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TIME-RESPONSE-BASED DAMAGE DETECTION APPROACH

M.P. Limongelli[1]

[1] *Professor, Dept. of Structural Engineering , Politecnico di Milano. Italy*
Email: limongelli@stru.polimi.it

ABSTRACT :

Damage detection is usually carried out through analysis of recorded responses searching for changes in the structure's modal parameters. This paper presents a new approach to damage detection based on the comparison between the accuracy of a spline function in interpolating the response of a structure, in the damaged and the undamaged (reference) states. The comparison is carried out in terms of an error function defined as the difference between responses recorded on the structure and responses calculated via the spline interpolation. The variations of the error with respect to a reference value reports the existence of damage in the region of the structure close to the locations where the higher changes occur. The method has been tested on the numerical model of a multistorey frame where damage has been simulated as a storey stiffness reduction. Results relevant to several damage scenarios show that the method allows both the detection and the localization of damage with a level of accuracy that increases with the intensity of damage. The application of the method requires a densely instrumented structure and the availability of responses recorded before and after a damaging event. The main advantages of the proposed method are that it does not require a numerical model of the structure nor heavy post-processing of recorded data. Hence, after a damaging earthquake, it can provide, nearly in real time, reliable information about the location of damage. These characteristics make the method a potentially useful tool for automated post-earthquake damage assessment.

KEYWORDS: damage detection, spline interpolation, post earthquake damage assessment.

1. INTRODUCTION

The possibility to timely detect damage in a structure struck by an earthquake can be critical in post-earthquake safety evaluation to establish a hierarchy of both immediate rescue operation and of future strengthening intervention.
Traditional methods of damage detection based on visual inspection may be costly, taking a long time to be performed. Experimental techniques, based on magnetic field, thermal field, radiography, ultrasound, etc , allow to obtain detailed information about a local damage state but only if the location of damage is already known. Hence they need to be used in junction with global damage detection methods.
A promising alternative that has received an increasing attention in the last two decades consists in the use of techniques for global damage detection and localization based on the analysis of responses recorded on the structures.
Great part of these methods is based on the definition of damage as a modification of the characteristics of a structure that causes a change in its response. The onset of damage can thus be detected through comparison of the undamaged state of the system with the damaged one. The different ways to carry out this comparison have led to methods proposed in literature: in reference [1] a complete bibliographic review is reported.
In this paper is proposed a vibration-based damage detection approach, based on the analysis of the time histories recorded on the structure. Specifically, the method is based on the analysis of the changes of an error function defined as the difference between responses recorded on the structure and responses calculated through an analytical model of the response of the structure. As will be shown in the following sections through numerical examples, the variation of the residual error with damage allows to both detect a state of deterioration of the structure and to locate and quantify damage.
The method does not require any finite element modelling of the structure nor requires knowledge of its mechanical and dynamical characteristics.
Furthermore, being based on the mere evaluation of differences between the transfer functions of the recorded signals, the method can be implemented in a "on line" damage detection warning system that, after a damaging event, can provide, nearly in real time, reliable information about the location of damage that can be critic for post-event intervention.

1. VIBRATION BASED DAMAGE DETECTION APPROACH

1.1. The basic idea

The idea underlying the proposed method of damage detection, can be explained with reference to Figure 1. The two pictures show a snapshot of the deformed shape of two multistorey frames undergoing a seismic excitation. The only difference between the two frames is the value of the stiffness of the 5th storey columns that, in the frame on the right, is equal to the 70% of the corresponding value in the left frame. This reduction of stiffness can be assumed to model a damage concentrated at the 5th storey.

