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OPTICAL METHODS AS AN ALTERNATIVE TO THE INSTRUMENTATION ON DYNAMIC AND SEISMIC TESTS

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Abstract

Experimental tests on structures are still the base of the research in earthquake engineering. The success of such a tests deeply depends on the instrumentation recording the response parameters. The expense could be high enough depending on the required response and the extent of the specimen to be tested. This paper proposes the application of optical methods for response estimation as an alternative to traditional instrumentation: i) for static tests, a Fourier based method to estimate strains and displacements, and ii) for dynamic tests, the use of a system of optoelectronic cameras to estimate displacements and accelerations. Several static and dynamic tests were performed to validate this proposal. These tests were instrumented with LVDTs, accelerometers, strain gages and extensometers. The results show a good agreement between the proposed methods and the reference results and prove that these methods have the potential for replacing or for being a complement of traditional instrumentation, while give more significant information with reduced costs.

Keywords: structural tests; instrumentation; image processing; dynamic tests.

1. Introduction

The experimentation and simulation are the base of most of the developments on seismic engineering and structural dynamics. Even if numerical models have had significant advances, experimental tests, static and dynamic, at a real or reduced scale, are still required to validate those models. The success of such tests deeply depends on the instrumentation recording the response parameters, which will be indicators of behaviour (strain, displacement or acceleration). The expense could be high enough depending on the required response and the extent of the specimen to be studied. It may even limit the quantity of tests and the information that can be obtained on a specific test. For instance, a large quantity of strain gages is necessary for establishing a deformation field or a failure analysis; but as these instruments are destroyed during the test, its number will be determined by economical and no by technical reasons. Also for dynamic tests, accelerometers or LVDTs (Linear Variable Differential Transformer) are used to record the response on some specific points, and the information of intermediate points must be extrapolated or just ignored.

Thereby, alternative methods for recording response parameters during the whole loading process are required. Also, they must allow to estimate response on places of difficult access, where a traditional instrument is not possible to place. Computer vision techniques are a suitable option meeting these requirements. The response estimation by means of image processing of pictures or videos has been already used in several fields as robotics, mechanical engineering, bioengineering and recently in civil engineering for the study of fibre-reinforced elements, concrete walls and porous rocks[1, 2, 3, 4].

This work proposes the application and adaptation of optical methods for response estimation as an alternative to traditional instrumentation. Two approaches were used: one for the estimation of displacements and strains in static tests and another for the estimation of displacements and accelerations on dynamic tests.

For static tests high resolution videos were taken during the loading process and images processing is used to assess the response parameters. A proposed method based on Fourier analysis of the image information was applied. For dynamic tests, a system of optoelectronic cameras was used. These cameras follow a set of reflective markers placed on key locations where the response is to be measured.

These approaches were compared to measures obtained by traditional instrumentation (e.g. strain gages, LVDTs and accelerometers) on columns and beams for static tests, and, on reduced scale models on shake table tests. The results show a good agreement between the optical methods and the reference results and prove that these methods have the potential for replacing, or for being a complement, of traditional instrumentation. The main advantages are the low costs on the long term and the possibility of recording much more significant information on a laboratory test.

2. Optical Methods for estimating mechanical deformations

The mechanical and dynamic characterization of materials, elements and structural systems requires representative tests of several loading states as tension, compression, shear or bending. Common practice to obtain any response parameter is to use instruments as LVDTs (Load Variable Displacement Transducer), mechanical extensometers, strain gages or accelerometers, placed directly on the element at a point of interest. This direct, traditional method produce accurate results provided the use of high precision instruments, good calibration practices and enough instruments to record all the relevant information. However, direct instruments recording of response has also some drawbacks: i) The strain gages are disposable and require smooth surfaces to be placed; ii) For having a complete deformation field instead of a localized deformation, a significant number of strain gages is required; iii) LVDTs and mechanical extensometers cannot record responses during the whole loading process to avoid damages on their selves when fragile failures occur; iv) there is a human error associated to mechanical extensometers since the operator could miss some registers or take them with some delay; and, v) The associated costs of strain gages, LVDTs or accelerometers could be prohibitive in most cases when a detailed response is required (e.g. walls, scaled structures).

Indirect methods to obtain response parameters have been already investigated. Procedures for finding movement, shape estimations and deformation parameters based on image processing are among these methods. The processing techniques are varied from digital image correlation (DIC), interferometry, estimating in-plane movement as well as depth on flexible or rigid surfaces [4, 5]. The algorithms could be relatively complex and time and machine resource consuming depending on the method.

