# Experimental Damage detection
# In Planar Frames

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**SUMMARY**
All structures could sustain structural damage in their life time. Adequate damage detection will allow scheduling the required to repair, retrofit, or change of the damage elements. There are several damage detection techniques. One classification is the way that the information is collected. A possible classification is centralized and decentralized data collection. In the first ones, all the information is collected in a single node, to be later process and analyze. In the second type of technique, the information is processed and analyzed at the sensor level. The objective of this paper is to experimentally detect damage of shear planar frames. A modification of the Proper Orthogonal Decomposition methods was used in a decentralized fashion. Result shows that this technique can detect damage with area reduction of 10% and above, for all the columns except for the ones at the first floor in which there are false positives.

*Keywords: wireless sensors, sensor placement, system identification*

## 1. INTRODUCTION

Structures could suffer damage during their life time. The types of damage will depend in the use of the structure and its physical location. Buildings located in the coastline could sustain important wind forces. In addition, the presence of geological faults can induce seismic forces in the structures. Ageing of materials, as well as fatigue, could also deteriorate and diminish the security conditions of the structure. It is important to detect dangerous conditions before they could produce catastrophic results.

There are several damage detection techniques. Some are based in the change of frequencies, modal shapes or their curvatures, among others. Other fundamental differences between these techniques are the way that the information is collected. A possible classification in this regard is defined as centralized and decentralized data collection. In the first ones, all the information is collected in a single node, to be later process and analyze. Because it uses all of the data from the structure, the results may be more accurate. Nevertheless, these methodologies may not be scalable due to the number of channel needed, and therefore expensive, to acquire the information of all the sensors of the structure. In the second type of technique, the information is processed and analyzed at the sensor level. This is possible with the new technologies available with smart sensors.

The objective of this paper is to experimentally do damage detection of shear planar frames. The selected method is a modification of the Proper Orthogonal Decomposition and it is applied in a decentralized fashion. Sensor clusters are proposed and are represented by a leader at each bay for each floor. Only sensors leaders will share information to other leaders. Based on this decentralized methodology, the method seeks to find the changes in the capture energy at each mode shape of the structure.

## 2. DAMAGE DETECTION METHODS

Some of the damage detection methods are based on visual inspections of the structure. Although these methods do not require an instrument per se, require a qualified personal with experience. Additionally, not all the elements are completely exposed and the removal of non-structural elements may be required. The cost involve in this process could be prohibited, and therefore not feasible.

Other methods use acoustic signals do detect damage. The propagation of sound for a source point is later capture by piezoelectric sensor with very high sensitivity. Any loss of signal can be related to the presence of cracks in the element. This methodology is better use in homogeneous materials, otherwise the fracture process in heterogeneous become complex to detect.

The majority of methods for damage detection are those based in modal analysis. Natural frequencies and mode shapes are dynamic properties sensible to the presence of damage in the structure. However, small changes of the stiffness of any given member could not be detected in the global behaviour of the structure. A most narrow approach is required to capture changes in local modes. Differences in mode shapes, as well as in their curvatures have shown to detect damage in certain types of structures.

In the paper the methodology based in the Proper Orthogonal Decomposition is used. This technique will be explained in detailed in the next section.

## 3. PROPER ORTHOGONAL DECOMPOSITION

The Proper Orthogonal Decomposition (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 $d_i$ at N points of the system (number of sensors), sample until the M stop time. The collected values of displacements are then normalized by subtracting the mean value (equation 1)

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

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 2):

$$A = \begin{bmatrix} a_1(t_1) & a_2(t_1) & \cdots & a_N(t_1) \\ a_1(t_2) & a_2(t_2) & \cdots & a_N(t_2) \\ \vdots & \vdots & \vdots & \vdots \\ a_1(t_M) & a_2(t_M) & \cdots & a_N(t_M) \end{bmatrix} \tag{2}$$

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

$$R = (1/M)A^T A \tag{3}$$

The R matrix is symmetrical and real of order $N$ x $N$; 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) it can be localized the damage.

