COMPARISON OF THE PERFORMANCE OF TWO DIFFERENT APPROACHES FOR DAMAGE DETECTION ON FRAMED STRUCTURES

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Abstract
Continuous monitoring based on vibrational identification methods is increasingly employed with the aim of evaluating the state of health of existing structures and infrastructures and the performance of safety interventions over time. In case of earthquakes, data acquired by means of continuous monitoring systems can be used to detect and localize a possible damage occurred on a monitored structure using appropriate algorithms based on the variations of structural parameters. Most of the damage identification methods are based on the variations of damage indices defined in terms modal and/or non-modal parameters. In this work results retrieved from the application of two damage localization methods based on the detection of curvature variation are compared. In this paper the two methods have been applied using numerical data retrieved from nonlinear FE models subjected to a damaging seismic excitation.

1 INTRODUCTION

Structural Health Monitoring (SHM) and Damage Detection Techniques have received an increasing interest from both the research community and the professionals over the last few years as evidenced by the large number of monitoring systems installed in various countries around the world. In seismic regions these systems allow performing an objective and prompt estimation of the damage to buildings after an earthquake. In recent years vibration based damage identification techniques have been widely applied to the assessment of the health state of the structures. Many researchers have worked to set-up new methodologies for SHM based on the detection of variations, after a strong seismic event, of the structural dynamic characteristics, namely the modal parameter (frequencies, mode shapes, damping) or non-modal parameters like the operational modal shapes (ODS) ([1-6]).

Many of the methods proposed in literature carry out the damage identification through comparison of the original (undamaged) state and the (possibly damaged) current state. The different ways to perform this comparison have led to a number of different approaches ([7-20]). Methods based on frequency changes can be reliably applied to detect damage, but they are hardly able to give information about the location of damage. To this aim are more
effective methods based on the analysis of changes of modal shapes or of their derivatives such as slopes, curvatures or strain energy ([21-24])

In this work have been compared the results retrieved from the application of two methods for damage localization based on the detection of curvature variations: a curvature evolution based method and an interpolation error based method. The main difference between the two methods is that the curvature evolution methods detects changes occurring during an earthquake by comparing the values of the curvature retrieved at different times from the responses recorded during the earthquake. For this reason this method does not require data relevant to e reference configuration. On the contrary in the Interpolation Method damage is identified through variations of the curvature between a reference and the current configurations thus data recorded in a baseline configuration are required. Herein the two methods have been applied to the responses of nonlinear numerical models of reinforced concrete framed structures under strong earthquakes.

2 METHODOLOGIES

2.1 Curvature evolution based method

In this section, the methodology for damage detection and localization on framed structures based on the mode curvature variation is described. The procedure is based on the use of few sensors installed on the structure (one three directional accelerometer for each floor) and on the use of a band-variable filter able to extract the nonlinear response of each mode of vibration.

The Band-Variable Filter [25] is used to extract the dynamic characteristics of systems that evolve over time by acting simultaneously in both time and frequency domain. The filter was built using the properties of convolution, linearity and invertibility of the S-Transform [26]. The S-Transform is a time frequency localization spectral method similar to the short time Fourier transform [27] but with a Gaussian window whose width scales inversely and whose height scales linearly with the frequency.

The filtering method is based on the algorithm described in the following steps:

- Assessment of S-Transform $S(\tau, f)$ of the signal $h(t)$;
- Generating the filtering matrix $G(\tau, f)$, selecting the time-frequency subdomain directly from the S-Transform result;
- Calculating the convolution in the time-frequency domain $M(\tau, f) = G(\tau, f) \cdot S(\tau, f)$;
- Retrieving the filtered signal $h_f(t)$ through the calculation of the inverse S-Transform matrix $M(\tau, f)$.