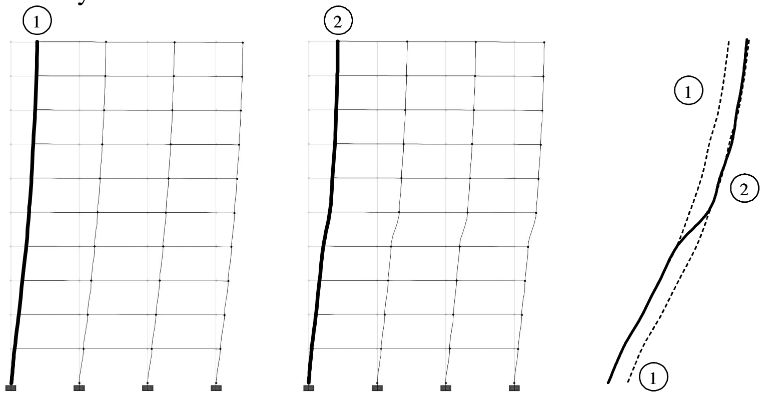

Figure 1 Effect of damage on deformed shape

The comparison of the deformed shapes of the frames shows that damage causes a sharp variation of the deformed shape occurring at the damaged storey. In the storeys located beyond and above the damaged one the two deformed shapes can be almost perfectly superimposed with a simple horizontal shift in the region above the damaged storey.
This observation leads to suppose that if a certain function is able to accurately model the deformed shape of the frame in the undamaged condition, it will be able to model with a comparable level of accuracy the deformed shape in the damaged condition in the regions of the structure not directly affected by damage.
In a previous paper [2], the author showed that a cubic spline function is able to provide a very accurate model of the deformed shape of buildings characterized by a uniform distribution of storey stiffness along their height.
Basing on all these circumstances, the basic idea of the method proposed herein can be summarized in the following assumptions:

1) if the spline interpolation is able to predict with a given level of accuracy the response of a multi-storey building to an earthquake, it will be able to predict the response of the same building to another earthquake with a comparable level of accuracy, if the building is undamaged.
2) if damage occurred in the time interval between the two events, the accuracy of the interpolation will decrease and it will decrease more for the signals recorded by sensors that are close to the location of damage.

The two assumption will be verified in this paper through numerical examples.
The method is based on the availability of responses recorded:

1) in a number of locations of the undamaged structure during a seismic event;
2) in the same locations during a following seismic event.

At this stage of the research, data recorded on a real building, diffusely instrumented, before and after the occurrence of damage, are not available to the author, hence the proposed method has been tested using the responses calculated for the numerical model of a plane multistory frame subjected to a base excitation.

1.2. Definition of the interpolation error and of the damage parameter

The proposed interpolation through a spline function gives an estimate $\ddot{s}(\bar{z},t)$ of the real structural response in terms of absolute acceleration $\ddot{u}(\bar{z},t)$ in a given location $\bar{z}$. For a given number and distribution of recording sensors, such estimate is characterized by an error function of time $e(\bar{z},t)$ that can be defined as the difference with respect to the real response. Assume that sensors are available in a number of locations along the building, say at the level of the all storeys. Assume that a spline interpolation of the responses is calculated considering as knots of the spline all the instrumented locations, except the one where the error of the interpolation is being calculated. This latter knot will be assumed as a

"control knots". The interpolation can be repeated for each location where a sensors is available and assuming this location as a control knot. The difference between the recorded and the interpolated signal in the control knot quantifies the error of the interpolation in its location, provided that recording sensors are located in all the other locations.
To remove the influence of the amplitude and of frequency content of the input on the response, the error function at the control knots can be defined in terms of the magnitude of the transfer functions of the recorded and calculated response respectively $\ddot{U}(\bar{z}, f)$ and $\ddot{S}(\bar{z}, t)$ defined with respect to the base input. In order to characterize the error at a given location through a single parameter, the mean value $E_M(\bar{z})$ of the error over the frequency range of the signal, is calculated:

$$E_M(\bar{z}) = \frac{1}{N}\sum_{i=1}^{N}\left[\ddot{U}(\bar{z}, f_i) - \ddot{S}(\bar{z}, f_i)\right] \tag{1}$$

