Detection of damages using temporal variation of natural frequencies and principal component analysis.

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ABSTRACT

Detection of structural damage is an important topic. The use of forced vibration is a good way to characterize a structure but costs, logistic and energy needed made it a non-usual system in Civil Engineering. The use of ambient vibration seems to be the best manner to characterize structures. The problem in both cases, but more with ambient vibration, is that detecting damages needs a knowledge of the non-damage state or a deeper knowledge of the materials used for its construction. For this reason, some promising techniques have been developed. One of them is the application of principal component analysis at the temporal variation of natural frequencies. In brief, a non-damaged structure needs only one principal component to explain the change of the modal frequencies with weather variables meanwhile more than one are needed for damaged structures. As other detection techniques, it has its advantages and disadvantages. The main advantages are: the lack of knowledge of the previous state of the structure, the relative short time required (about 10 days), the low cost and the few instrumentations needed. The main disadvantage of the Principal component analysis applied to structural damage is the need of more studies to correlate the degree of damage with the number of principal components. This paper presents the results obtained for: the Mallorca cathedral, four buildings in Barcelona and a reduced model structure in a laboratory. Furthermore, we suggest a semiautomatic algorithm to track the modal frequencies along the time, and a discussion of operational modal analysis in real buildings.

INTRODUCTION

The need of evaluate the damage of a structure is an important topic in seismic engineering and in studies of structural pathology. Sometimes damages stay hidden back of other elements and are not easy to be detected. Change of modal frequencies produced by damages is clearly a good starting point proposed by several authors [1-3]. The main problem with this technique is the need of a deep knowledge of non-damaged condition or structural parameters being monitorized permanently with a dynamic monitoring system. Other techniques have been developed using experimental and operational modal analysis. The first one is not feasible in civil engineering due to the amount of energy required, the high stress produced on some places of the structure, and the difficulty to control the non-desired inputs (as wind or ambient noise). The second one requires time invariant frequencies, small damping, well-separated frequencies and stationarity of the excitation noise [4]. Both techniques need a large number of sensors and are expensive.

However, detection of damages using temporal variation of natural frequencies are cost-effective. Finding patterns into high dimension data can be hard which makes principal component analysis (PCA) a powerful tool for analyzing data [5,6]. In short, PCA is a statistical procedure that diagionalize the covariance matrix of data with the goal to transform the original data and project these data into a new vectorial space spanned by the so-called principal components where these components are orthogonal. Therefore, if there were correlated data, the matrix range of the covariance matrix is lower than if there were no correlated data and there were less number of principal components.

Theoretically, if all the data are correlated only one principal component it is enough to explain all the variance of the data.

In practice, the presence of random errors in each data means that the covariance matrix cannot be diagonalized but almost. If we reorganize the new variables (called components) by explained variance, with the first variable accounts for the largest possible variance in the data set and the last variable being the one with the smallest variance, the latest components could be discarded [7]. The accumulated variance of the discarded components has to match with the expected variance of the random errors. If the errors are random the amount of explained variance of the discarded component has to be statistically constant. Therefore, if we plot the accumulated variance with the principal component number, the slope of the curve must be statistically near constant.

For damage detection technique, the matrix data is each of the natural frequencies detected at each time. Modal frequencies change with atmospheric (external) and inner (air-conditioned) conditions. Mainly by temperature, humidity and insolation changes. For an undamaged structure, in the linear regimen, change of the modal frequencies are correlated and they need only one principal component to explain the matrix data; whereas as more damaged is the structure more PCs are needed. A covert idea of the method is to eliminate the contribution due to the environmental conditions because they are correlated with the data. The Principal Components Analysis (PCA) technique does not require to measure environmental parameters because they are taken into account as embedded variables (Yan et al., 2005).

PCA applied to frequency changes has been used to classify damages using an aluminum plate instrumented with four piezoelectric transducers [8]. Results showed that all the simulated damages were successfully classified, both in the baseline undamaged model and in further diagnosis tests in which damage was induced in the model. Furthermore, Golinval [9] employing PCA detected damage in a steel truss tested in laboratory into both: non-damaged and damaged states subjected to forced harmonic response.

Moropoulou and Polikreti [10] demonstrated the effectiveness of PCA in the characterization of building materials from historical monuments subjected to weathering condition. They applied the PCA on the bricks of Aghia Sophia (Istanbul, Turkey) and, conclude that the clay that forms the bricks is not similar to the clay of other contemporary constructions in Istanbul but presents high similarity to the raw material from a contemporary church. In a second case study, the PCA helped in presenting a classification of mortars from medieval monasteries based on their microstructural characteristics and strength measurements establishing a grouping was that gave an illustrative diagram that depicts the correlation between mortar syntheses and resulting characteristics. In the last case, the PCA was used to establish the correlation between environmental pollution data and data from the weathering layers of marble surfaces.

However, the main disadvantage of PCA applied to Civil Engineering damage detection is the necessary long-term monitoring; in general, it is believed that six-month period would be needed. In addition, the long time required to carry out the PCA applied to temporal variation of modal-frequencies makes it expensive. Therefore, the PCA is believed to be mainly applicable to research purposes or to certain types of structures such as historical buildings. The time required to be confident on the PCA results has been investigated in the studded cases. This study about the confidence of the PCA where performed, in a first step, computing the accumulated variance of the PC using only the modal frequencies measured the first day. Adding the data obtained in the next days the accumulated variances were recalculated. It is easy to show when the different curves converge plotting the curve of the accumulated variance versus the PC number for each number of added days. These studies combine the reduction of the variance produced by the increment of the temperature rang with the reduction produced by the increase of data used. As it is believe that the more important fact that reduce the variance produced by an inaccurate set of data is the temperature range, we also study this fact isolated. To carry out the study of the minimum range of temperature needed to assure the stability of the accumulated variance, we have computed the accumulated variance of the principal component with the modal frequencies data measured with the same air temperature (1° C of range). After it, we have increased the temperature range keeping constant the amount of data and we have computed the accumulated variance of the principal components. The temperature range needed to stabilize the accumulated variance curve is extracted showing the plots of the accumulated variance versus the PC numbers for each temperature range. The stability of the PC analyses with the temperature has been carried out for the two buildings with a closer meteorological station.

The accurate detection of the temporal evolution of the modal frequencies in cracked structures could have an important role. Due to the expected long-term monitoring, tracking modal frequencies could be a tedious job, an algorithm has been developed and tested and it is presented in the semi-automatic algorithm section.

STUDIED BUILDINGS AND SCALED MODEL

Mallorca cathedral is the first building studied. This is one of the high gothic churches, with greater slenderness, largest ratio between height and width of columns and greater rose window. It was built between the 14th and 16th century in Palma de Mallorca city (Spain). Whereas the inner design keeps a Mediterranean gothic style (slender columns), outside was redesigned to a European style with double flying arches [11]. Mediterranean gothic style could have slender columns because most of the main nave load is transmitted to big buttresses through the lateral naves that have similar high as the main one but without fly arches. However, in Mallorca Cathedral the ratio between main nave high and lateral naves is one and, double fly arches system was adopted to transmit the main nave load to buttresses. Nowadays, the Cathedral shows several important damages and cracks in almost all the structural elements (covert, walls, buttresses, fly arches and columns) which has been the main reason of some studies [12-14]. Some of these studies [15,16] have determined that there is a high correlation between the changes in the temperature of the air (from -2ºC to 40ºC) and some modal frequencies variations. The high change of some of the modal frequencies (30%) reveal high changes in rigidity, probably related with the opening/closing of some important cracks in certain structural elements. The fundamental period shows variations of 0.5 Hz in an hour (Fig. 1). Others of the observed nonlinear effects are the low power spectra amplitude of the fundamental mode and the breading effect of some modal frequencies [15,16]. Due to these effects and the existence of several very close modal frequencies, tracking the temporal evolution of these modal frequencies becomes difficult. The continuous monitoring system consisted of a three triaxial accelerometers, two installed on two arches of the main nave and another on the floor of the cathedral, though for this study only one of the upper part of the Cathedral has been used. The vibration was digitized at 100 Hz and wirelessly transferred [16].