### 3.1. Modified proposed method

Carpio (2009) investigated diverse techniques to identify damage. He used the POD methodology in the damage location in planar frames without success. Carpio proposed a modification of the method using only the change in the correlation matrix R as damage detection element. In figure 1 is presented the comparison between the original method and modified version.

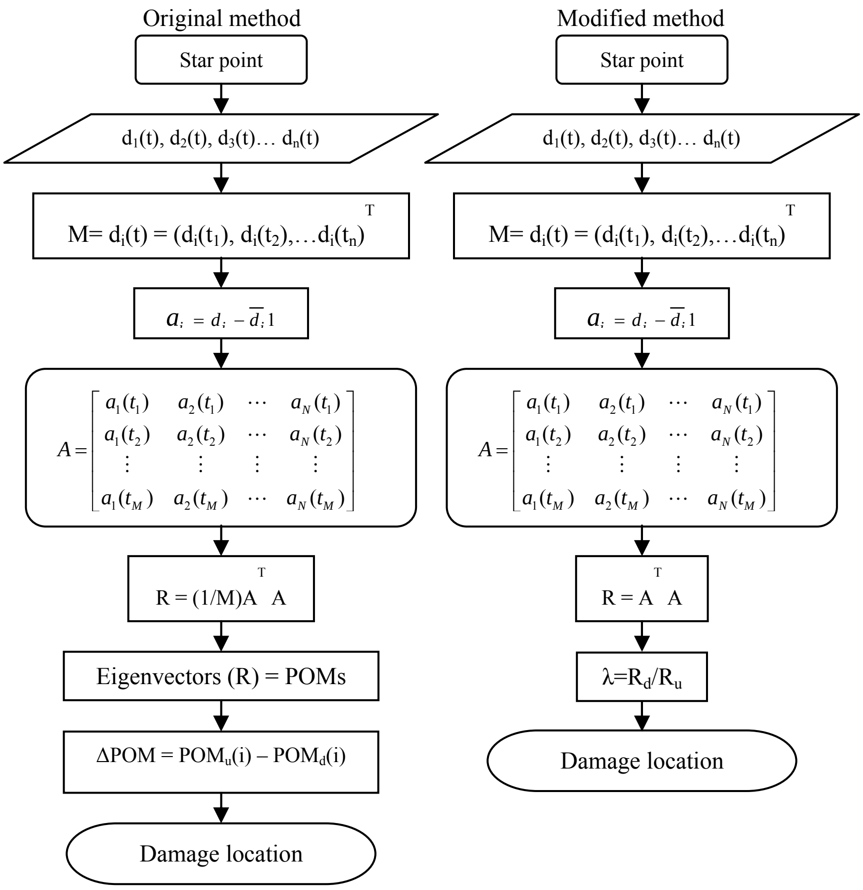


**Figure 1.** Flow diagram of the original and the proposed method

The value λ is the relation between the correlation matrices in the damage and undamaged cases. Given that R is a matrix, the value used in this relationship is the average of all the values in the matrix. λ will a value of one if there is no damage present. A number lower than one could be an indication than the damage is located in that region.

## 4. STUDIED STRUCTURES

In this paper two planar frames with a shear deformation were studied. The first has in one bay and two stories. The second one has two bays and three stories. The assumption of shear deformation is achieved by having the rotational stiffness of the beams 650 times greater than the columns. The dimensions of the elements used are presented in figures 2 and 3.