2.1 Static tests

One of the most used techniques is the digital image correlation (DIC), a method developed two decades ago, which takes nowadays a number of different forms for different fields and purposes [6]. This technique consists in tracking subsets that must match on two images of a region of interest coming from two different time points during a loading test. The first point is usually the beginning of a test (when the sample has no deformation) represented by a reference image and the second is a deformed shape at any point of the test represented by a target image. The matching procedure is based on a correlation algorithm which may be carried out in the frame matrix or in the Fourier space [6, 7]. For this images to be taken the specimen must be prepared before the test with a painted speckle pattern on the surface to assure a random distribution of intensity on the gray scale. This is achieved by painting black dots on the specimen. Also, this technique requires an optical sensor that could be normal CCD or CMOS up to laser viewer. This method has been applied for the estimation of field strains in welded elements, fiber reinforced masonry specimens and mechanical elements with discontinuities among others [1, 2, 7, 8]. It has shown to be effective in producing accurate enough estimations of a deformation field. However, it requires optical sensor, calibration and resolution determination, selection of the pattern and processing algorithms to enhance the image.

Other methods for static tests involve identifying pixel clusters in a surface and following them during a loading process [3]. This method does not need a painted pattern on the surface but requires some visible defects to identify and follow. It may be suitable in concrete surfaces.

2.2 Dynamic tests

The estimation of response in dynamic tests is usually done by high speed transducers as LVDTs and high resolution accelerometers, as mentioned before. There are only a few techniques based on image processing for the estimation of dynamic parameters in structural tests. These techniques are also based on digital image correlation method but with some modifications and of course the use of two cameras for three dimensional measurements of contours and displacements [9, 10, 11]. According to Siebert and Crompton [10], this method permits of estimating vibration phases and displacements with high spatial resolution and using high speed cameras it is possible to estimate strain fields. However its application is still limited to reduced surfaces where it is possible to paint a speckle, hence the estimation of response parameters on a larger structure subjected to dynamic loads is hard to achieve.

3. Proposal of using computer vision techniques to estimate structural response parameters

This paper proposes two methodologies for the estimation of responses as displacements, strains and accelerations. One for static tests and another one for dynamic tests. Both are based on the use of optical devices and images processing and are intended to improve the quantity and the quality of the obtained information and to reduce the instrumentation costs at the same time.

3.1 Static Tests

For static tests a method based on frequency analysis is proposed. High resolution videos were taken during the loading process of a specimen, focused on painted speckle over the surface intended for analysis. Then a Fourier analysis is applied on a number of selected frames of the image, namely the frames associated to load increments, although it is possible to analyze the information at any moment. The approach proposed consists in relating the change of the phase function that generates the specific pattern between a reference frame (associated to an initial state without load) and any other frame during the loading process (deformed state) to the change in length between these two states. Doing so it is possible to estimate displacements as well as strains, provided that high resolution images are used.

Before the main procedure to be explained, it is important to clarify which time-points of the whole video should be analyzed. As tests on specimens and structural elements are intended to estimate mechanical properties, strength or response parameters, it is necessary to relate loads with deformation parameters. Thereby, the following procedure must be applied to a frame associated to a specific load value. As a single frame may not contain reliable information for illumination issues for instance, it was decided to consider 1 second before and after a load point. For example, if the recording rate is 30 fps (frames per second), the analysis was made on 61 frames, 30 before the loading point, just on the moment the load has its specified value and 30 after this point.

3.1.1 Experimental Setup

Over one sample's face (either wood or concrete), a block matrix pattern is painted. The selected pattern looks like a chessboard, typically over a white background a sequence of 2mmx2mm square blocks is painted. It could be interpreted as a bi-valuated function considering the high value as white and the low value as black (similarly to the continuous line in Fig. 1). The main idea is to be able to measure the displacement as a phase shift as shown in figure 1.