Four buildings of the Polytechnic University of Catalonia (UPC) in Barcelona (Spain) were monitored and studied. The first one was the ETSEIB building (Fig. 2a), a twelve-stage steel building constructed by Robert Terrades in 1964. The first floor has a rectangular shape with 59 meters long and 47 meters wide. The rest of the stages have and U shape being the two lateral wings 59 meters long by 14 meters wide while the central core, where the staircase and set of elevators are located, is situated in a side of the two wings and is 18 meters long by 13 meters wide. The external steel columns have a side in the open air and are liable to air temperature and solar insolation. The continuous monitoring system consists in a triaxial accelerometer located at the roof in the end of the east brace of the U from December of 2016 to February of 2018. This building is close to a meteorological station (less than 100 meters long). The ETSEIB building has some structural damages whereas the structural damages of the other three UPC buildings are still uncertain.

Another UPC building is the Architectural School (Fig. 2b). It was built in 1962 by the architects Sagarra, Bora and Martínez. The Architectural School has a rectangular shape of 58 by 19 meters and has 7 stages. For this building, the external reinforced concrete columns have also a side at the open air. The continuous monitoring system consists in a triaxial accelerometer located at the roof in the North-east corner of the roof from January of 2017 to February of 2018. This is the other building close (about 250 meters long) to a meteorological station.

The last two UPC buildings are D2 and C2 module of Campus Nord (Fig. 2c). Both buildings have the same rectangular shape of 40 m large by 20 wide but internally they have different distribution. Both buildings have an external wall covering the concrete structure. The C2 building was monitored by a triaxial accelerometer located at the last floor near a corner of the building from May to July of 2018 and the D2 building was also monitored with the same configuration from July to September of 2018.

A reduced steel model of the Seismic Enginyering Laboratory (UPC) has been also studied (Fig. 2d). The model consists of 6 columns and 35 beams made of steel. The columns are continuous L shape 20mmx20mmx2mm profiles and the beams are 20x10 mm rectangular bars. The length of each beam is approximately 72 cm for the two-bay frames, and 77 cm for the one-bay frame. In the middle of each horizontal beam there is a static load of 4,5 kg. This added load consisted of eight 200mmx50mmx1mm lead straps connected to the model with a steel plate and four bolts. The anchorage of the model to the support is not rigid allowing flexions in some directions depending on the column. The temperature range applied by an air-conditioned system was from 12 to 34.5 ºC and vibration was measured by 10 piezoelectric accelerometers. The model was tested without damaged and with three types of damage. The non-damaged state was achieved screwing all the connections with two screws at maximum torque force of 5.1 kg·m. The first damaged state, named “heavy damage in one connection”, was performed releasing the two screws of the connection between the beams of the first floor and a corner column. The second damaged state, named “heavy damage in two connections”, was performed releasing the four screws of the two connections between the same column of the previous test and the two first floor beams of the node. The last damage state tested, named “distributed medium damage”, was done applying half of the maximum torque force (2.5 kg·m) to all the first-stage screws. The model was excited applying two different shakes in the longitudinal direction in the centre of the base, one of approximately 4 N (strong shake) and the other of approximately 2 N (weak shake).

SEMI- AUTOMATIC ALGORITHM

As ambient vibration could be considered as a near white noise vibration, good estimations of the power spectral density have been computed averaging some autospectra. As a rule of thumb, 20 autospectra are needed for non-damaged masonry structures, however for damaged ones more autospectra are needed, depending on the damage level. On the other hand, the inverse of the temporal span (window) is the spectral resolution. Consequently, the inverse of the window’s time multiplied by the number of windows is the total time needed to obtain good autoespectra. Overlapping windows, the time can be reduced as using Hanning windows (overlap of 33%). Thus, for a non-cracked masonry structure with fundamental frequency around one hertz with a 1% of resolution, good autospectra estimation requires 1354 s (about 22.5 minutes). As it has been mentioned before, the fundamental frequency of Mallorca Cathedral changes about 0.5 Hz per hour, thus with this time span needed to compute autoespectra the fundamental frequency can change about 0.18 Hz. This fact implies that using a well-determined autospectra strongly smooths the changes in frequency.

A possible solution of this problem is to use an appropriated algorithm to calculate the instantaneous modal frequency from the spectrogram. Tracking modal frequencies rely on compute the following probable modal frequency from an expected one. Applying non-averaged spectrograms perform instability at the picks of modal frequencies. For this reason, the computed frequency cannot be the frequency with higher energy, but have to take into account amplitude distribution over an interval of time and frequencies.

The algorithm to calculate the modal frequencies from the spectrogram has to satisfy two conditions, one related with the distance between modal frequencies and the other with the non-average spectrograms used.

Certain structures have modal frequencies with quickly fast temporal variation. Conversely, other modal frequencies show very low temporal variations. This event recommends choosing an algorithm with a parameter governing the allowed temporal variability of each mode. This parameter has to enable high deviations for modes with rapid temporal variations and low deviations for stable modes. At the same time, this parameter has to avoid errors in the frequency determinations of low-energy modes produced by close high-energy modes. As both thinks could be incompatible for some modes in some structures, the implementation of any algorithm has to consider a manual intervention in order to change the low-energy mode to their correct frequency.

The proposed algorithm elects the modal frequency at any time as the weight-average in time and in frequency, of the maximum of the spectrogram. The temporal weight-average is a triangular weight and controls the temporal smoothing. The length of triangular weight-average is a parameter of the algorithm that can be estimated from the fastest modal frequency variation. The weighting in frequencies is a truncated hyperbolic secant (Fig. 3):

$$f_t = \max(y_i)\ where\ y_i = \begin{cases} \operatorname{sech}(d \cdot (f_i - f_{t\pm1})) & if \quad f_i < f_{t\pm1} \pm r \\ 0 & if \quad f_i \geq f_{t\pm1} \pm r \end{cases} \tag{1}$$

where $f_{t\pm1}(t\pm1)$ is the frequency selected or computed at t-1 for forward search and at $t+1$ for backward search, d is a coefficient that adjust the decay of the function and r is the truncation distance. The truncation distance parameter avoids mixing closed modes being little for modes near other modes with high energy or for stable modes and it could be high for separate modes. Whereas high values of d keep down temporal frequency variability while low values of d are appropriate for modes with a large temporal variability of the frequency and properly frequency decoupled of other modes. In summary, it is possible to obtain a good track of the modal frequencies that are far from neighboring modes using appropriated coefficients: high r and low d coefficients for modes with quick temporal variations, and low r and high d coefficients for slow temporal variations. For modes close to others and slow temporal variation, low r coefficient or high d can allow a good track of it.

The main issue of the algorithm is tracking nearly modes with high temporal variation. For these high temporal variation modes it is necessary to use high r coefficient and low d that can produce the blending of both modes when are close to other high energy modes. As it has been explained above, in order to track properly this modes, there is the possibility of manually directing the low energy mode to the correct frequency in the implementation of the algorithm. In this case, the algorithm changes slightly.