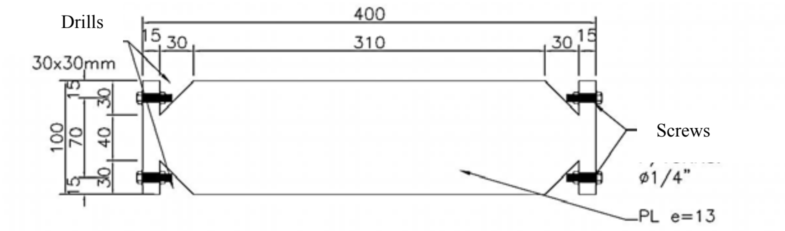


**Figure 2.** Dimension of the beam used in the models

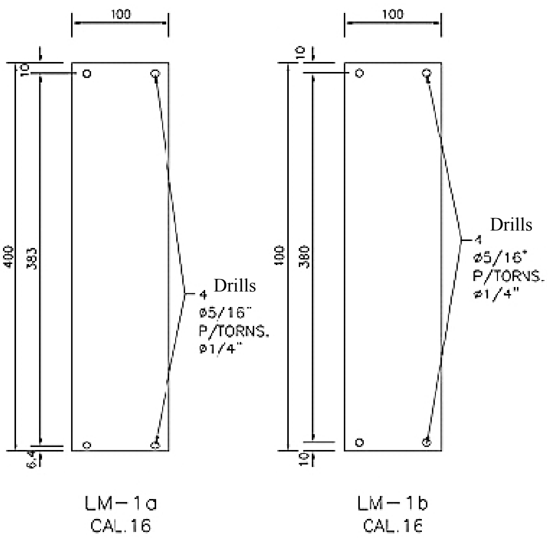


**Figure 3.** Dimension of the columns used in the models

The ensemble models are shown in figure 4

**Figure 4.** Dimension of the columns used in the models

The simulation of damage is done by the substitution of column elements with a reduced cross section. The area reductions are 10, 20, 30 y 40% of the original value. Due to the symmetry of the models only the columns of one side were changed. In the second model was changed the middle columns. Figure 5 shows the elements used to simulate damage. Figures 6 and 7 show the combinations of damage simulations used.

**Figure 5.** Columns used to simulate damage (10, 20, 30 and 40% area reduction)

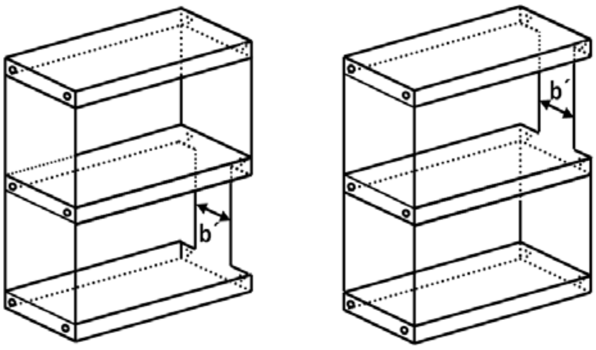


**Figure 6.** Damage position for the first model.

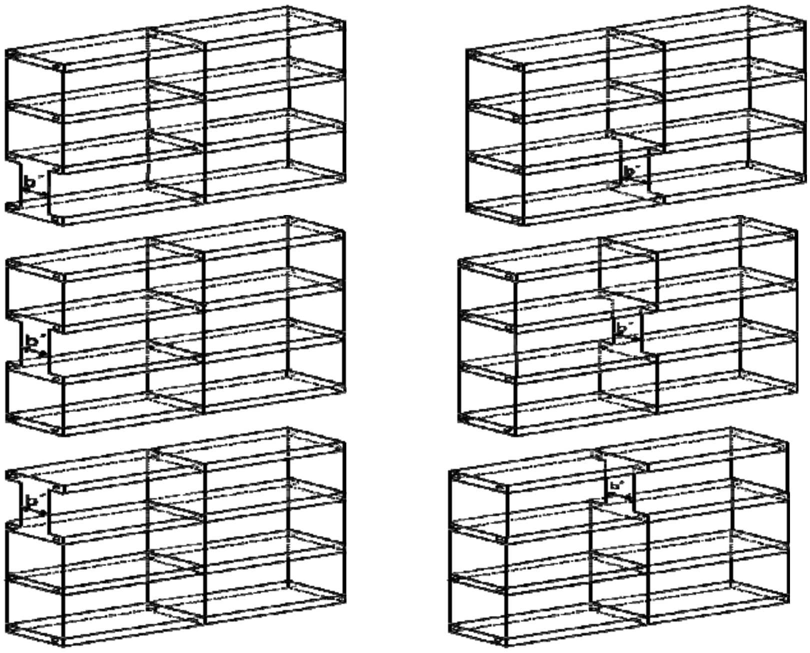

**Figure 7.** Damage position for the second model.

### 4.1. Analytical models

The structures were modelled in a Matlab (2009) code. The elements have 6 degrees of freedom considering axial deformation, displacement and rotation of the beginning and end nodes. This program also ensembles the stiffness and mass matrices of the structure.