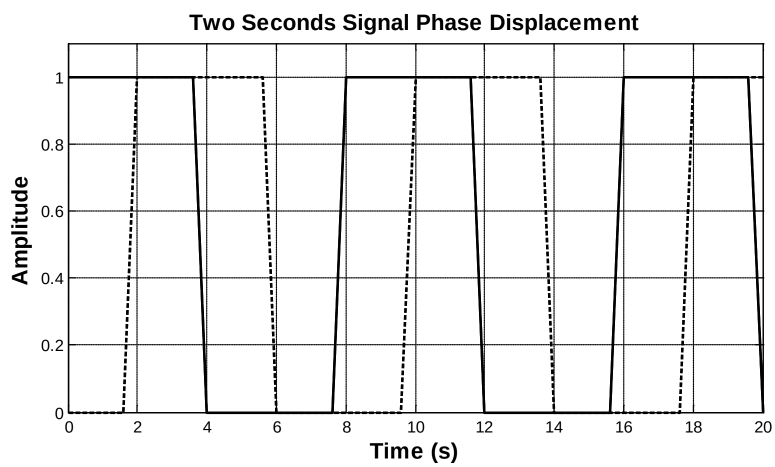


Fig. 1 – Example of a two seconds signal phase displacement

A commercial reflex camera (Canon EOS Rebel t2i with a 18-55mm lens in a 1080 HD video at 30 fps and a Nikon 750D with a 35-200mm lens, in a 1080 HD video at 60fps) is placed on a tripod focusing the middle of the sample's region of interest as shown in Fig. 2. The distance from the sample and the lens zoom settings are evaluated at each test in order to have the best spatial resolution, i.e. more pixels on each pattern block; due to physical restrictions it ranges from 35 to 50 cm.

Fig. 2 – Experimental setup for the camera and the sample to be tested

Concerning the lighting conditions, it is the combination of natural light and the general artificial lighting at the laboratory (fluorescent tubes), there is no light source pointing to the sample. As the lab technicians and general personnel usually are moving around the sample, they may generate shadows on certain video frames. It was made this way on purpose, in other words nothing is different form a traditional test.

3.1.2 Video Processing

The video processing to extract the deformation follows the Fig. 3 algorithm. For more detail of this procedure and the used formulae, see the Annexe 1.

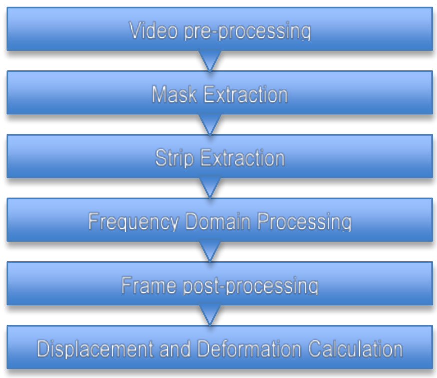


Fig. 3 – Simplified flow chart of the proposed method

The video pre-processing step involves: 1) frame by frame cropping on the region of interest, 2) image tilt correction, 3) A four pixels border addition in order to clearly determine the block pattern, 4) histogram equalization (enhancing low contrast frames) and 5) recovering of the loading times from audio track.

The mask extraction is the cropping of one-frame reference strips (Top, Middle and Bottom) of the sample and the removal of saturated values. This stage helps to reduce the effects of non-uniform lighting and allows to obtain a region behavior instead of a simple point by point displacement.

Strip extraction is the cropping of all video frames.

Frequency domain processing consists on: 1) Applying the spatial Fourier Transform to the mask reference frame, 2) Applying spatial Fourier Transform to the remaining video frames, 3) Magnitude function division of all frames by the mask magnitude (this helps to reduce the amplitude variation due to frame brightness and contrast differences), 4) Phase difference calculation of all frames relative to the mask phase (allows to detect a movement related to phase change), 5) Magnitude averaging of the two seconds around the loading times, 6) Phase difference averaging of the two seconds around the loading, 7) The Inverse Fourier Transform is calculated using the averaged magnitude and the averaged phase difference thus obtaining a spatial signal related to the displacement.

Frame post-processing consists on a thresholding function, followed by a pixel grouping if there are at least five contiguous pixels in a row or column it is considered as a region displacement, either in x or y-direction.

Displacement and deformation calculations consist on: 1) estimation of two points distance on the first frame (Lx or Ly in pixel units), 2) estimation of the two points displacement, this is perform considering the neighborhood through a median filter using a 3x3 or a 5x5 mask (Δx of Δy), 3) Finding the deformation as usual, as the relative change in length: $\Delta X/Lx$ and $\Delta Y/Ly$.

3.2 Dynamic Tests

For dynamic tests, a method capable of recording response parameters at different rates in time is required. This is also a requirement in the field of bioengineering, where several systems have been proved, from the use of direct motion recorders (as light accelerometers) to image processing of videos. This work propose the adaptation of a system frequently used in bioengineering applications to follow patients' motions. It is a set of optoelectronic cameras (BTS Smart DX-400 system) capable of determine the 3D displacement of a set of retro-reflective markers at 100 Hz frame-rate. These cameras follow a set of reflective markers placed on key locations where the response is to be measured, while a video camera records the specimen motion, see Fig. 4.

