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DAMAGE DETECTION OF MIXED CONCRETE/STEEL FRAME SUBJECTED TO EARTHQUAKE EXCITATION

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Abstract

This paper deals with the application of wavelet analysis on damage detection in mixed concrete/steel frame structures subjected to earthquake excitation. Such buildings are typically the result of a building initially constructed as a reinforced concrete building and, at a later time, more storeys were added as steel moment resisting frames. These structures consist of reinforced concrete frames at the lower storeys and steel frames at the upper storeys. They are characterized by the material inconsistency in height. The proposed method of wavelet analysis of structural response is an output-only damage detection method. Non-linear dynamic analysis has been performed and response data at each story are obtained which are used as simulation data. Damage in the frame is due to hysteretic behaviour of columns and beams. Since the dynamic behaviour of an inelastic structure subjected to an earthquake excitation is a non-stationary process, discrete and continuous wavelet analysis were performed in order to retrieve the simulation response data. The proposed method is based on the assumption that there is a correlation between structural damage, due to non-linear behaviour of structural elements and spikes that can be clearly detected in the wavelet details. This is supported by the fact that at the time when the spikes are recorded, structural damage occurs as well. The numerical results indicate that the discrete wavelet analysis is a promising method for the detection of damage in structures without the need for visual inspection

Keywords: Mixed concrete/steel frame, Damage detection, Discrete wavelet analysis, Continues wavelet analysis, Structural dynamics, Earthquake engineering.

1 INTRODUCTION

Damage observed during the service life of a structure may be caused by excessive earthquake excitations. The first step to detect the existence and the location of the damage in structure is the visual inspection. However, in some cases visual inspection may not be feasible; e.g. in hotels or hospitals where the interior of the building is covered by fixed furniture, equipment or plasterboards. Bridges in viaducts are also a case where it is difficult to access and observe the damage of critical structural elements which are located below the bridge.

Damage detection includes the determination of the existence, severity and location of the damage, as well as the prediction of the remaining service life. In order to apply a damage detection method an appropriate tool is structural health monitoring (SHM), which provides the suitable data for making the appropriate decisions. SHM, is an efficient strategy to monitor system performance and make corresponding maintenance decisions. A main group of methods for damage detection is modal analysis methods, which are based on the fact that the change in structural properties causes a variation in the modal parameters, natural frequencies, damping ratios and mode shapes. Many analytical and experimental studies have been conducted to establish analytical correlations between damage severity and modal parameters. Kirmser, [1], investigated the relationship between natural frequencies and the introduction of a crack in an iron beam. A literature review on methods of damage detection using vibration signals for structural and mechanical systems was provided by Fan and Qiao, [2]. Another work based on changes in modal parameters is that of Humar *et al.* [3]. Ciambella *et al.* [4] investigated damage localization and assessment based on eigenfrequencies and eigenvectors curvatures.

Neural network approaches are more innovative methods and can also be used for damage detection. Wu *et al.* [5] trained a neural network to recognize the behaviour of an undamaged structure as well as the behaviour of a structure with various possible damage states. When the trained network is subjected to the measurements of the structural response, it is able to detect any existing damage. Masri *et al.* [6] trained a neural network with measurements from a healthy structure and this trained network was fed comparable vibration measurements from the same structure under different episodes of response in order to monitor the health of structure. Vanik and Beck [7] and Chandrashekhar and Ganguli [8] used fuzzy logic to determine the damage location. Friswell and Mottershead [9] used a combination of sensors and an analytical model of the structure for the damage detection. Yun *et al.* [10] used genetic algorithms for their damage detection approach. Papadimitriou and Ntotsios [11] updated the parameters of the model that is related to damage so that the dynamic characteristics of the model corresponded to the sensor measurements. Sakellariou and Fassois [12] introduced a stochastic output error for damage detection and assessment (location and quantification) in structures under earthquake excitation. Chatzi *et al.* [13] propose a methodology for the on-line identification of non-linear hysteretic systems where the parameters of the system are unknown and also the nature of the analytical model describing the system is not clearly established. Dertimanis and Chatzi [14] investigate a hybrid optimization algorithm to the state–space parameter estimation problem. The hybrid algorithm was designed in a way that takes advantage of its deterministic and stochastic counterparts, combining fast local convergence and increased reliability in the search of the global optimum.