Argueta (2009) studied the effect of the level of discretization in the response of the structure. He established that by using only the degrees of freedom at joints nodes, as well as middle points, can capture the dynamic characteristics of the structure without losing precision in the calculations. Following those recommendations a set of analytical model were constructed with degrees of freedom at join and middle points. Figure 8 shows the analytical model 1 constituted by 12 elements and nodes. In particular this figure shows the position of the damage element in the right column at the first floor. Figure 9 shows the analytical model for the second structure. This model is consisted of 30 elements and 27 nodes.

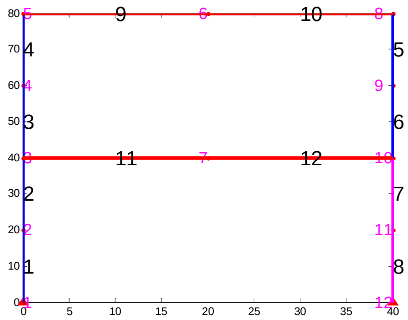

**Figure 8.** First model with number of elements and nodes.

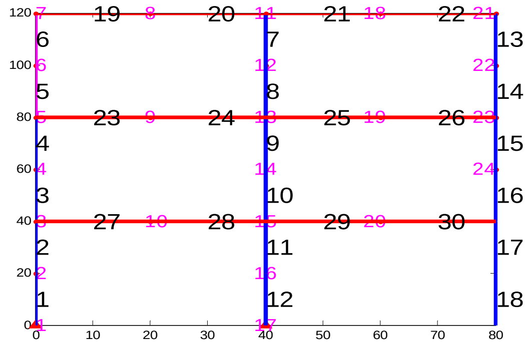

**Figure 9.** Analytical model with number of elements and nodes.

## 5. ANALYTICAL RESULTS

A modify version of POD method will be used in this research. One of the main differences is that will be applied in a decentralized way. Sensors are placed at joints and midpoints of the elements. Instead of sending the information a central point (data acquisition system) a leader node is appointed as the one collocated at the joint nodes. The leader will receive the information from its adjacent nodes. The scheme described is presented graphically in figure 10 for model 1 and model 2.

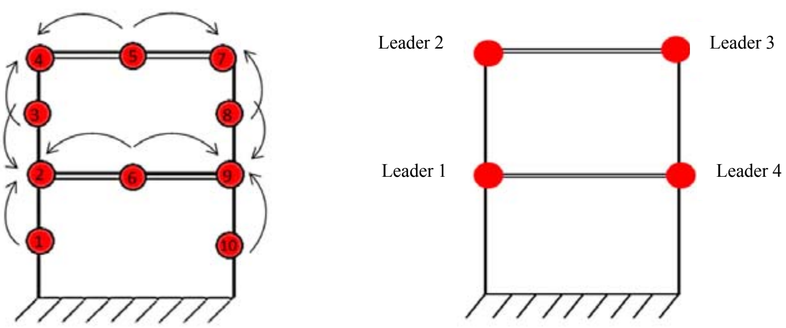


**Figure 10.** Decentralization of the information for model 1

The size of the matrix R for leader 2 of model 1 will be of 3 x 3, while for the leader 4 will be of 4 x 4. To calculate the parameter λ all of the values of R are average so only a number is obtained for each leader.

A simulation using white band noise as an input at the base of the structure was done for each of the models. 4 case damage of each column were done. Therefore for the model 1 was conducted 8 simulations. For model 2, 24 simulations were done.