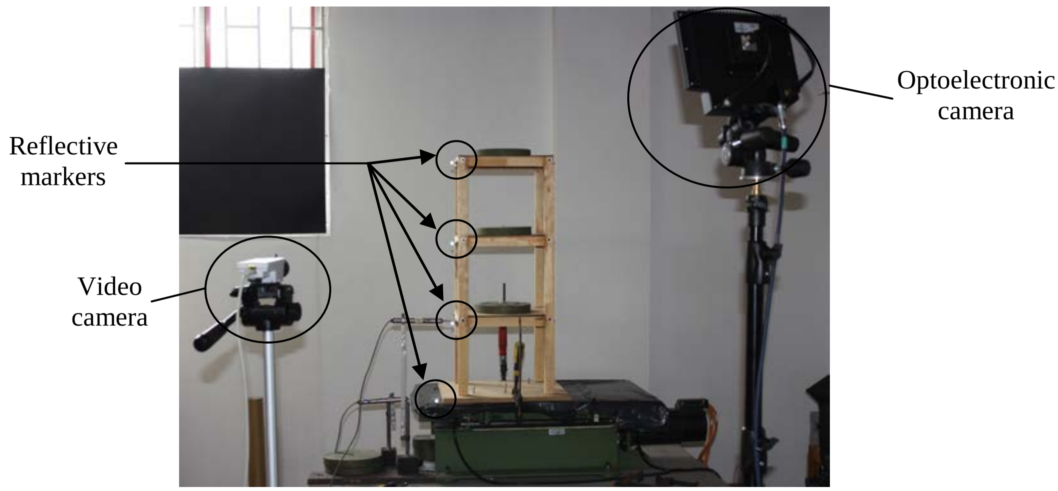


Fig. 4 – Experimental setup for dynamic tests

The procedure has three stages: 1) Test setup, 2) Calibration and test recording and 3) Data processing.

The test setup consists in placing the markers at each location of which a response parameter is required and placing the cameras in strategic points so that each marker is visible from two cameras. This camera's setup assure enough accuracy and reliability. Thereby although two cameras are enough to accurately estimate the displacement of a point, three cameras are suitable for most applications in order to assure that each point is followed by two cameras at the same time in a three dimensional model. The lighting conditions requirements are minimum; in fact, they may be used outdoors.

The calibration process includes the establishment of an origin of coordinates and a dimension volume in which the motion will take place.

The data processing depends on the application. The cameras have a software for the identification and motion markers capture. The user build its own application to obtain a response parameters. It includes smooth filtering of the markers position, in this case with a moving average window of 0.1 s. Once the position is established, other parameters as velocity and acceleration may be calculated from its derivatives.

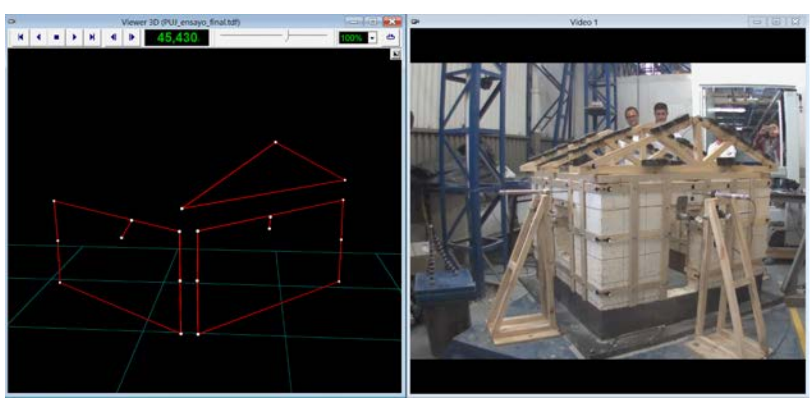


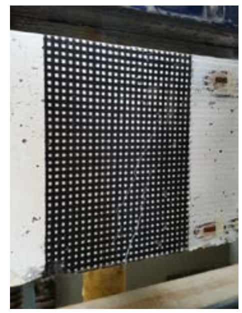
Fig. 5 – Markers position on the system coordinates for recording the displacement of a reduced scale rammed earth model

4. Tests and Results

In order to validate the proposed methods, several static and dynamic tests were conducted on structural elements and reduced scale structures. Some of these results are exposed hereafter.