being N the length of the sampled signal. The mean error $E_M(\bar{z})$ quantifies the ability of the spline interpolation to model the structural response at location $\bar{z}$. The values of $E_M(\bar{z})$ calculated in all the locations $\bar{z}$ of the structure where sensors are available, characterize the current status of the structure. In terms of the error function $E_M(\bar{z})$, the assumptions on which the method is based, mentioned in section 1.1, can be analytically expressed as follows:
1) if no damage affects the structure, function $E_M(\bar{z})$ does not change remarkably;
2) the variations of parameter $E_M(\bar{z})$ are higher at locations $\bar{z}$ close to the regions where the structural changes occur.
These two assumptions allow to build a procedure to detect the existence and the location of damage on the base of responses recorded on the structure during two subsequent seismic events.
The first time an earthquake strikes the structure, responses are recorded at selected locations $\bar{z}$ and the parameters $E_{M1}(\bar{z})$ can be calculated for this first event. During a following earthquake, a new evaluation $E_{M2}(\bar{z})$ of the error parameters can be performed. The absolute value of the difference between these two values of the error function, normalized to its value in the initial (reference) configuration at a given location $\bar{z}$, will be assumed as the damage sensitive parameter $D_E(\bar{z})$ at $\bar{z}$:

$$D(\bar{z}) = \frac{D_E(\bar{z})}{E_{M1}(\bar{z})} = \frac{\left|E_{M2}(\bar{z}) - E_{M1}(\bar{z})\right|}{E_{M1}(\bar{z})} \tag{2}$$

Normalization is introduced in order to remove the influence of the amplitude of the interpolation error in a given location. The comparison of the values $D(\bar{z})$ in the control knots of the structure allows to detect the portion of the structure where the greatest changes have occurred.

2. NUMERICAL SIMULATION

2.1. Building description

A ten storey plane multistory frame has been considered (see Figure 1). The building has been supposed to be equipped with a network of accelerometers located at all the 10 storeys hence responses in terms of absolute acceleration have been calculated at all the storeys and assumed as responses recorded by the sensors.
Each storey, one by one, is assumed as the location of the control knot and the response in terms of absolute acceleration has been calculated via the spline shape function assuming as known the responses at all the other storeys. The error $D(\bar{z})$ is then calculated in this location using equation (2).
Repeating the procedure for all the storeys, the values of the damage function are calculated at all the locations $\bar{z}$ where recording sensors are available.

2.2. Input motion

In order to check the first assumption on which the proposed method is based that is the independence of the error function $E_M(\bar{z})$ from the base input, the values of this function in the control knots have been calculated for several ground motions. The value of $E_M(\bar{z})$ for a given $\bar{z}$ is the error in control knot at location $\bar{z}$ between the real response and the spline interpolation calculated assuming known all the responses except the one at the control knot.

Base input characterized by different values of peak acceleration a_{max} and predominant period T_{max} (period corresponding to the maximum value of the Fourier Amplitude Spectrum) have been considered.
Table 1 reports the characteristics of the considered earthquakes.

Table 1. Characteristics of the input motions

	EARTHQUAKE	a_{max} [g]	T_{max} [sec]
1	CALETA DO CAMPOS (09/19/1985)	0.13	1.04
2	TOKACHI OKI (16/05/1968)	0.20	1.16
3	KOBE (01/17/1995)	0.60	0.70
4	LUCERNE (06/28/1992)	0.63	10
5	EL CENTRO (05/18/1940)	021	0.04
6	WHITTIER NARROW (10/01/1987)	0.03	0.03
7	NORTHRIDGE (01/17/1994)	0.21	0.08
8	ALHAMBRA (04/25/1998)	0.02	0.06
9	YORBA LINDA (09/03/2002)	0.006	0.05
10	BIG BEAR (02/22/2003)	0.01	0.02

The first four signals are representative of base input recorded in different soil condition and distance from the epicenter of the earthquake. Earthquakes 5 to 10 are examples of signals recorded in a small area (specifically Pasadena) during different seismic events hence they are representative of seismic events that can struck a single building during its life.
The comparison of $E_M(\bar{z})$ calculated for the different inputs, for the undamaged configuration, is reported in Figure 2. that shown that negligible differences can be observed thus confirming the independence of function $E_M(\bar{z})$ from the input. This function will be thus assumed as a reference of the initial state of the considered structure.