So the complete process can be written as:

$$h_f(t) = \int_{-\infty}^{+\infty} \left( \int_{-\infty}^{+\infty} [S(\tau, f) \cdot G(\tau, f)] d\tau \right) \cdot e^{-i2\pi ft} df$$

(1)

The filter gives the possibility to extract from a nonstationary and/or nonlinear signal just the energy content of interest preserving both amplitude and phase in the region of interest [25]. Using this kind of approach it is possible to extract from a nonlinear signal recorded on a damaging structure during an earthquake, the time-varying behavior of each mode of vibration. In this way it is possible to evaluate both frequency and mode shape variations during an earthquake. The basic idea is to isolate, by mean the band-variable filter, the fundamental mode shape over time and evaluate its changes in terms of shape and related curvature [28].

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As described in Cao et al. [29], considering a framed structure as a beam the curvature can be written as:

\[ W''(v) = \frac{-M}{EI(v)} = \frac{W(v-h)-2W(h)+W(v+h)}{h^2} \]  

(2)

Where \( M \) is the bending moment, \( EI(v) \) is the bending stiffness, \( W(v) \) is the displacement and \( W''(v) \) is the related curvature. Treating the fundamental mode shape of a framed structure as a beam displacement, following Cao et al. [29] it is possible to localize the damage analyzing the singularity on the curvature of the fundamental mode shape.

In this paper in order to identify the damage and to localize its position, the curvature differences among floors has been evaluated over time.

\[ \delta W''_{(i+1)-i} = W''_{i+1} - W''_{i} \]  

(3)

Where \( W''_{i} \) is the curvature evaluated at the \( i \)-th floor and \( W''_{i+1} \) is the curvature evaluated at the \((i+1)\)th floor.

Figure 1 shows the frequency evolution of the fundamental mode extracted by means of the band variable filter and the time-instants from which the mode shapes were evaluated. By applying the procedure, is possible to evaluate the dynamic characteristics of the structure over time. Particularly we can consider three important time-instants for a structure subjected to an earthquake: (A) one instant before the earthquake, (B) the time-instant where the damaging structure exhibits the minimum fundamental frequency and (C) one instant after the earthquake. Comparing the mode shape characteristics evaluated in the different times A, B and C it is possible to detect and localize structural damage after the earthquake.

2.1 Interpolation method

The Interpolation Method is based on the observation that the comparison of the operational shapes related to the undamaged and damaged phases points out a sharp variation of the deformed shape occurring at the damaged story. The damage feature is thus defined as the error related to the use of a spline function in interpolating the operational deformed shapes of the structure. A variation of the interpolation error between the undamaged and the inspection phase indicates the onset of damage.

Specifically, at a given location of a structure, the interpolation accuracy can be defined as the difference between the measured displacement and the displacement calculated at that location by interpolating, through a spline function, the displacements measured at all the other locations equipped with a sensor. If the comparison between the interpolation error in two different phases (the reference phase on the undamaged structure and the inspection
phase after a potentially damaging event) highlights a significant decrease of accuracy, this is an indication of the existence of damage at a location where this change has been detected.

In order to remove the influence of the amplitude of displacements on the evaluation of the error function and to remove the numerical errors related to the estimation of displacements from recorded accelerations, the error function has been defined in terms of the difference between the transfer functions with respect to the input acceleration of the recorded and interpolated accelerations [30].

The first step of the methodology is the evaluation of the FRF (Frequency Response Function) at each instrumented location \( z \) where responses in terms of acceleration have been recorded. At each location an estimation of the FRF can be obtained by interpolating through a spline shape function the FRFs calculated from signals recorded at all the other instrumented locations [31].

The interpolation error is defined as the magnitude of the difference recorded and interpolated FRFs.

\[
E(z, f_i) = |H_R(z, f_i) - H_S(z, f_i)|
\]

where \( H_R \) is the FRF of the response recorded at location \( z \) and \( H_S \) is the spline interpolation of the same FRF at \( z \). In order to characterize each location with a single error parameter, the norm of the error on the whole range of frequencies is considered:

\[
E(z) = \sqrt{\sum_{i=n_0}^{n_0+N} E(z, f_i)^2}
\]

\( N \) is the number of frequency lines in the Fourier transform correspondent to the frequency range starting at line \( n_0 \), where the signal-to-noise ratio is high enough to allow a correct definition of the FRF.