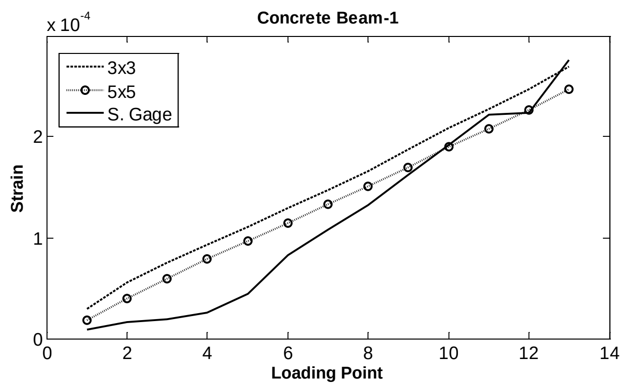
For static conditions, compression and bending tests were performed on wood short columns (8x8x30cm and12x20x40 cm) and concrete beams (15x20x140 cm), see Figs. 4 and 6. Each sample was painted with the speckle described before and instrumented with strain gages and mechanical extensometers in order to have validation results from traditional instruments. Fig. 7 shows the strain results for the 3x3 and the 5x5 masks, compared to the measures of a strain gage located in a control point.

a)

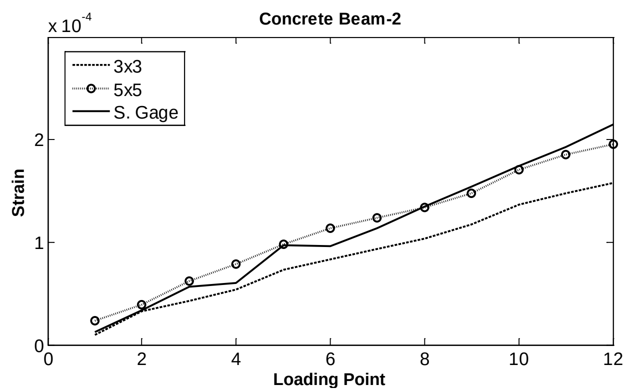


b)

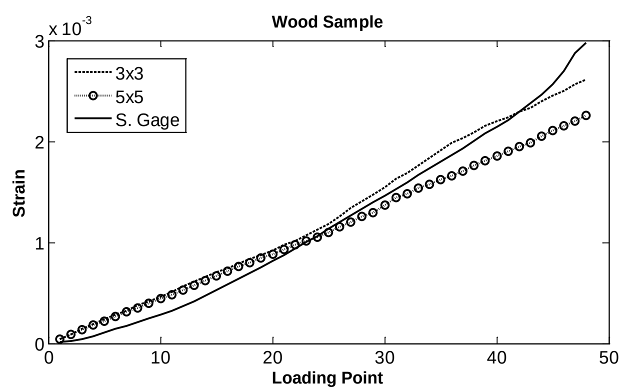
Fig. 6 – Concrete beam: a) bending test b) central portion with a painted speckle



a)



b)



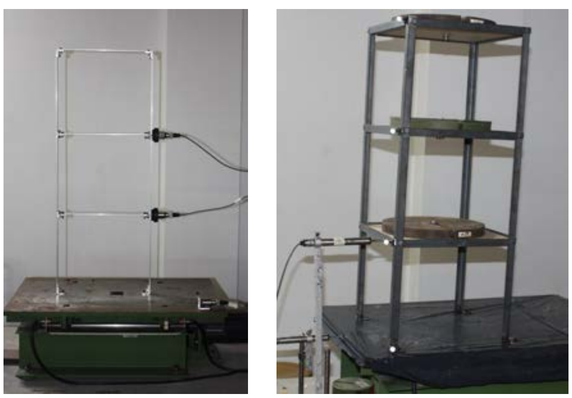
c)

Fig. 7 – Comparison of the results of the Fourier based proposed method and the measures of a strain gage for: a) and b) concrete beams and c) a wood column

According to these results the 5x5 mask gives better results for the concrete beams since it approaches in a better way the strain gages measurements. For the wood column the 3x3 mask gave better results. Most of the test worked better with the 5x5 masks, however more tests on different materials and under different loading conditions are required in order to definitively choose the better mask. Nevertheless, the results of the proposed method are successful in estimating the trends and magnitudes of average strains of the order of 20 $\mu\varepsilon$, for both concrete and wood elements. It is important to point out that the estimated strains correspond to a particular point in one direction. Additional tests are required to study the complete strain field (different directions, different points).