Implementing the tracking algorithm to estimate the modal frequency of each mode consists in compute the most probable frequencies at any time from preselected frequencies in a given moment. As this algorithm has been designed for long-term studies and computes and draws very long spectrograms, is not manageable; the time story of modal frequencies has to be computed in a piecemeal way from fragmented spectrograms. In this way, the preselected frequencies for each fragmented spectrogram have to continue the selected modal frequencies of the fragmented spectrograms used. For this reason, the preselected frequencies needed for the algorithm can be read from a file with the results of the selected frequencies of the previous fragment, assuring the continuity of the modal frequencies. After drawing the spectrogram overlapped by the first automatic frequency selections, these selections can be modified to avoid the earlier-mentioned errors that can be committed by the attraction of high energy modes in the near low-energy modes. Manual selection consists in select with the mouses cursor an approximate point where the modal frequency is clear detected. The manual new selection does not need to be exact due to the weight-average in frequencies and in time is applied to select the new preselected frequency. From this selected frequency the algorithm applies Equation (1) backwards or forwards. In some cases, the attraction of nearby modes could require the selection of more than one preselected frequencies. In this case, the algorithm changes slightly as Equation (2) shows.

$$f_t = \max(y_i) \; where \; y_i = \begin{cases} \operatorname{sech}(d \cdot (f_i - f_x)) & if \; f_i < f_x \pm r \\ 0 & if \; f_i \geq f_x \pm r \end{cases} \qquad (2)$$

where f_x is the frequency linearly interpolated between $f_{t\pm1}$ and f_s (t-1 for forward search and $t+1$ for backward search), and f_s is the manually selected frequency.

Every time that a frequency manually selected is chosen, the program computes all frequencies of the mode. Other interesting option implemented in the program is the possibility to change the parameters *d* and *r* to all the points or only to an interval. This is suitable when a quickly change of modes approaches to a high-energy mode. There are two other features that could be useful to apply the results of the algorithm to PCA, they are to blank an entirely or interval of a mode in a spectrogram. These last two features are important to avoid non-well determined modal frequencies at any time interval that can produce errors in the PCA.

RESULTS

Mallorca Catedral

The algorithm was developed to track the modal frequencies of this structure and it works properly; however, some modes require manual selection of some points to correctly track its frequency temporal variation. Mainly, the first mode has the higher temporal variation and depends on the weather conditions [16]. This mode has a very low energy, and it needs frequent manual tracking. Modes 4, 5 and 6 (Table 1) are very close and need some manual tracking. As it has been mentioned before, this structure has a very complex modal frequency distribution and temporal variability of some of them. In short, it appears 12 modal frequencies below 5 Hz: 1.2, 1.47, 1.58, 1.9, 2.0, 2.1, 2.3, 2.4, 2.7, 3.0, 3.7 and 4.3 Hz. The first mode shows temporal variation above 23% in one day with a maximum of 90%. The mode that shows less variation in a day is the seventh with a variation of only 0.2%, and the most stable mode is the third with a maximum variation in a day of less than a 4%.

There is a mode of about 1.52 Hz that has not been used for the analysis due to its high instability. In addition, mode 1.58 Hz sometimes appears double in the transversal direction.

Table 1. Accumulated variance (%) at each PC number for Mallorca Cathedral.

PC number	1	2	3	4	5	6	7	8	9	10	11	12
Accumulated variance	67	84	91	94	97	98	99	99	99	100	100	100

About three principal components are needed to explain more than 91% of the variance of the modal frequency variability (Table 1) and from the fifth PC the slope of the curve is near constant (Figure 4).

For the study of monitoring system time, about 15 days are enough to stabilize the PC analysis (Fig 5).

Industrial Engineering School building results

Industrial Engineering School building (ETSEIB) shows 10 modes below 4 Hz: 0.79, 0.85, 1.14, 1.38, 2.36, 2.43, 2.62, 3.06, 3.37 and 3.97Hz. Mode 1 and 2 has a difference of frequency of 7% and mode 5 and 6 of only 3%. In general, automatic tracking has worked well but the mentioned nearly modes sometimes required manual tracking. The maximum daily frequency variation has been for mode 6, which is 6%, and the minimum is 2% for mode 2. The linear dependence between each mode and external temperature is low, with correlation coefficients of 0.29 for mode 1 (minimum value) and 0.59 for mode 8 (maximum value), which can be seen in Table 2. The temporal variation of the modal frequencies has also a low linear dependence with humidity. In this case, the lower correlation is for mode 8 with a correlation coefficient of 0.23 and the higher for mode 3 with a coefficient of 0.28. In general, the correlation between frequencies and insolation is in the middle of temperature and humidity (ranging from 0.28 to 0.47).

Table 3 and Figure 6 show the accumulated variance after applying PC analysis to temporal variation of modal frequencies. For ETSEIB building, the first two principal components explain around 95% of modal frequency variance and remains near stable.

Using the large time recorded in this building, we have also studied the interval needed to accurately determine the principal component number. Two types of studies have been done: the lapse of time and air temperature needed. After 10 days recording, the accumulated variance of the principal component number is stable (Fig 7).

With a range of only eight degrees of external air temperature, the variance-PC curve stabilizes (Fig 8).

Architecture School building results

The modal frequencies of the Architecture school under 10 Hz used were 1.56, 1.97, 2.02 and 3.21. In this building the modal frequencies are quite stable with a maximum daily variation of 9% for mode 4 and less than 4% for modes 1, 2 and 3. Modes are fare separated (20% of distance between mode 1 and 2) except mode 2 and 3, but these last two modes have the highest power spectral density in orthogonal directions. In general, the automatic tracking has worked adequately. There are more upper modes but none of them are suitable for PC analysis applied to structural damage. Some have very low energy and cannot be detected for a long time, which is what is needed for the case of study of structural damage. Apparently, others modes (about 18 Hz, 23 Hz and 24 Hz) have a very strange behavior: appear at about 5:00 UTM with a slowdown change of the frequencies to 8:30 and from 11:00 to 18:00 show a slow increase when suddenly disappears, only the school days (Fig 9). So, it seems to be related to the difference behavior between some upper stages slabs charged and discharged by the load produced by students.

The correlation coefficient between the frequency variation and external air temperature (0.39 and 0.49) and solar insolation (0.16 and 0.39) is also very low (Table 4) and with humidity variation is even lower (between 0.15 and 0.01).

Only one PC is needed to explain more than 95% of the variance (Table 5) and remains stable for the second one (Figure 10).

About the studies of the time and temperature interval needed to determine accurately the principal component number, results are similar to the obtained for ETSEIB and Mallorca Cathedrals. After recording 13 days, the accumulated variance of the principal component number is stable (Fig 11). With only a range of 16ºC of external air temperature the variance-PC curve stabilizes (Fig 12).

C2 Campus Nord building results

Six vibration modes of the C2 building can be used for modal components study under 25 Hz: 4.6, 4.7, 6.2, 14.8, 16.1 and 20.6 Hz. All studied frequencies are highly stable with a maximum variation of 3% for mode 1 and with a minimum variation of 0.4% for mode 5. Only modes 1 and 2 are close enough (less than 1% of distance) to present some problem to the algorithm. Fortunately, both modes (1 and 2) fluctuate simultaneously and mode 2 only appears in the longitudinal direction.

Table 6 and Figure 13 show the accumulated variance after applying PC analysis to temporal variation of modal frequencies. For the C2 building, the first principal component explains approximately 98% of modal frequency variance.

Correlation between frequency change and air temperature or humidity is also very low (Table 7).