The case of 10% of cross section reduction of the top column of model 1 is presented. Table 1 show the R matrix when the structure has no damage. Table 2 show the R matrix when the structure has damage.

**Table 1.** Matrix R of the leader 1. Undamaged case

| Sensor | | | |
|---|---|---|---|
| 1 | 2 | 3 | 6 |
| 1.0138 | 2.1491 | 2.9472 | 2.1491 |
| 2.1491 | 4.5584 | 6.2740 | 4.5584 |
| 2.9472 | 6.2740 | 8.8101 | 6.2740 |
| 2.1491 | 4.5584 | 6.2740 | 4.5584 |

**Table 2.** Matrix R of the leader 1. 10% of cross section reduction

| Sensor | | | |
|---|---|---|---|
| 1 | 2 | 3 | 6 |
| 1.3974 | 2.9663 | 4.1391 | 2.9663 |
| 2.9663 | 6.2997 | 8.8160 | 6.2997 |
| 4.1391 | 8.8160 | 12.5419 | 8.8160 |
| 2.9663 | 6.2997 | 8.8160 | 6.2998 |

The average values of the previous tables are: 4.2277696 and 5.909103126 respectively. The λ value is then 1.397688068. Table 3 presents the λ values for all the other leaders and levels of cross section reductions. The process of damage detection is as follow:

1. The highest value of λ is selected from the leaders between columns (1 and 2; 3 and 4). In this example is 1.4372 (yellow) for 1 and 2, and 1.4374 (green) for 3 and 4.
2. The average of these values is calculated (1.4372+1.4373)/2=1.4373
3. It is calculate the difference for each node (1.4373-1.3977=0.0396)
4. The highest positive value is taken (0.0396). This will be an indication of a possible damage zone (blue color).

The damage element is the upper right column, is located between leader 3 and 4. Results from table 3 indicate that this methodology is successful to identify the location of the damage except for the 10% level diminution of cross section.

Table 4 shows a summary of the results for the analytical model 1 for each of the position of the columns and level of damage.

**Table 3.** Identification of damage location for the upper right column of the model 1

| 10% | | | 20% | | | 30% | | | 40% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | λ | Difference | | λ | Difference | | λ | Difference | | λ | Difference |
| 1 | 1.3977 | 0.0396 | 1 | 1.267 | 0.0655 | 1 | 1.455 | 0.1218 | 1 | 1.225 | 0.1383 |
| 2 | 1.4372 | 1.00E-04 | 2 | 1.333 | 0.0002 | 2 | 1.577 | 0.0003 | 2 | 1.362 | 0.0005 |
| 3 | 1.4374 | -1.00E-04 | 3 | 1.266 | 0.067 | 3 | 1.454 | 0.1228 | 3 | 1.224 | 0.139 |
| 4 | 1.3979 | 0.0394 | 4 | 1.333 | -0.0002 | 4 | 1.577 | -0.0004 | 4 | 1.363 | -0.0005 |
| Average | 1.4373 | | Average | 1.333 | | Average | 1.577 | | Average | 1.363 | |

**Table 4.** Summary of the success of damage detection for model 1

| | Position | |
|---|---|---|
| Damage | Superior | Inferior |
| 10% | | |
| 20% | | |
| 30% | | |
| 40% | | |

From table 4 it can be said that the method works for the superior columns, but has limitations for the columns at the first floor. Also, it cannot detect damages at 10% reduction of cross section.

Table 5 presents the methodology applied when the middle column of the first floor. Table 6 presents a summary of the success in damage detection for model 2.

