5, 7, 9, 11, 16, 18, 20, 22, 27, 29, 31 and 33 are required.
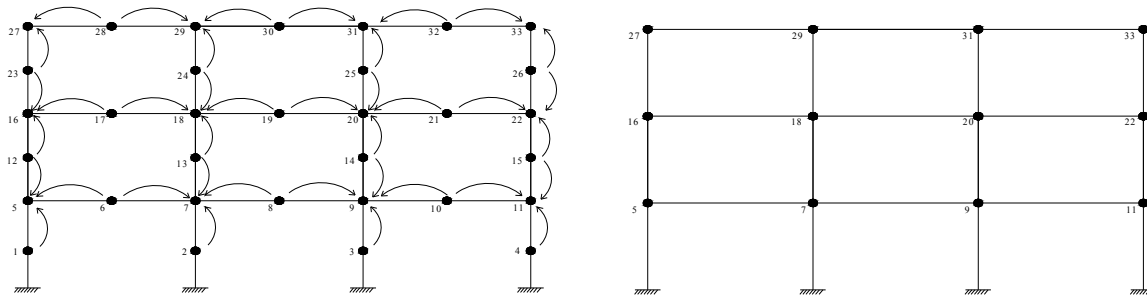
Figure 4.   Data processing, and nodes used.

Frame shown in Figure 5 is used as example. Points in which sensors are located are represented in darkened circles, and nodes on the frame are represented with white circles.
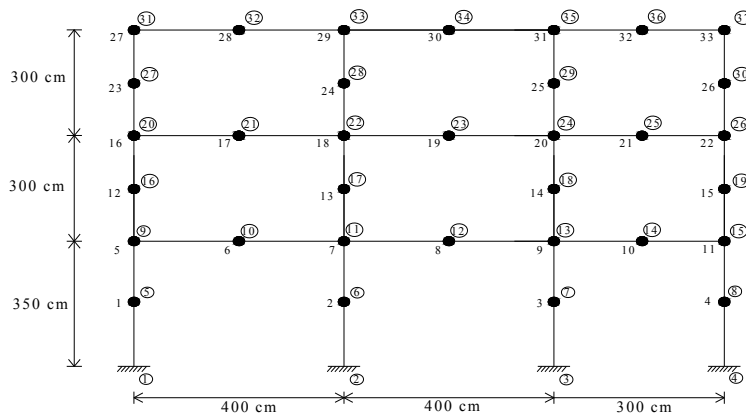

Figure 5.   Planar frame.

Damage is simulated by reducing 20% of the inertia at nodes 9, 16 and 20. The frame was subject to a white noise excitation at their base. In this decentralized scheme, the POD methodology will only be applied at intersection sensors.

Numerical example for sensor 5 (node 9)

To illustrate the application of the POD in a decentralized fashion, the results at node 5 are presented. The displacement matrix, as well as A matrix (with and without damage), are calculated using the information of sensors 1, 5, 6 and 12. Finally, R matrix is obtained.
In the procedure for damage detection, it is necessary to obtain the ratio between R without

damage and R with damage for each intersection sensor. The point, or points, with lower ratios will indicate damage.

There are 9 proposed additional master nodes (MN) from A through E. These nodes receive the information of every intersection node; that is, MNA will have the information from nodes 16, 18, 27 and 29 (see Figure 6).
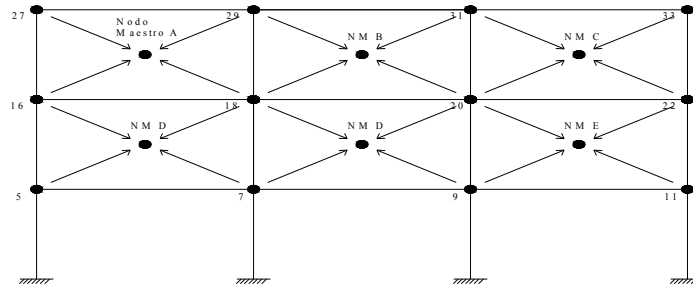

Figure 6.   Master nodes.