D2 Campus Nord building results

Fourteen vibration modes of the D2 building can be used for modal components study under 25 Hz: 0.9, 1.8, 2.7, 4.4, 4.7, 6.5, 12.4, 16.1, 17.4, 20.4, 20.9, 23.5, 23.9, 25.0. Nevertheless, the external shape of this building is the same as the C2 building the internal structure is clearly different. All modal frequencies are quite stable, with a maximum daily variation of 2.5% for mode 5. Modes 1, 2, 3 and 8 have daily frequency variation of less than 0.4%. There are only three pair of close modes: 4 and 5 (6.3%), 10 and 11 (2.4%), and 12 and 13 (1.7%). In all these cases, the distance is greater than the daily variation and the semiautomatic algorithm has performed perfectly.

Only one principal component explains approximately 99% of the frequency temporal variation variance (Table 8 and Fig 14).

As can be seen in Table 9, the correlation of frequency temporal variation with external air temperature and humidity is low or very low for all modes.

Steel scale model results

For the steel model the modal frequencies detection was performed with an average of 10 windows maintaining a constant ambient temperature and the tracking algorithm was not used. Figure 15 shows two behaviors: a localized non-linear behavior due to weak shakes, and a continuous non-linear behavior due to strong shakes.

More than 22 modes under 30 Hz where computed for strong shake test and 18 modes for weak shake. The maximum variation of a frequency mode in the test without damage is 1.6% and the minimum is 0%. In the case of “heavy damage in one connection”, the frequency variation ranges from 0% to 1.3%. For “heavy damage in two connections” the maximum frequency variation is about 6% and the minimum is about 0.4%. For “distributed medium damage” the frequency variation ranges from 0% to 1.3%.

Only one PC is needed to explain more than 95% of the variance, remaining stable for non-damaged tests (weak and strong shake). For heavy damage in one connection tests, two PC explain more than 93% of variance remaining stable. In the case of heavy damage in two connection tests, three PC explain more than 96% of variance remaining stable from this point. Finally, the comportment of weak and strong shake is different for distributed medium damage. The variance explained by PC for weak shake shows two changes of slope, one at two PC with a variance explained of 89% and another at 5 PC with an variance explained greater than 99%. For strong shake, there is only one

Figure 16 and Table 10 show the different behavior of the PC evolution for strong and weak shake with damage in the structure. In the case of localized heavy damage, it seems that the first PC explains less variance in the case of strong shake than for weak shake. Opposite, in the case of generalized medium damage in one floor, the first principal components explain less variance than strong shake. This change of the behavior with the shake could be only related due to the non-lineal behavior of the screws and anchorage of the model.

Conclusions

In order to analyze the viability of the use of PCA applied to the change of modal frequencies, five structures and a reduced scale model have been studied. Three of them are concrete buildings, one steel building, and the last is a Cathedral masonry structure. The steel building is supposed to have small damages while the Cathedral has important damages. The reduced scale model has been tested without damage and with different types of damages applied as unscrewing some columns-beams joints.

One of the first problems to undertake the mentioned analysis is a good tracking of the modal frequencies. For this reason, an algorithm is presented and tested in the five structures. This algorithm consists in selecting the frequency with higher power spectra multiplied by a truncated hyperbolic secant as the modal frequency at any time. The weight function is centered in the frequency of the time after or before depending on if we are tracking the modal frequencies backward or forward, respectively. The implementation of the semiautomatic algorithm has been a very important aid to determine the modal frequency evolution for long-term monitoring, especially in the Mallorca Cathedral.

In all non-damaged cases, only one PC has been needed and more than one PC for all the expected damaged structures. The Mallorca Cathedral needs three PC to explain the frequency temporal variation according to the existing heavy and extended damage. The other supposed damaged building (the ETSEIB building) needs two PC two explain the change of frequency. Moreover, the first principal component of ETSEIB building explains around the 91% of the variance, the same as the three first PC of the Mallorca Cathedral.

In the case of the reduced scale model, it is clear that for “heavy damage in two connections” the number of principal components needed (3 PC) are greater than for “heavy damage in one connection” (2 PC) and the amount of variance explained by the first principal component is greater for weak shake than for strong shake. But this comportment disagrees with the “distributed medium damage”. For weak shake, more than 3 PC are needed and the first PC explains very low variance. Opposite, in the case of strong shake, only two PC are needed and the first PC explains a lot of variance. In fact, in the case of strong shake with distributed medium damage, the first PC explains greater variance than for heavy damages in one connections or heavy damages in two connections meanwhile for weak shake the behavior is the opposite.

Furthermore, we have also studied the minimum time required of monitoring system to assure a good stability of the results in three structures and the minimum temperature range in two buildings. PC analysis reaches a good stability between 10 and 15 days of monitoring. With only 8 to 16 ºC of external air temperature change, PCA is stable. These conclusions are important because made this technique applicable in an easy and affordable way.

The two buildings (C2 and D2) that have an external wall covering the structure shows a very low correlation between frequency change and external air temperature, solar insolation (at the meteorological station) and humidity meanwhile the two buildings (ETSEIB and Architectural School) that have external parts of the structure at the open air show only low correlations.

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Table caption

Table 1. Accumulated variance (%) at each PC number for Mallorca Cathedral.

PC number	1	2	3	4	5	6	7	8	9	10	11	12
Accumulated variance	67	84	91	94	97	98	99	99	99	100	100	100

Table 2. Correlation coefficients with temperature, insolation and humidity for each modal frequency for ETSEIB school.

Modal frequency	1	2	3	4	5	6	7	8	9	10
Correlation coefficient with temperature	0.29	0.48	0.30	0.32	0.33	0.41	0.57	0.59	0.57	0.42
Correlation coefficient with insolation	0.28	0.44	0.42	0.37	0.37	0.33	0.43	0.43	0.47	0.36
Correlation coefficient with humidity	0.30	0.31	0.38	0.27	0.25	0.26	0.27	0.23	0.27	0.25

Table 3. Accumulated variance for each principal component number for ETSEIB school.

PC number	1	2	3	4	5	6	7	8	9	10
Accumulated variance	91	95	96	98	99	99	100	100	100	100

Table 4. Correlation coefficients with temperature, insolation and humidity for each modal frequency number.

Modal frequency	1	2	3	4
Correlation coefficient with temperature	0.50	0.56	0.43	0.51
Correlation coefficient with insolation	0.44	0.45	0.17	0.52
Correlation coefficient with humidity	0.11	0.06	0.33	0.11

Table 5. Accumulated variance at each principal component number for Architectural school.

PC number	1	2	3	4
Accumulated variance	95.2	99.7	99.9	100

Table 6. Accumulated variance at each principal component number for the C2 building.

PC number	1	2	3	4	5	6
Accumulated variance	98.3	99.1	99.5	99.7	99.9	100

Table 7. Correlation coefficients with temperature, insolation and humidity at each modal frequency for the C2 building.

Modal frequency	1	2	3	4	5	6
Correlation coefficient with temperature	0.12	0.36	0.12	0.03	0.01	0.12
Correlation coefficient with insolation	0.16	0.01	0.01	0.15	0.20	0.20
Correlation coefficient with humidity	0.13	0.16	0.02	0.04	0.02	0.11

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Table 8. Accumulated variance at each principal component number for the D2 building.

PC number	1	2	3	4	5	6	7	8-14
Accumulated variance	98.7	99.1	99.4	99.7	99.8	99.9	99.9	100

Table 9. Correlation coefficients with temperature, insolation and humidity at each modal for the D2 building.