The values of the FRFs depend on the state of the structure; hence, if the estimation of the error function through Equation (5) is repeated in the baseline (undamaged) and in the inspection (potentially damaged) phases, the comparison between the two values \( E_0 \) and \( E_i \), respectively, gives an indication about the existence of damage at the considered location.

\[
\Delta E(z) = E_i(z) - E_0(z)
\]

3 APPLICATIONS

The two methodologies presented in this paper have been applied to the nonlinear numerical models of two reinforced concrete framed structures characterized by 5 and 8 floors with regular geometric configuration and designed only for gravity loads (Figure 2).
The height of each story is 3 m, for a total height of the building equal to 15 m for the 5 story building and of 24 m for the 8 story building. A software based on nonlinear finite element (SAP2000 non-linear) has been used to model the 3-D structure. In order to simulate a structural nonlinear behavior during a strong ground motion, link elements and plastic hinges have been added at the ends of both beam and column elements. Link elements have a Pivot hysteretic behavior, while plastic hinges have an axial load-dependent one.

The numerical analysis was performed using natural accelerograms compatible with the Italian Seismic Code for a soil type B [32]. In order to identify the frequency at a time instant before the earthquake and at a time after the earthquake, a section of pink noise at the beginning and in the end of the accelerograms in input has been inserted. Figure 3 shows the seven accelerograms used for the numerical analysis and the correspondent response spectra.

![Figure 3: (a) Seven natural accelerograms; (b) Response spectra relating to natural accelerograms](image)

### 4 RESULTS

In this section the main outcomes retrieved for the structures with 5 and 8 floors considered in the numerical campaign are presented. Particularly the curvature differences among floors and the interpolation error have been computed and compared.

After evaluating these parameters, the interstory drift has been computed and compared to the results given by the two curvature-based methods. It is an efficient damage indicator that gives information about the damage and the characterization of the seismic behavior of a building. The drift allows defining, through the different performance levels, the expected damage both to non-structural elements and to structural elements [33].

Figure 4 shows for the 5 story structure the comparison between a) the variation of curvature obtained by applying the curvature evolution based method, b) the variation of the interpolation error retrieved from the interpolation method and c) the interstory drifts.
Figure 4: Curvature difference among floors, variation of interpolation error and interstory drift for the structure with 5 floors: (a) accelerogram A1, (b) accelerogram A4, (c) accelerogram A6.

In Figure 5 the comparison between the different damage parameters is reported for the structure with 8 floors.
The results obtained by applying the two different methodologies show that the evaluation of the curvature difference between floors and the interpolation error both allows to localize the structural damage and identify the most damaged floor after strong motion earthquake. Furthermore figures 4 and 5 show that the drift is agreement with the two damage parameters. Particularly it can be seen that the module of the curvature difference follows the trend of drift amplitude and the two parameters are closely correlated. From the results obtained in this work on the different numerical models it has been observed that, despite the different structural damage evaluation, the two methods show comparable results in agreement with each other.

5 CONCLUSIONS

In this paper a comparison between two different methods for damage detection and localization after a strong motion earthquake is presented. Both methods are based on the detection of curvature variations between two different configurations of the structure. The curvature evolution based method, starting from the properties of the S-Transform and of the band-variable filter, allows to separate the variable contribution of each mode of vibration within both linear and nonlinear fields. This enables to follow the damage propagation on the structure by investigating the evolution of the curvature of the main mode involved into the damage process thus a better understanding of the mechanisms of damage as well as a more precise localization of damage.

The Interpolation method enables to detect localized variations of curvature through the interpolation of the Operational Shapes with a smooth cubic spline function: an increase of the interpolation error points out a decrease of smoothness thus an increase of curvature. This depends on the so-called Gibbs phenomenon for splines which is used in the Interpolation Method as a ‘curvature discontinuity detector’.

Herein the two methods have been applied to the localization of damage in the nonlinear finite element models of two multistory buildings under strong seismic excitation. Results show that the two methods give consistent results detecting the same location of damage for the two considered numerical models. The same results are found basing on the pattern of interstory drifts along the height of the two buildings which confirms the reliability of the two methods to detect, in a fast and intuitive way, structural damage after an earthquake inducing a nonlinear structural behavior.
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REFERENCES