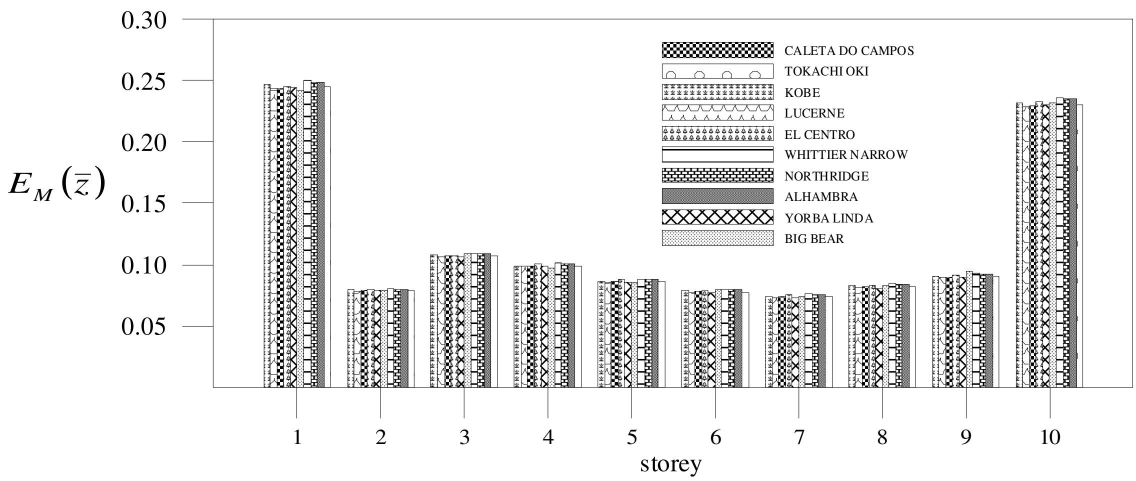

Figure 2 . Error function in the original configuration

2.3. Simulation of damage state

Damage has been simulated as a reduction of stiffness in one or more storeys of the building. Specifically, reductions of storey stiffness of 10%, 30% and 50% of the original values have been considered. Several damage scenarios have been simulated considering both concentrated and distributed state of damage.
Damage to the i-th story (to the columns beyond the i-th floor) has been indicated as DI, as shown in Figure 3, where are also reported the locations of responses recorded on the structure.The building has been considered subjected to event number 5 (El Centro) in its original (undamaged) configuration hence function $E_{M1}(\bar{z})$ has been calculated in all the control knots with reference to this event.
Given the independence of the function $E_M(\bar{z})$ from the base input, the same results would have been obtained if function $E_{M1}(\bar{z})$ was calculated with reference to a different base input.

2.4. Analysis of damage

Different damage scenarios have been considered.

1) Damage concentrated at the columns of a single story;
2) Damage at the columns of two or three stories
3) Damage uniformly distributed at all the stories

2.4.1 Damage to a single story

For each intensity of damage (10% to 50% reduction of storey stiffness), ten different damage patterns have been modeled considering damage concentrated to the columns of one of the storeys. The values of function $D(\bar{z})$ given by equation (2), have been calculated in all the control knots for the five seismic events numbered from 6 to 10 in Table 1. Results are reported in Figure 3 for 10% and 30% reduction of stiffness.