Modal frequency	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Correlation coefficient with temperature (%)	1	14	13	39	39	23	39	10	8	8	13	25	25	37
Correlation coefficient with insolation (%)	3	12	12	7	2	5	3	3	3	8	1	13	13	4
Correlation coefficient with humidity (%)	4	13	14	25	10	10	16	1	5	3	10	7	7	15

Table 10. Accumulative variance explained at each PC number for each test performed to the steel scale model.

	1	2	3	4	5	6	7	8	9	10
Weak shake Non-damaged	95.2	96.1	96.4	97.8	98.8	99.5	99.8	99.9	100.0	100.0
Strong shake Non-damaged	99.5	99.8	100	100	100	100	100	100	100	100
Weak shake Heavy damage in one connection	87.1	93.1	96.2	97.6	98.6	99.3	99.6	99.8	99.9	100
Strong shake Heavy damage in one connection	78.8	93.9	96.1	97.9	98.7	99.2	99.6	99.8	99.9	100
Weak shake Heavy damage in two connections	80.4	91.8	97.3	98.4	99.1	99.5	99.8	100	100	100
Strongshake Heavy damage in two connections	71.5	88.2	96.1	99.2	99.7	100	100	100	100	100

Weak shake medium damage	67.5	89.4	93.5	97.1	99.5	100	100	100	100	100
Strong shake medium damage	91.0	96.7	100	100	100	100	100	100	100	100

Figure caption

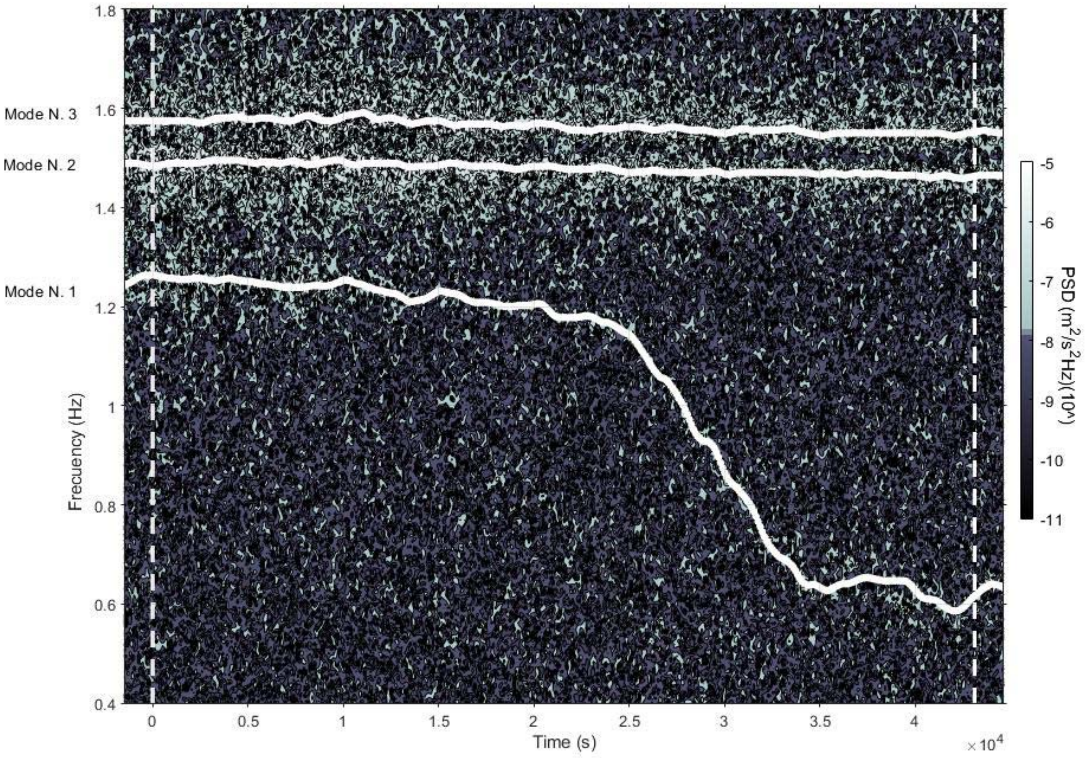

Figure 1. Spectrogram and frequency track of the first three modal frequencies of Mallorca cathedral (19/01/2011 from 12:00 to 24:00 hour).

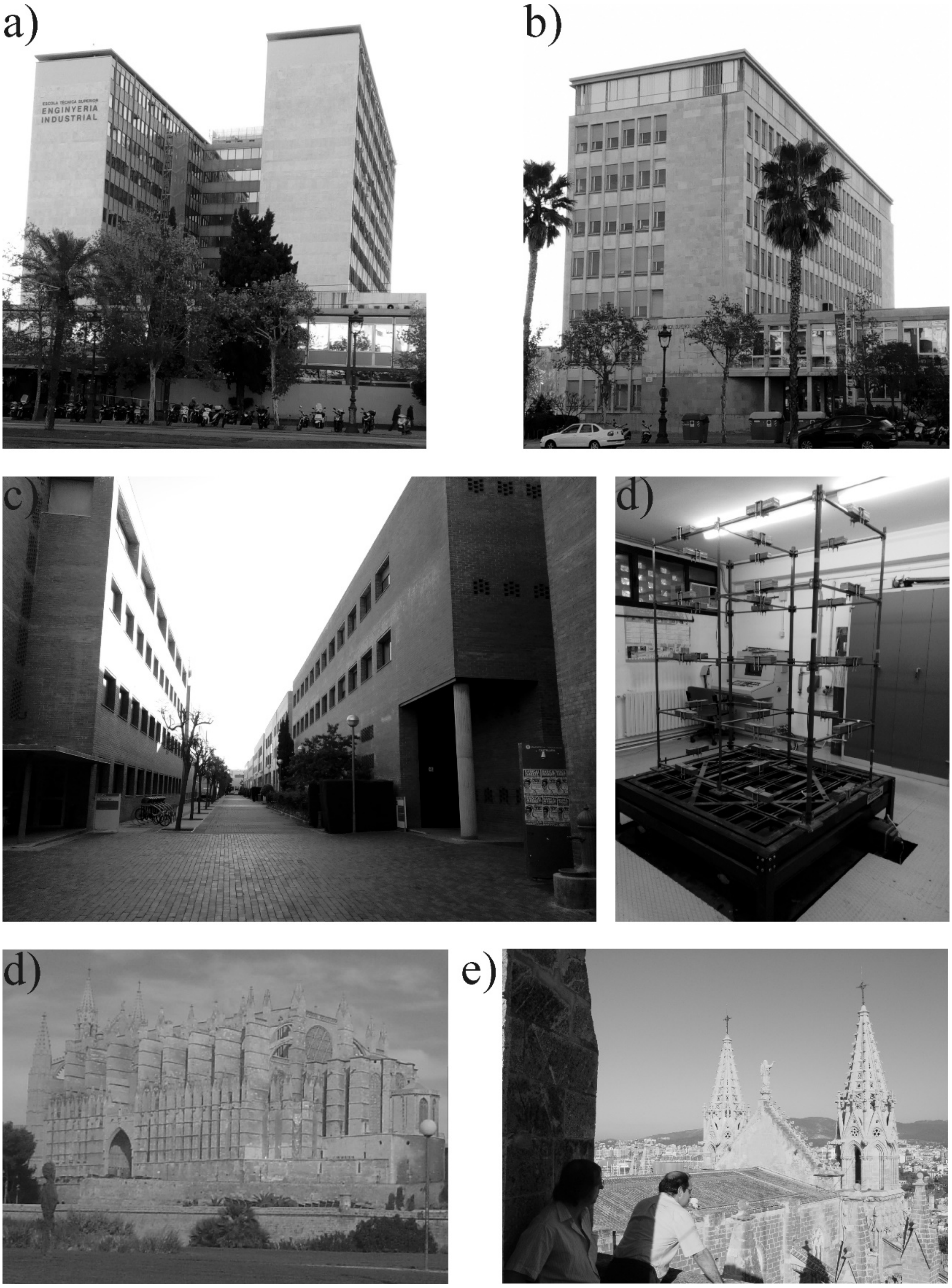

Figure 2. Photography of a) ETSEIB building. b) Architectural school. c) Photography of D2 (left) and C2 (right) buildings. d) Photography of the reduced steel model of the Seismic Enginyering Laboratory (UPC).