**Table 5.** Identification of damage location for the middle column at the second fool of the model 2

| 10% | | | 20% | | | 30% | | | 40% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | λ | Difference | | λ | Difference | | λ | Difference | | λ | Difference |
| 1 | 1.1270 | 0.0109 | 1 | 1.0324 | 0.0414 | 1 | 1.1606 | 0.0663 | 1 | 1.2242 | 0.0944 |
| 2 | 1.1376 | 0.0003 | 2 | 1.0734 | 0.0004 | 2 | 1.2261 | 0.0008 | 2 | 1.3174 | 0.0012 |
| 3 | 1.1342 | 0.0037 | 3 | 1.0663 | 0.0075 | 3 | 1.2124 | 0.0145 | 3 | 1.2977 | 0.0209 |
| 4 | 1.1341 | 0.0038 | 4 | 1.0657 | 0.0081 | 4 | 1.2113 | 0.0156 | 4 | 1.2962 | 0.0224 |
| 5 | 1.1384 | -0.0005 | 5 | 1.0747 | -0.0009 | 5 | 1.2286 | -0.0017 | 5 | 1.3210 | -0.0024 |
| 6 | 1.1264 | 0.0115 | 6 | 1.0296 | 0.0442 | 6 | 1.1562 | 0.0707 | 6 | 1.2181 | 0.1005 |
| 7 | 1.1342 | 0.0037 | 7 | 1.0663 | 0.0075 | 7 | 1.2124 | 0.0145 | 7 | 1.2977 | 0.0209 |
| 8 | 1.1376 | 0.0003 | 8 | 1.0734 | 0.0004 | 8 | 1.2261 | 0.0008 | 8 | 1.3174 | 0.0012 |
| 9 | 1.1363 | 0.0016 | 9 | 1.0324 | 0.0414 | 9 | 1.1606 | 0.0663 | 9 | 1.2242 | 0.0944 |
| Average | 1.1339 | | Average | 1.0527 | | Average | 1.1930 | | Average | 1.2704 | |

**Table 6.** Summary of the success of damage detection for model 2

| | Position | | | | | |
|---|---|---|---|---|---|---|
| Damage | Exterior 1st | Central 1st | Exterior 2nd | Central 2nd | Exterior 3rd | Central 3rd |
| 10% | | | | | | |
| 20% | | | | | | |
| 30% | | | | | | |
| 40% | | | | | | |

Conclusions from table 6 are than the method works for the superior columns, but has limitations for the columns at the first floor. Also, it cannot detect damages at 10% reduction of cross section at the exterior columns.

## 6. EXPERIMENTAL RESULTS

The accelerometers placed over the structure were the PCB (2012) 393A03. The data acquisition system used the SigLab model 20-42 with 20 bits of digital-analog conversion. This system has an anti-alias filter and has a capability of having 4 input channels active at the same time.

Since the structure has more 4 locations in which the sensor need to be place, several arrangements were used. In the entire set of arrays one sensor was always at the same location. The purpose of this sensor is to have a common measurement point to normalize all the records. Figure 11 shows the array of sensors needed for the model 2.

Because the frames have shear behaviour, it is assumed that there will be no rotation at the nodes. This supposition reduces the number of degrees of freedom to be considered. Therefore, only accelerations in horizontal direction were recorded (see figure 12)

In table 7 and 8 present the summary of the damage location of models 1 and 2 when using experimental information.