For dynamic conditions, several reduced scale structures were tested on two unidirectional shake tables: 1) a 1:6 reduced scale rammed earth building (see Fig. 5) on a shake table (1.5 m x 1.5 m) controlled by a 100-kN load capacity MTS dynamic actuator with a 250-mm total stroke, supporting models weighing up to 15 kN, and 2) several models of aluminium, micro concrete and steel, see Fig. 8, on a shake table (0.80 m x 0.60 m) controlled by a Bosch Rexroth electric motor supporting models weighing up to 1 kN. The traditional instrumentation consisted in: i) 3 high sensitivity (1000 mV/V) Wilcoxon accelerometers (with a 5 g acceleration range) which signals were recorded by using an integrated electronic piezoelectric (IEPE) signal conditioning NI-9234 connected to cDAQ-9184 ethernet chassis from National Instruments (NI), and ii) a set of Vishay LVDTs which signals were recorded with a *System 5000* acquisition system. As for the static tests, the natural lighting conditions of the laboratory was not modified in order to work in normal conditions.

As the sampling rate of cameras and accelerometers were not equal (100 f/s vs. 2048 s/s), the accelerometer signals were low-pass filtered at 50 Hz and then resampled to 100 s/s).



a) b)

Fig. 8 – Reduced scale models subjected to shake table tests and their instrumentation: a) 2D Aluminium frame, and b) Steel frame

Fig. 9 show the results of one the forced vibration tests on the aluminium frame. The graphics show the excitation expressed as base acceleration and the history of acceleration responses for the three levels, all derived from the images of the cameras system following 4 markers: one at the base, on the shake table, and the other three at each level of the frame.

Fig.10 compares the acceleration response at the second level of a frame, obtained from the accelerometers and the cameras in two cases: a forced vibration test and a free vibration test. It is observed that the trends are well estimated by the proposed method in both cases. As for the magnitudes, the free vibration tests produce better estimates of the acceleration than the forced vibration tests. It is probably due to an excessive friction in the shake table bearings which produces a high noise, which is then registered by the accelerometers. Free vibration tests instead do not present these high frequency noise in the recorded responses.

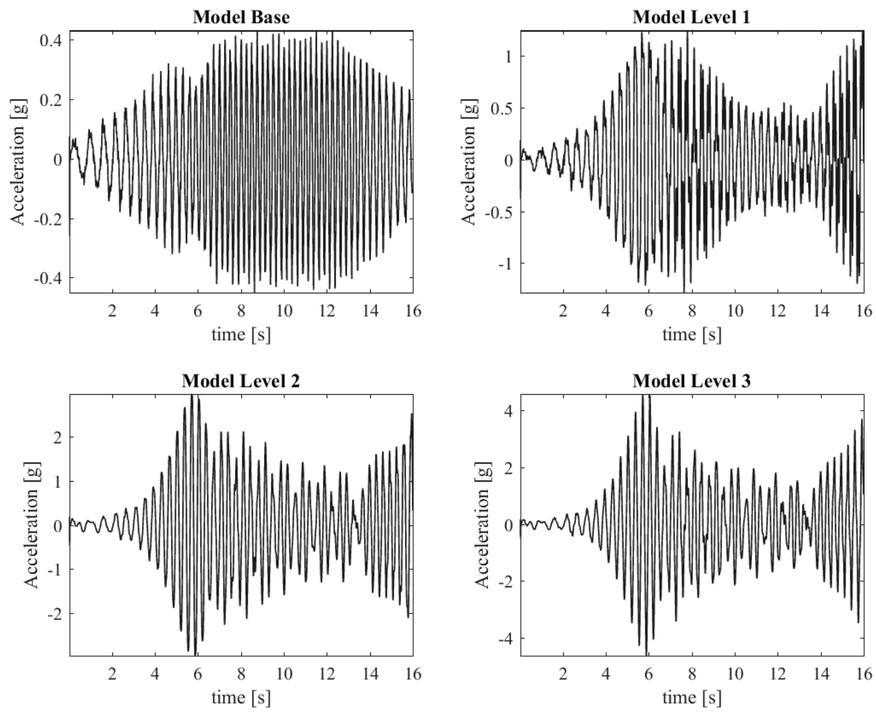
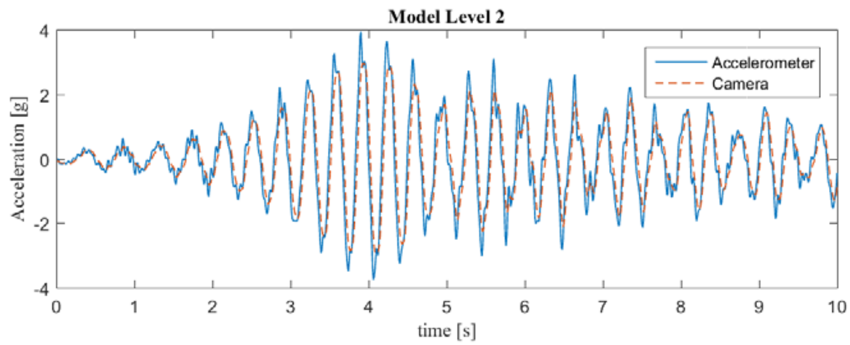
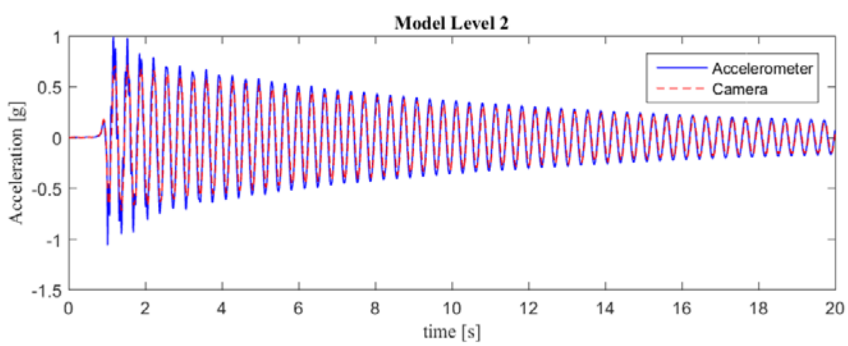