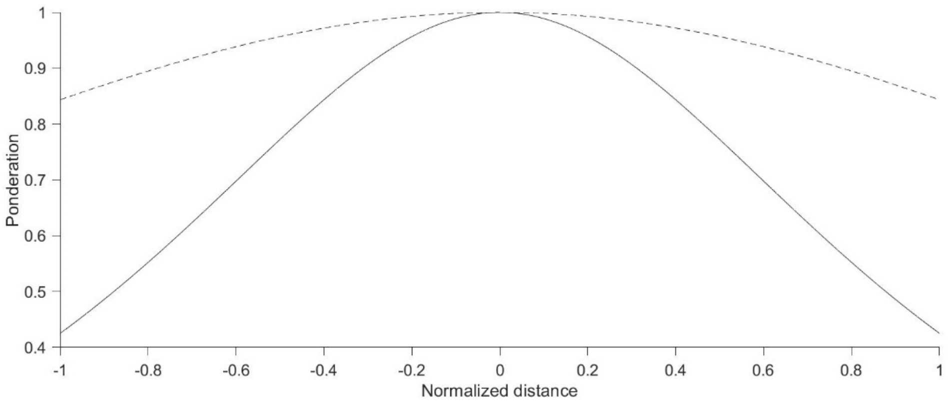

Figure 3. Truncated hyperbolic secant function with two different d coefficients (continuous line: 1.5; dotted line: 0.6).

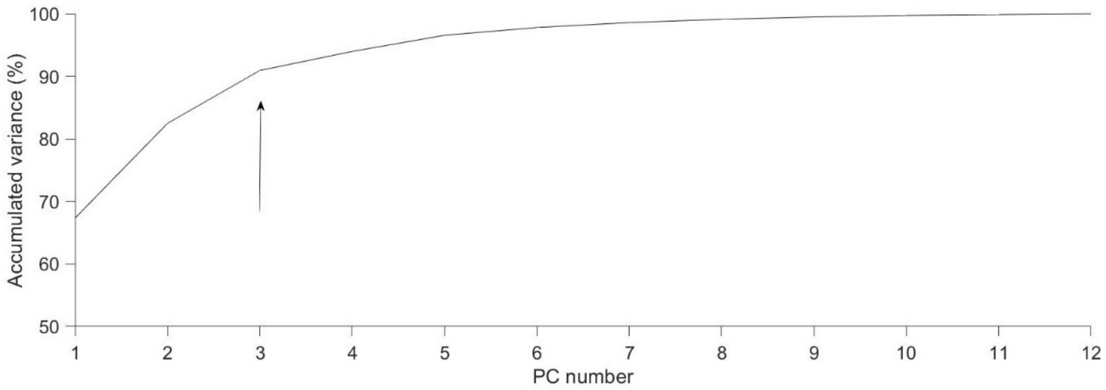

Figure 4. Accumulative variance versus PC number and chosen inflection point (arrow) for Mallorca Cathedral.

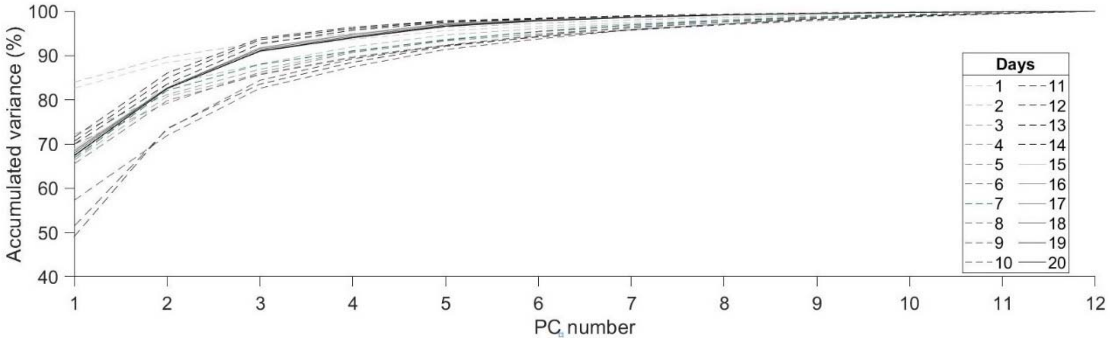

Figure 5. Accumulative variance versus PC number with monitoring system time for Mallorca Cathedral.

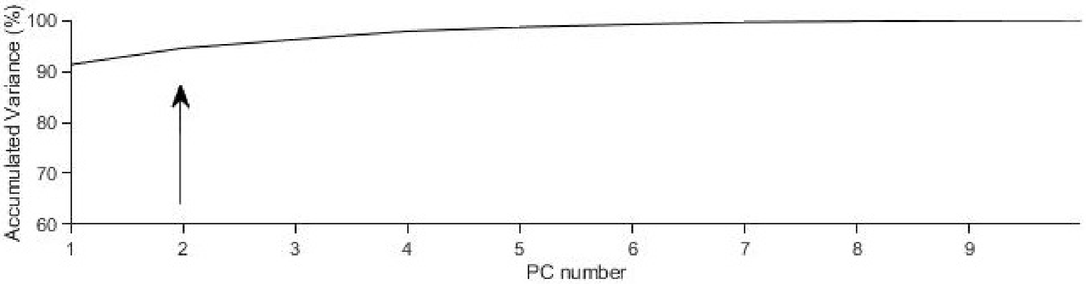

Figure 6. Accumulative variance versus PC number and chosen inflection point (arrow) for ETSEIB school.

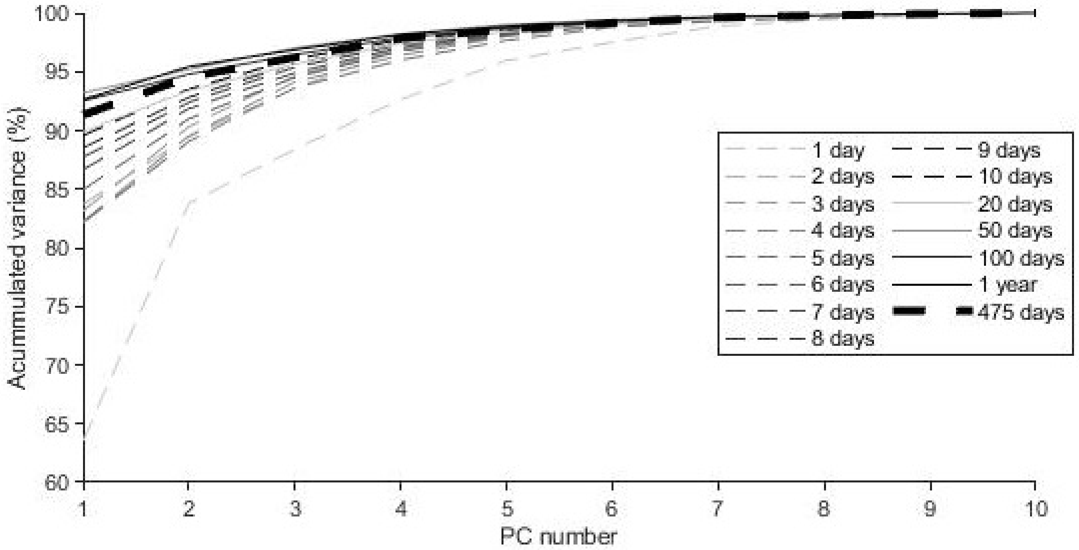

Figure 7. Accumulative variance versus PC number with monitoring system time for ETSEIB school.