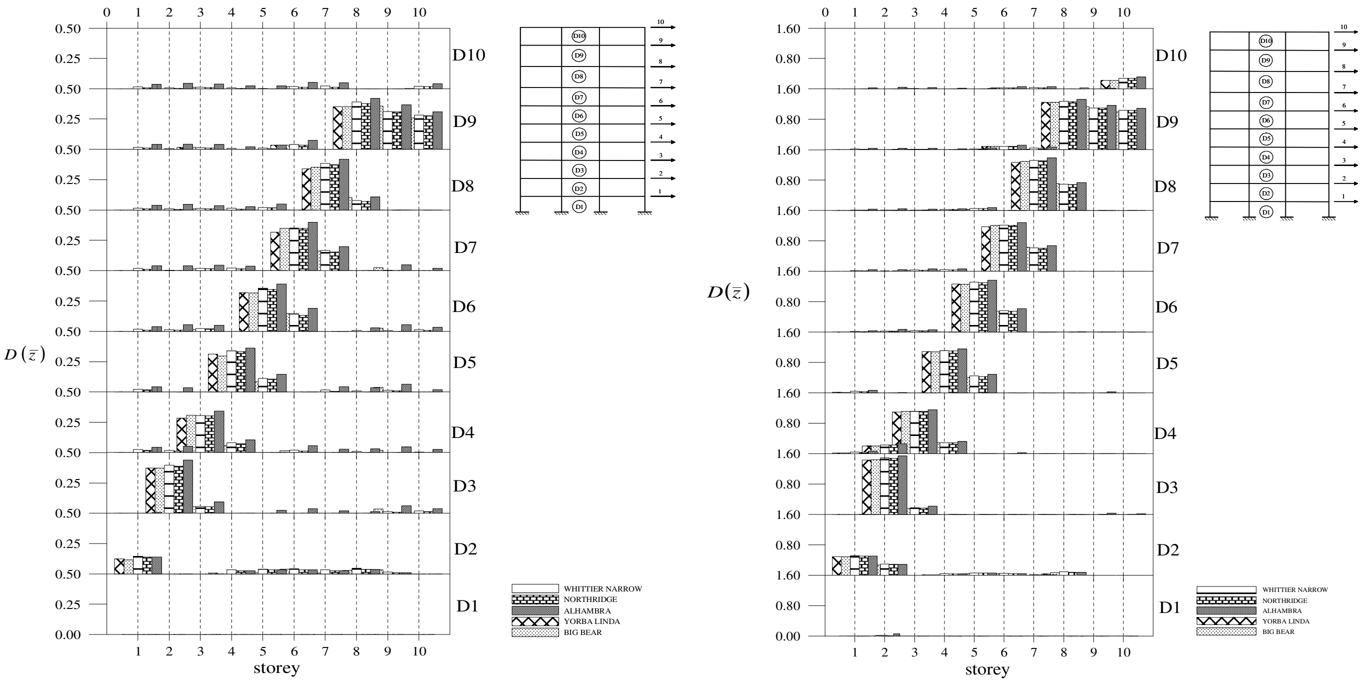

Figure 3 . Damage to a single story. Damage function for 10% and 30% reduction of stiffness

The figures show that the function $D(\bar{z})$ reaches the highest values in the control knots located at the bottom and top of the columns of the damaged story. The maximum value of the damage function is reached at the floor immediately beyond the story where damage is located. The only exception to this pattern is represented by damage scenarios D1 and D10 that is when damage occurs at storey 1 and 10 of the multistory frame. These regions are close to the border of the domain of the spline function used for the interpolation. At these locations the boundary conditions for the spline interpolation are imposed and, as shown in Figure 1 these locations are the ones where the interpolation error $E_M(\bar{z})$ reaches the higher values, that is, where the spline interpolation looses accuracy. If damage is located in these regions, the damage function $D(\bar{z})$ is not able to accurately detect it.

The comparison between figures relevant to different amount of damage shows that the amplitude of function $D(\bar{z})$ increases with the reduction of column stiffness. This increases the ability of the function to point out the location of damage.

2.4.2. Damage to two and three storeys

The examples reported in the previous section showed that function $D(\bar{z})$ is able to detect even small (10%) reduction of storey stiffness and furthermore its behavior is not dependent on the base input.

Hence, for damage scenarios with damage located at more than one storey, only a reduction of 10% and 30% of storey stiffness and only one of the base input (specifically Big Bear earthquake) has been considered.

Results relevant to 30% stiffness reduction are reported in Figure 4. Function $D(\bar{z})$ presents, also in these cases, its higher values in the locations where damage occurs.
Comparing results with the ones relevant to 10% stiffness reduction, not reported herein due to space limitation, it can be shown that and the only difference between cases relevant to different intensity of damage is the amplitude of function $D(\bar{z})$.