Fig. 9 – Results of the base excitation and the response acceleration for the 2D aluminum frame, derived with the camera data



a)



b)

Fig. 10 – Results produced by an accelerometer and the image system for the acceleration response of one story of the aluminum frame for: a) a forced test and b) a free vibration test

4. Conclusions

Two methods based on image processing were proposed in this paper for the estimations of structural response parameters: i) a Fourier analysis based method for strains and displacements in static tests and, ii) an adaptation of an image processing method for dynamic tests. Both procedures are intended for the application in laboratory or field conditions so that lighting conditions were kept natural (without any additional source of light). The validation of these approaches was made through the comparison with measurements taken by traditional instruments: accelerometers, LVDTs, strain gages and extensometers. The general results show a good agreement with the reference results in static as well as dynamic tests. For the static tests, the main focus in this paper was the estimation of strains since their magnitudes are smaller than those of displacements, hence more difficult to obtain. The proposed method is capable of estimating average strains of 20 $\mu\varepsilon$. For dynamic tests the estimation of accelerations at the floor levels was also satisfactory. These results suggest that these methods are suitable to be applied on tests on earthquake engineering, obtaining more and better information of the structural response with reduced costs.

5. Acknowledgements

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6. References

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Annexe

FLOW CHART OF THE PROPOSED FRECUENCY BASED METHOD

Capture the first frame F_0

Rotate an angle ϴ

Crop pattern white and black from the image

Invert colours: black to white

Put a white square around a crop image to 4 pixels (BLOQ)

Extract Top, Central and Bottom masks (MR_T, MR_C and MR_B)

Choose a working mask (MR=MR_T, MR=MR_C or MR=MR_B)

Remove pixels with value 255 from MR

Apply Fourier Transform (mag_MR and phase_MR)

Validate MR doesn´t have cero pixels on zero

Extract and process a BLOQ again

Extract Top, Central or Bottom Stripe (IRef_T, IRef_C or IRef_B)

Apply Fourier Transform (mag_IRef and phase_IRef)

To acquire $|M_{F\_0}|$ y $\Delta\Phi_{F\_0}$:

$$|M_{F\_0}| = \frac{|mag\_IRef|}{|mag\_MR|}$$

$$\Delta\Phi_{F\_0} = \angle\Phi_{phase\_IRef} - \angle\Phi_{phase\_MR}$$

Smooth $\Delta\Phi_{F\_0}$

Select a frame from each loading point, Fx_i

Extract frames from 1 second before and 1 second after Fx_i, Fx_i (a_k60)

Capture frame a_k60

Modify a_k60 histogram to be similar to F_0 histogram

Rotate an angle ϴ a_k60

Crop pattern white and black from image a_k60

Invert colours: black to white in a_k60

Put a white square around a crop image to 4 pixels a_k60

Extract Top, Central or Bottom Stripes (Stripe_T, Stripe_C or Stripe_B)