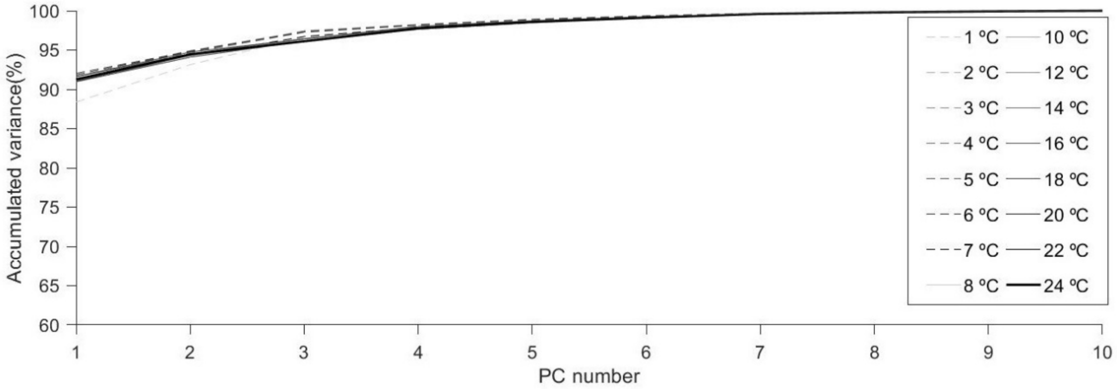

Figure 8. Accumulative variance versus PC number with monitoring system external air temperature range for ETSEIB school.

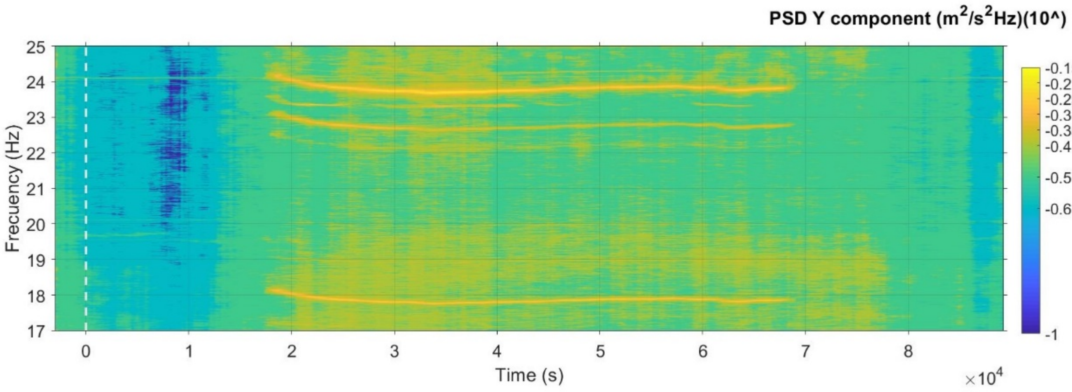

Figure 9. Spectrogram of Architectural school (30/01/2017 from 0:00 to 24:00 hour).

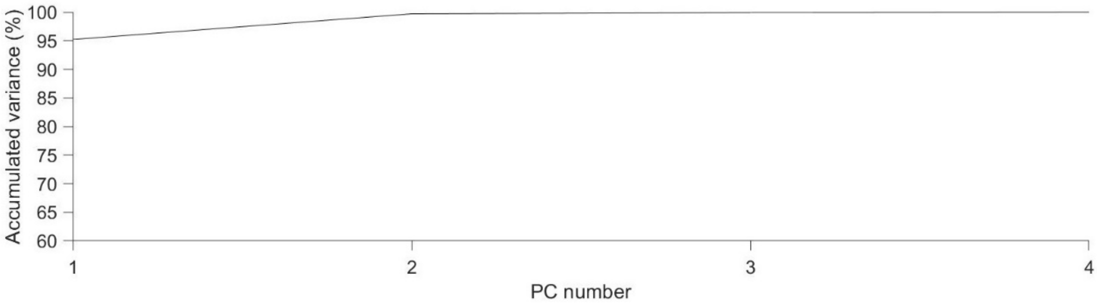

Figure 10. Accumulative variance versus PC number for Architectural school.

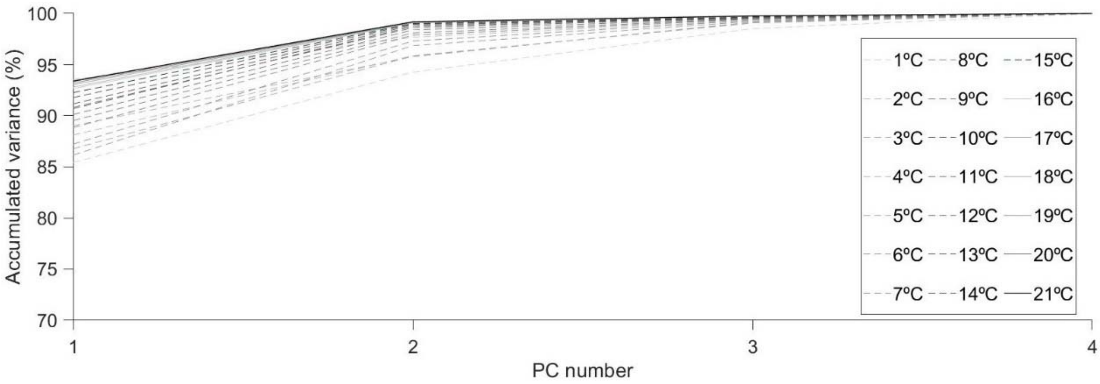

Figure 11. Accumulative variance versus PC number with monitoring system time for Architectural school.

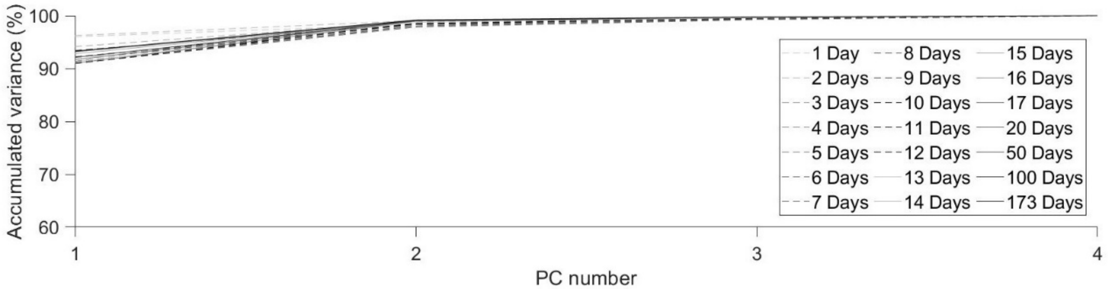

Figure 12. Accumulative variance versus PC number with monitoring system external air temperature range for Architectural school.