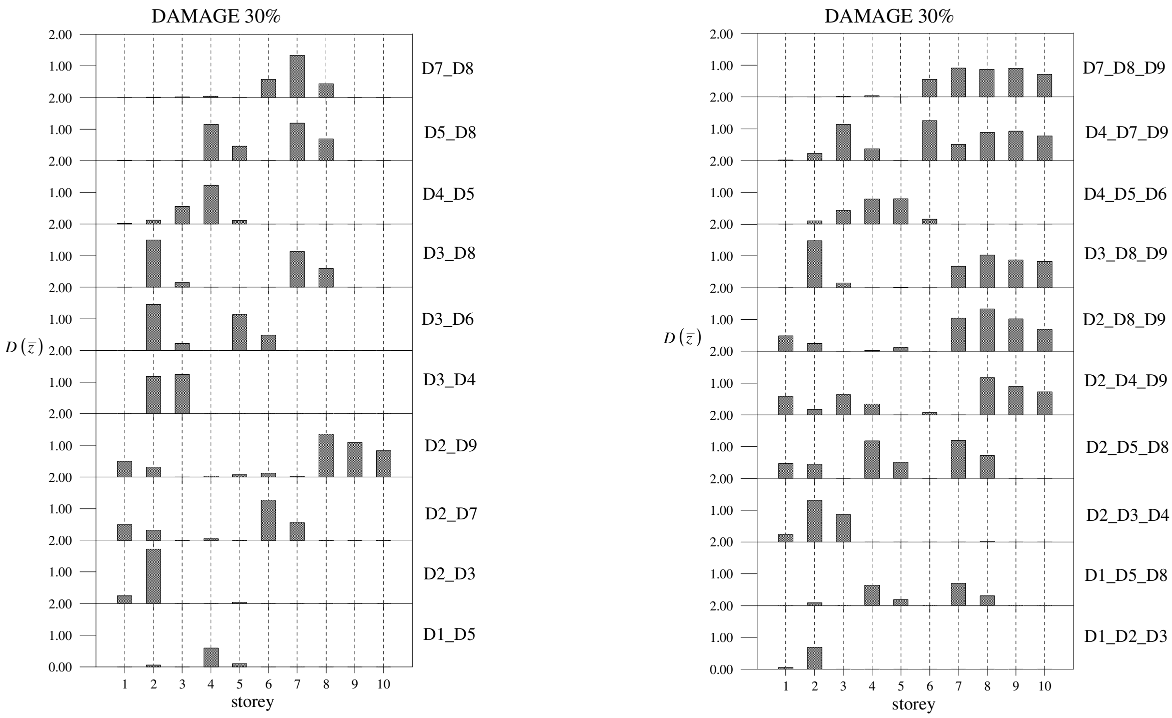

Fig. 4. Damage to two and three storyes; 30% reduction of stiffness.

2.4.3. Damage uniformly distributed
A uniformly distributed damage pattern has been considered assuming a reduction of the stiffness of all the columns of the frame. Reductions of 10%, 30% and of 50% of the original column stiffness have been considered.
Results are reported in Figure 5. To compare results relevant to different amounts of damage, the values of function $D(\bar{z})$ have been plotted normalized to their maximum value $D_{\max} = \max[D(\bar{z}_1), D(\bar{z}_2)......D(\bar{z}_N)]$.
Function $D(\bar{z})/D_{\max}$ presents values that increase towards the mid height of the frame and decrease at the border. The existence of a diffuse state of damage is pointed out by the variations of function $D(\bar{z})$, even if its the values do not strictly reflect the real distribution of damage, characterized in this case by constant values of stiffness reduction.