Apply Fourier Transform (mag_Stripe_k60 and phase_ Stripe_k60)

To acquire $|M_{T\_K60}|$ y $\Delta\Phi_{T\_K60}$:

$$|M_{T\_K60}| = \frac{|mag\_Stripe\_k60|}{|mag\_MR|}$$

$$\Delta\Phi_{T\_K60} = \angle\Phi_{phase\_Stripe\_k60} - \angle\Phi_{phase\_MR}$$

Adding result to Fxi_60

Fxi_60 > # Total_Frames

To get mean Fx_i:

$$|M_{Fx\_i}| = \frac{\left|\sum_{-1s}^{1s} M_{T\_K60}\right|}{\#\ Total\_Frames}$$

$$|\Delta\Phi_{FX\_i}| = \frac{\left|\sum_{-1s}^{1s} \Delta\Phi_{T\_K60}\right|}{\#\ Total\_Frames}$$

Smooth $\Delta\Phi_{FX\_i}$

$$\Delta\Phi_{Ti} = \Delta\Phi_{FX\_i} - \Delta\Phi_{F\_0}$$

To get:

$$F_{FX\_i} = F^{-1}\left[|M_{Fx\_i}|\right]e^{j\Delta\Phi_{Ti}}$$

Thresholding F_{FX_i} with Otsu level from a normalize histogram

Thresholding $F_{FX\_i} = F\_thres$

Find vertical and horizontal moving zone (Mov_V, Mov_H), counting 5 continuous black pixels on F_thres
Find: $F\_vi = Mov\_V * F_{FX\_i}$
Find: $F\_hi = Mov\_H * F_{FX\_i}$
Choose two closes pixels in IRef_T, IRef_C or IRef_B (P_1 and P_2)
Calculate an initial distance between P1 and P2: $P_{1i} = (x_1, y_1)$ $P_{2i} = (x_2, y_2)$ $LXi = \lvert LX_{P1} - LX_{P2}\rvert = \lvert x_1 - x_2\rvert$ $LYi = \lvert LY_{P1} - LY_{P2}\rvert = \lvert y_1 - y_2\rvert$ $LTi = \sqrt{LX^2 + LY^2}$
Calculate a horizontal change in the final distance from 5x5 region on P1 and P2 :
$\Delta X_{\frac{P_{1i}}{MR}} = median\left(F_{hi}(x_1 - 1{:}x_1 + 1, y_1 - 1{:}y_1 + 1)\right)$ $\Delta X_{\frac{P_{2i}}{MR}} = median\left(F_{hi}(x_2 - 1{:}x_2 + 1, y_2 - 1{:}y_2 + 1)\right)$ $\Delta XT_{p1p2i/MS} = \left\lvert \Delta X_{\frac{P_{1i}}{MR}} - \Delta X_{\frac{P_{2i}}{MR}} \right\rvert$
Calculate a vertical change in the final distance from 5x5 region on P1 and P2:
$\Delta Y_{\frac{P_{1i}}{MR}} = median\left(F_{vi}(x_1 - 1{:}x_1 + 1, y_1 - 1{:}y_1 + 1)\right)$ $\Delta Y_{\frac{P_{2i}}{MR}} = median\left(F_{vi}(x_2 - 1{:}x_2 + 1, y_2 - 1{:}y_2 + 1)\right)$ $\Delta YT_{p1p2i/MS} = \left\lvert \Delta Y_{\frac{P_{1i}}{MR}} - \Delta Y_{\frac{P_{2i}}{MR}} \right\rvert$
Calculate the total change final distance from 5x5 region on P1 and P2:
$\Delta DT_{p1p2i/MS} = \sqrt{\left(\Delta XT_{p1p2i/MS}\right)^2 + \left(\Delta YT_{p1p2i/MS}\right)^2}$
Calculate horizontal, vertical and total strain from 5x5 region on P1 and P2:
$\varepsilon_{xi} = \frac{\Delta XT_{p1p2i/MS}}{LX}$ $\varepsilon_{yi} = \frac{\Delta YT_{p1p2i/MS}}{LY}$
$\varepsilon_{ti} = \frac{\Delta DT_{p1p2i/MS}}{LT}$
i > Max_temporal_load_points
Plot strain tendencies to temporal load points to 3x3 and 5x5 pixel regions.
Find a relation between the first second and the last second of the video.