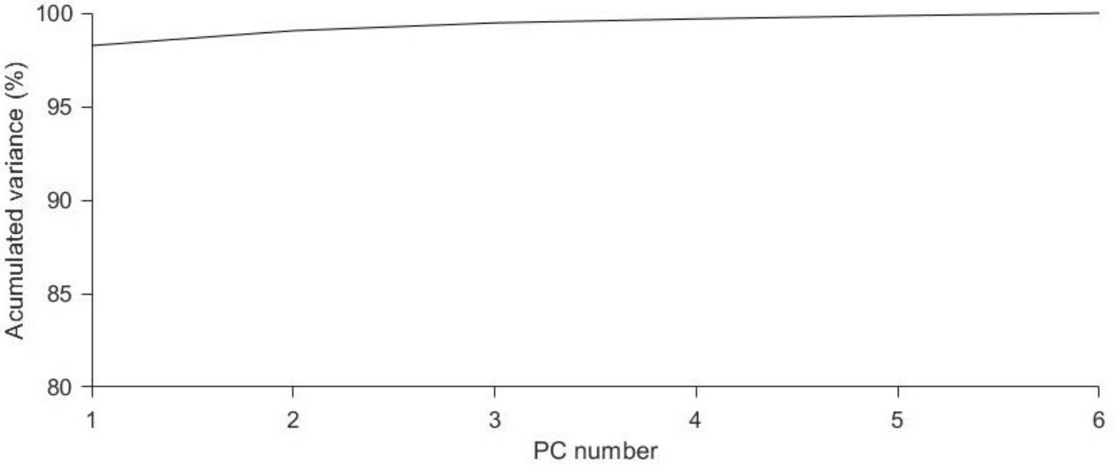

Figure 13. Accumulative variance versus PC number for C2 building.

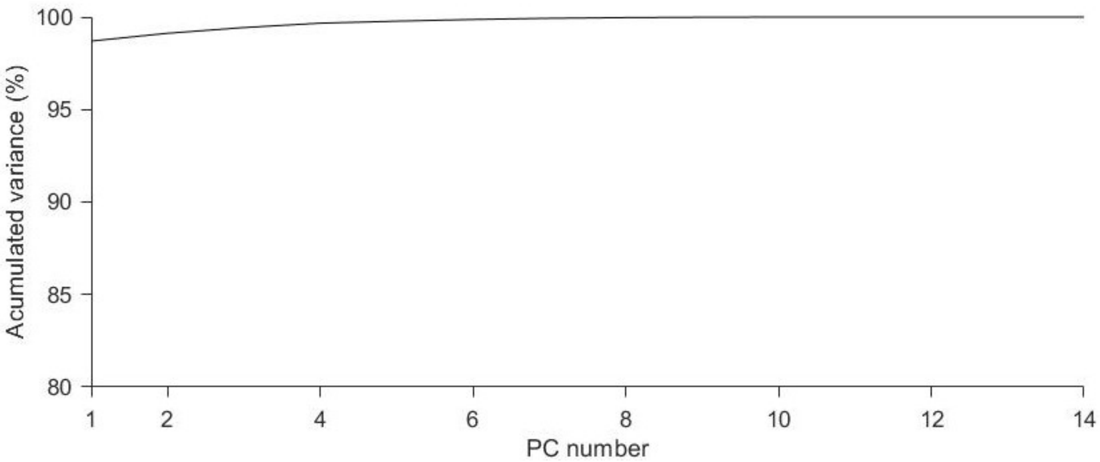

Figure 14. Accumulative variance versus PC number for D2 building.

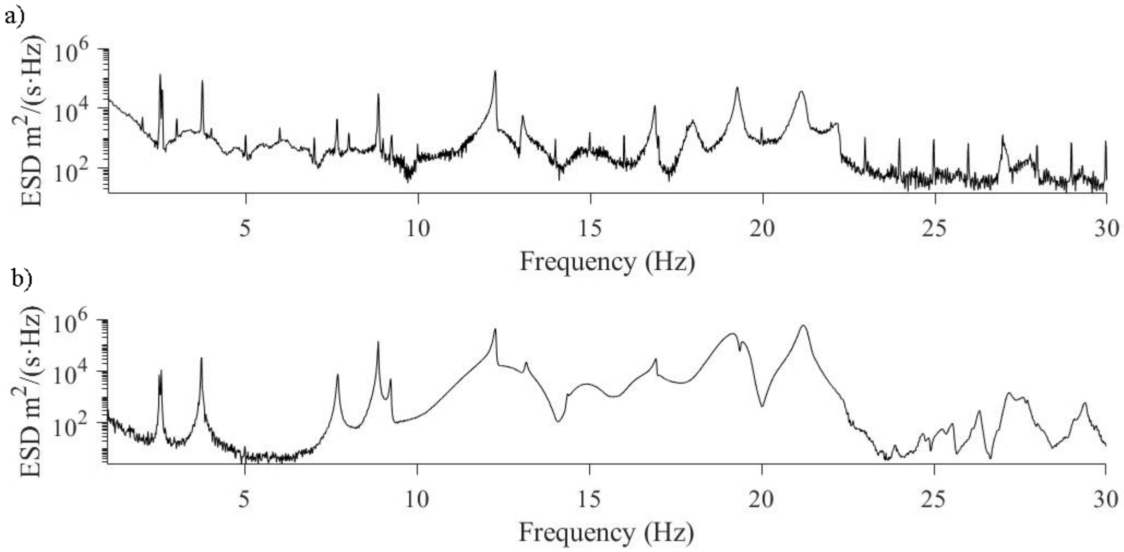

Figure 15. Energy spectral density for the steel model. a) Weak shake. b) Strong shake.

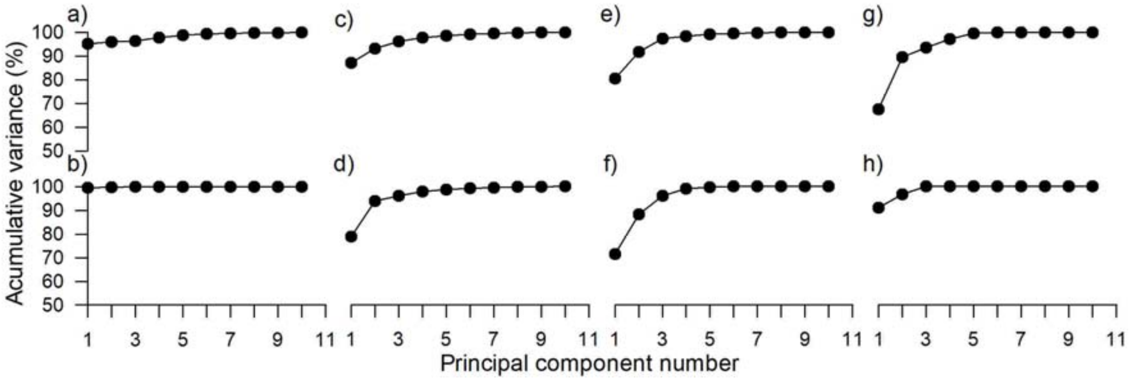

Figure 16. Accumulative variance versus PC number. a) Test of undamaged model under weak shaking. b) Test of undamaged model under strong shaking. c) Test of heavy damaged model (one released connection) under weak shaking. d) Test of heavy damaged model (one released connection) under strong shaking. e) Test of heavy damaged model (two connections released) under weak shaking. f) Test of heavy damaged model (two connections released) under strong shaking. g) Medium damage test under weak shaking. h) Medium damage test under strong shaking.