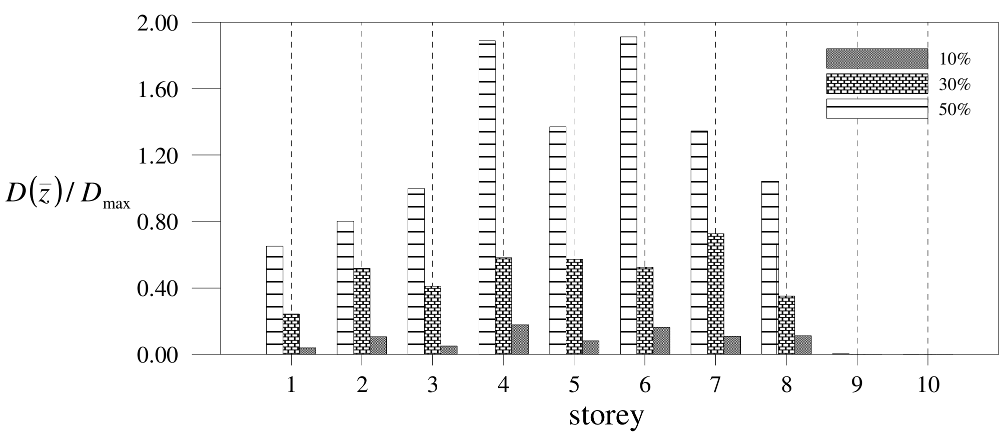

Fig. 5. Damage uniformly distributed.

3. SENSITIVITY OF THE METHOD

3.1. Effect of sensors number and location

The ability of the method to detect damage locations is dependent on the relative position of sensors and damage location. The denser is the distribution of sensors in the region close to the location of damage, the greater is the accuracy of the method in detecting damage. Thus, in order to accurately detect the location of damage, whatever its location, the structure should be densely and uniformely instrumented. This, in the case of a multistory building, means at least one bidirectional horizontal sensor at each floor

3.2. Effect of damage location and amount

If the structure is densely instrumented, the influence of the location of damage on the capacity of the method to predict the location of damage is almost negligible. The only exceptions are the regions close to the border of the interval of definition of the spline function where the accuracy of this function to interpolate the deformation along the height of the frame is lower. At the increase of the amount of damage, the absolute value of function $D(\bar{z})$ increases, making the location of damage more evident. In the examples herein considered a relationship of proportionality appears to hold between the values of damage function $D(\bar{z})$ and the amount of damage quantified by the percentage of stiffness reduction. However, further more extensive analyses are needed in order to determine the relationship between the two variables.

3.3.Effect of frequency truncation on the damage function

The evaluation of the damage function $D(\bar{z})$, according to equation (2), needs the estimate of the mean value of the error $E_M(\bar{z})$ on the frequency range corresponding to the length of the response. For the cases of concentrated damage, the function $D(\bar{z})$ is almost insensitive to the frequency range considered for its evaluation; on the contrary its influence is critical in case of distributed damage. Figure 6 shows the behavior of function $D(\bar{z})$ calculated for two different lengths of the signal in the frequency domain. Specifically, the first figure corresponds to the range in which the frequencies of the first seven modes of the structure lie, the second is the whole range of frequencies of the signal. Damage scenarios corresponding to 10%, 30% and 50% of distributed damage are considered. If the evaluation of $D(\bar{z})$ is carried out on the whole range of frequencies, this function $D(\bar{z})$ gives a false positive indication of damage at the second storey.