Table 6 shows the mean difference of the ratio of R without damage and R with damage for every intersection node. It can be observed that nodes 5 and 16 have the largest change between the two stages of the structure; therefore, the damage element is between sensors 5, 12 and 16.

Table 7.   Ration between the two stages.

Sensor, point i	(R w/o) / R damage
5	0.9813
7	0.9864
9	0.993
11	0.9961
16	0.9794
18	0.9843
22	0.9862
27	0.9823
29	0.9845
31	0.9847
33	0.9835

Once the bar is identified, a damage index is calculated as the mean of the matrices. In this particular case, the result is 0.98240.

Using this methodology, a set of simulations was performed, damaging every element with a different level of stiffness reductions. Figure 7 shows the damage index for every element.
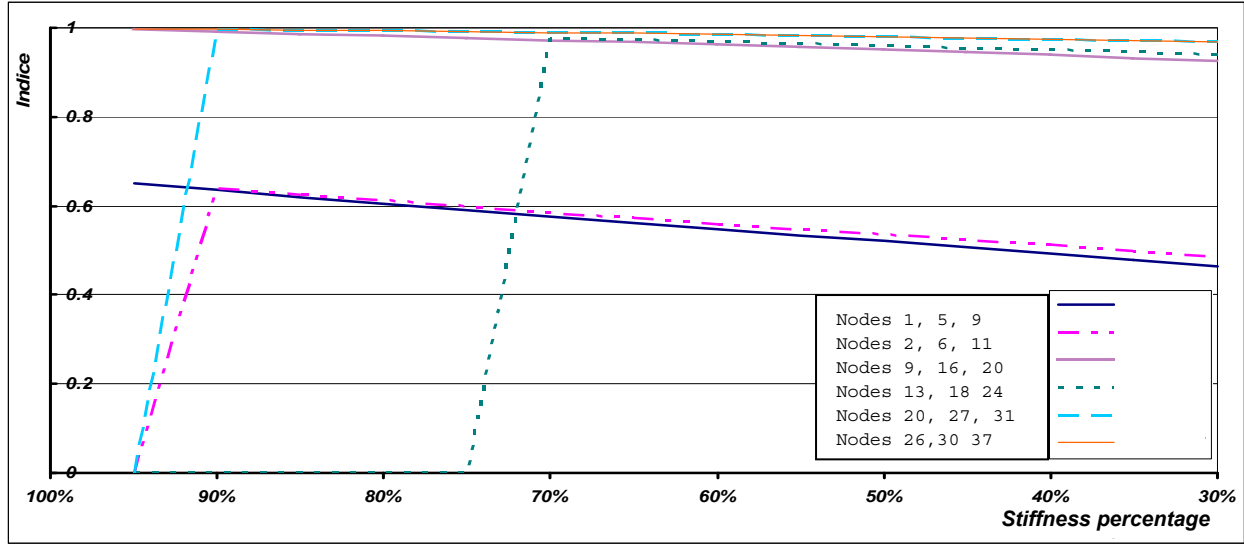
Figure 7.   Damage index for each bar of the planar frame.

Damage on all the elements was detected; however, elements between nodes 13, 18 and 24 were detected until it has above 20% of stiffness reduction. This may be due to the position of the element in the frame. More cases were studied, though cannot be presented in this paper due to space constraints.

Conclusions

This paper investigated two different damage detection methods. The energy deformation method was able to detect damage in a 2d truss; however, the results were not accurate for a planar framer. The Proper Orthogonal Decomposition method was applied to a planar frame. Results showed that the damaged element was able to be identified.

A decentralized methodology is presented based on the POD method. The use of smart sensors allows part of the processing to be performed at the node location. By comparing the ratio between damage and undamaged states, it was able to detect the damaged element.

Although damage is detected, there are some inter elements that require more than 20% of damage to be recognized. Future studies regarding network topology and synchronization are pending. Also, an experimental validation is in progress.

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