Wavelet analysis is another tool for damage detection in structures [15], [16]. Taha *et al.* [17] presented a view of wavelet transformation and its technologies. They discussed specific needs of health monitoring addressed by wavelet transformation. Kim and Melhem [18] provide a review of the research that has been conducted on damage detection by wavelet analysis. Hou *et al.* [19] proposed a wavelet-based approach for structural damage detection. Their model consisted of multiple breakable springs that may suffer either irreversible damage when the response exceeds a limit value or the cumulative number of cycles of motion exceeds the fatigue life. In any case, occurrence of damage and the time when it takes place can be clearly determined in the details of the wavelet decomposition of these data. Alonso *et al.* [20] used orthogonal wavelet decomposition for identifying the stiffness loss in a single degree of freedom spring-mass-damper system. Their work shows that pseudo-alias effects caused by the orthogonal wavelet decomposition (OWD) affect damage detectability. Rucka and Wilde [21] use neuro-wavelet technique to detect damage in beam, plate and shell structures; their results were also validated with experiments. Hera and Hou [22] applied wavelet analysis for the detection and location the damage. They found that structural damage due to sudden breakage of structural brace elements can be detected by spikes in the wavelet details. In the work of Khatam *et al.* [23], wavelet analysis is used for damage identification in beams subjected to harmonic loading. The damaged region can be determined by the spatial distribution pattern of the observed spikes. Soyoz and Feng [24] worked theoretically and experimentally on damage detection of bridge structures. Noh *et al.* ([25], [26]) introduced three wavelet-based damage-sensitive features (DSFs) which are defined as functions of wavelet energies at particular frequencies and specific time instances. These DSFs can be used to diagnose structural damage.

Adaptive-scale damage detection strategy for plate structures based on wavelet finite element model was developed by He and Zhu [27]. Law *et al.* [28] worked on statistical damage classification method based on wavelet packet analysis. Liu *et al.* [29] developed a structural time-varying damage detection method using synchro-squeezing wavelet transform. Wang *et al.* [30] used discrete wavelet transform for time-varying physical parameter identification of shear type structures. Finally, Fan *et al.* [31] proposed a novel transmissibility concept based on wavelet transform for structural damage detection.

Output only modal identification and structural damage detection of multi-degree of freedom of linear time variant systems based on time-frequency techniques such as short-time Fourier transform, empirical mode decomposition, and wavelets was developed by Nagarajaiah and Basu [32].

A wavelet-based distortion energy approach is presented in the work of Bukkapatnam *et al.* [33] as a method for quantifying and locating the damage to structural systems. Goggins *et al.* [34] used a wavelet-based equivalent linearization technique to determine the temporal variations in frame stiffness that occurs due to brace yielding and buckling. Lima *et al.* [35], use wavelet analysis for damage detection of non-linear structures. Damage detection of frame structures subjected to earthquake excitation using discrete and continues wavelet analysis is presented in the works of Pnevmatikos *et al.* ([36], [37]).

Applications of damage detection for buildings with material irregularity in height like concrete-steel frame structures (mixed concrete-steel frame structures) is very limited. These structures consist of reinforced concrete frames at the lower storeys and steel frames at the upper storeys. Such buildings are typically the result of a building initially constructed as a reinforced concrete building and at a later time more storeys were added as steel moment resisting frames. Due to the different time of construction, those buildings are often designed with different design codes and approaches. However, if the lower part of the building was constructed after the 90's, then both parts are designed according to the Eurocodes, so it can be considered as a mixed concrete/steel building since its original design.