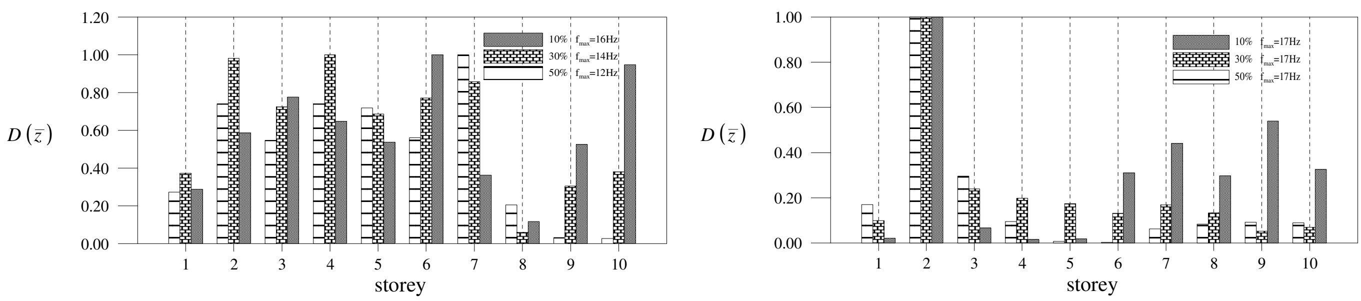

Figure 6. Damage uniformly distributed. With and without frequency truncation

This circumstance is due to the higher shift of the modal frequencies towards lover values, occurring in the case of distributed damage with respect to the case of concentrated damage. This shift causes the extension of the range of high frequencies with a low signal to noise ratio, hence an increase of the numerical errors in the evaluation of function $D(\bar{z})$. As a general criteria, the range of frequencies for the evaluation of $E_M(\bar{z})$ should be limited to the one where the frequencies of the fundamental modes lie.

3.4.Effect of structural behavior

The method is based on the use of a spline function to interpolate structural responses along the height of the building. This analytical function has proved very efficient for cantilever-type structures (see Ref [2]). For structures with a different behavior other functions could be more suited therefore a possible extension of the method is the definition of different shape functions for the interpolation, more suited to the particular structural scheme and corresponding behavior.

The examples presented in this paper are very simple and do not take into account the spatial behavior of real structures. However the ability of the method to detect damage has been checked for the 3D model of a real structure and results are reported in Ref [3].

4. CONCLUSIONS

In this paper has been proposed a new damage detection method based on the study of the variations of the interpolation error of responses recorded on the structure during different seismic events. Damage detection and localization is carried out through the analysis of the variations of the interpolation error between the reference and the damaged state. Reference data are recovered from the healthy structure. Interpolation is carried out using a spline shape function to calculate the response of the structure at a given location as a function of responses recorded in adjacent locations.
The method has been applied to detect the state of damage of a numerical model of a multi-storey frame. Several damage scenarios have been considered, ranging from concentrated damage (to one or more storeys) to distributed damage with several levels of intensity. Damage has been modelled as a reduction of storey stiffness.
The method has proved effective to both detect the state of damage and to locate it. Even very small amount of damage, up to 10% reduction of the original storey stiffness, can be detected by the analysis of the proposed damage function. The method can thus be useful to detect also the onset of damage beyond severe damage caused by destructive events.
While in the case of damage concentrated in a region of the structure the proposed function is a robust estimator of damage, in that of distributed damage, some care is required in the signal truncation in the frequency range due to numerical errors caused by a low signal to noise ratio.
The application of the method requires that the structure is densely and uniformely instrumented and responses recorded before and after a damaging event are available.
The first set of responses can be easily recovered during a small non damaging seismic event. The second set can be recorded during one of the aftershocks that usually follow a strong damaging event.
The advantages of the proposed method can be summarized in the following points:

- it does not require a numerical modelling of the structure nor knowledge of the characteristics of the structure;
- it does not need heavy post-processing of recorded data.
- after a damaging earthquake it can provide, in near real time, reliable information about the location of damage.

These characteristics enable to obtain nearly real time information about the damage state of the structure. This feature makes the method a potentially useful tool for automated post-earthquake damage assessment, to establish a hierarchy of both immediate rescue or evacuation operations and of future repairs, strengthening and rehabilitation interventions.
As far as the estimation of the amount of damage is concerned, the proposed function shows an increasing trend with damage, but more analyses are needed to find a relationship between the two variables. Further analyses are also needed to check the feasibility of the method to detect the state of damage from responses recorded on a real, damaged structure. As a general comment, the accuracy of the method is likely to decrease if applied to a real structure, due to all the sources of errors that affect recorded data. However the good results obtained for the numerical model herein presented make the method promising for the use on actual structure.
The effect of noise on recorded signals and of non linear structural behaviour have not been taken into account at this state of the research. Further development will be primarily devoted to tackle the effect of these phenomena on the accuracy of the proposed method.

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