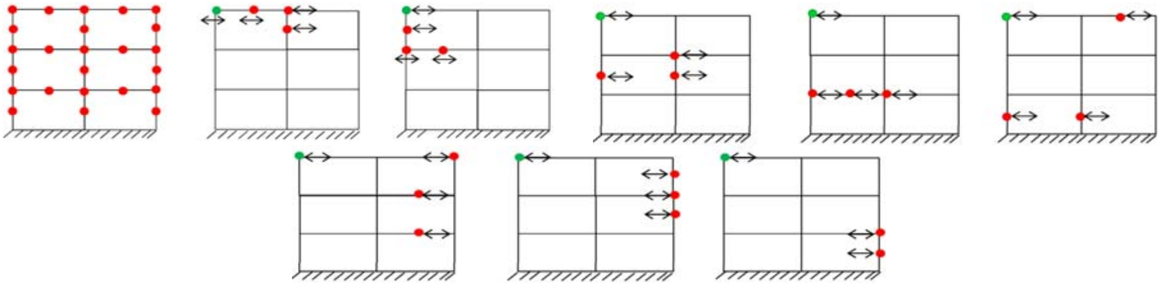

**Figure 11.** Instrumentation array for model 2

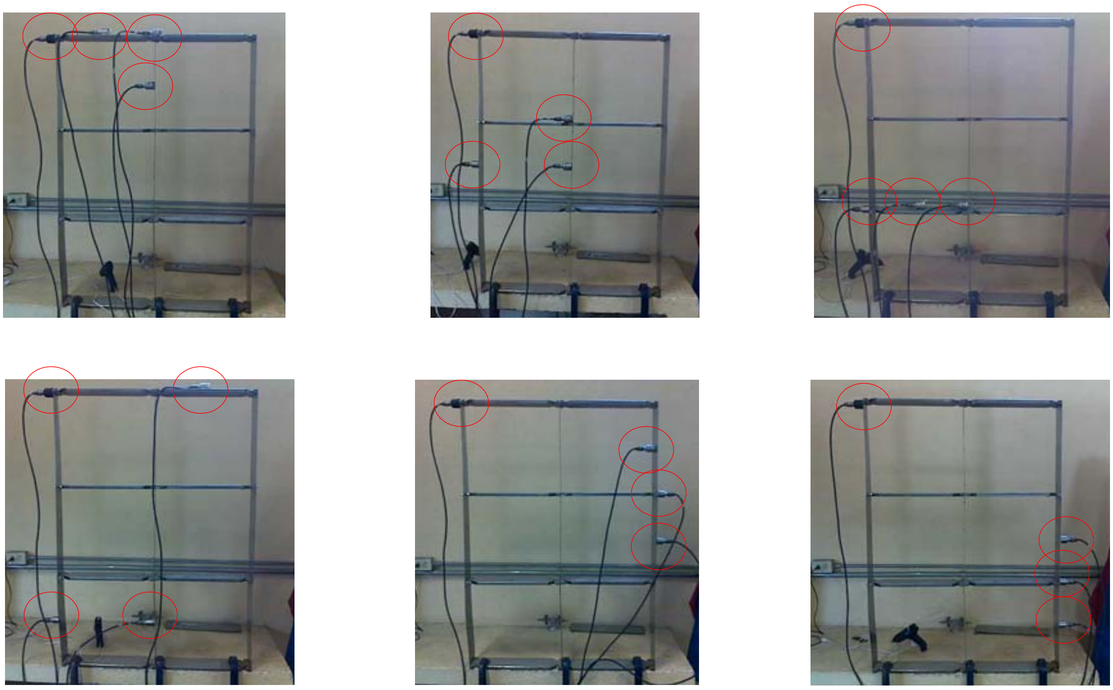

**Figure 12.** Instrumentation array for model 2. Red circle indicates the presence of a sensor.

**Table 7.** Summary of the success of damage detection for model 1,based on experimental results

| | Position | |
|---|---|---|
| Damage | Superior | Inferior |
| 10% | | |
| 20% | | |
| 30% | | |
| 40% | | |

**Table 8.** Summary of the success of damage detection for model 2, based on experimental results

| | Position | | | | | |
|---|---|---|---|---|---|---|
| Damage | Exterior 1st | Central 1st | Exterior 2nd | Central 2nd | Exterior 3rd | Central 3rd |
| 10% | | | | | | |
| 20% | | | | | | |
| 30% | | | | | | |
| 40% | | | | | | |

Some conclusions arise from the results of table 7 and 8. In the case of model 1, it was possible to detect damage for 10% of cross section reduction, at least for the inferior column. For the model 2 the exterior column in the second nivel seems no to be interested in this topic

## 7. CONCLUSIONS

In this paper the method POD was modified to be able to detect damage in planar frames with shear deformations. A set of two analytical models representing structure 1 and 2 were developed. The structures were subject to a white noise. The damage was simulated as a cross section reduction of the column elements.

Two experimental models were built. Because the dimension of the beam compared with the columns, it can be assumed that there are no rotations, therefore a shear behaviour.

The modified version of the POD was applied to the structures. Results demonstrated that independently of the damage sustained in the columns, the method is not able to detect damage in the lower level columns.

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