In this paper damage detection in mixed concrete/steel frame structures subjected to earthquake excitation is presented. Damage into the structure is introduced by the non-linear behaviour of the structural members. The data to be analysing were obtained by non-linear analysis of the mixed concrete/steel frame structure. Since the dynamic behaviour of inelastic structures during an earthquake is a non-stationary process, wavelet analysis is the most appropriate tool. A computational procedure for damage identification is developed based on discrete and continues wavelet analysis. The proposed procedure is based only to the output response of the structure in each story.

2 BACKGROUND OF CONTINUOUS AND DISCRETE WAVELET ANALYSIS

Wavelet analysis provides a powerful tool to characterize local features of a signal. Unlike the Fourier transform, where the function used as the basis of decomposition is always a sinusoidal wave, other basis functions can be selected for the wavelet shape according to the features of the signal. The basis function in wavelet analysis is defined by two parameters: scale and translation. These properties lead to a multi-resolution representation for non-stationary signals.

The continuous wavelet transform of a signal, $f(t)$, is defined as:

$$f(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\, \bar{\Psi}\left(\frac{t-b}{a}\right) dt \tag{1}$$

where a, b are the scale and translation parameters respectively and $\bar{\Psi}$denotes the complex conjugate of Ψ. The functions, $\Psi(t,a,b)$, are called wavelets. They are dilated and translated versions of the mother wavelet, $\Psi(t)$.

By discrediting the parameters, a and b, a discrete version of the wavelet transform (DWT) is obtained. The procedure becomes more efficient if dyadic values of a and b, are used, i.e.

$$a = 2^j \quad b = 2^j k \quad j,k \in Z \tag{2}$$

where Z is a set of positive integers. The corresponding discretized wavelets $\Psi_{j,k}$ are defined as:

$$\Psi_{j,k}(t) = 2^{-j/2} \Psi\left(2^{-j} t - k\right) \tag{3}$$

where $\Psi_{j,k}$ forms an orthonormal base. In the discrete wavelet analysis, the signal can be represented by its approximations and details. The signal is passed through a series of high pass filters, which relate to details, to analyse the high frequencies, as well as through a series of low-pass filters, which relate to approximations, in order to analyse the low frequencies. The detail at level, j, is defined as:

$$D_j = \sum_{k \in Z} a_{j,k} \Psi_{j,k}(t) \tag{4}$$

where $a_{j,k}$ is defined as :

$$a_{j,k} = \int_{-\infty}^{\infty} f(t)\, \bar{\Psi}_{j,k}(t) dt \tag{5}$$

and the approximation at level J is defined as:

$$A_J = \sum_{j>J} D_j \tag{6}$$

Finally, the signal, f(t), can be represented by:

$$f(t) = A_J + \sum_{j \le J} D_j \tag{7}$$

The discrete wavelet transform (DWT) can be very useful for on-line health monitoring of structures, since it can efficiently detect the time of a frequency change caused by stiffness degradation.

3 DAMAGE DETECTION METHODOLOGY OF MIXED CONCRETE/STEEL FRAME STRUCTURE SUBJECTED TO EARTHQUAKE EXCITATION

Damage detection methodology is an extension of the authors' work ([36], [37]) and is based on the fact that when plastic hinges have developed during excitation, the frequency of the system changes and this causes a shift of frequency of the response signal. On the other hand, when a signal changes its frequency and analysed by discrete wavelet transform this is imprinted as spikes in details of its signal. In the present work, two more indicators were introduced to distinguish automatically the occurrence of spikes in the detailed signal. Furthermore, the use of continues wavelet transform of the response signal is introduced.

The strategy which is used to detect the damage in the framed structure is as follows:

1. Output-only response signal for each floor is analysed by discrete wavelet analysis and the details of the signal are obtained. Two indicators that show the existence of spikes are calculated.
2. If spikes are observed in the details of the response signal, this indicates that a structural element which is related to the corresponding floor (beams in the floor and columns from above or below the floor), goes beyond the yielding point and damage has occurred. The time instant that the spikes appear in the details, represent the time when damage has occurred to the structural element.
3. If no spikes are observed in the detail of the response signal for the floor, the corresponding elements for this floor would remain elastic and no damage would appear.

The above steps are shown schematically in Figure 1.

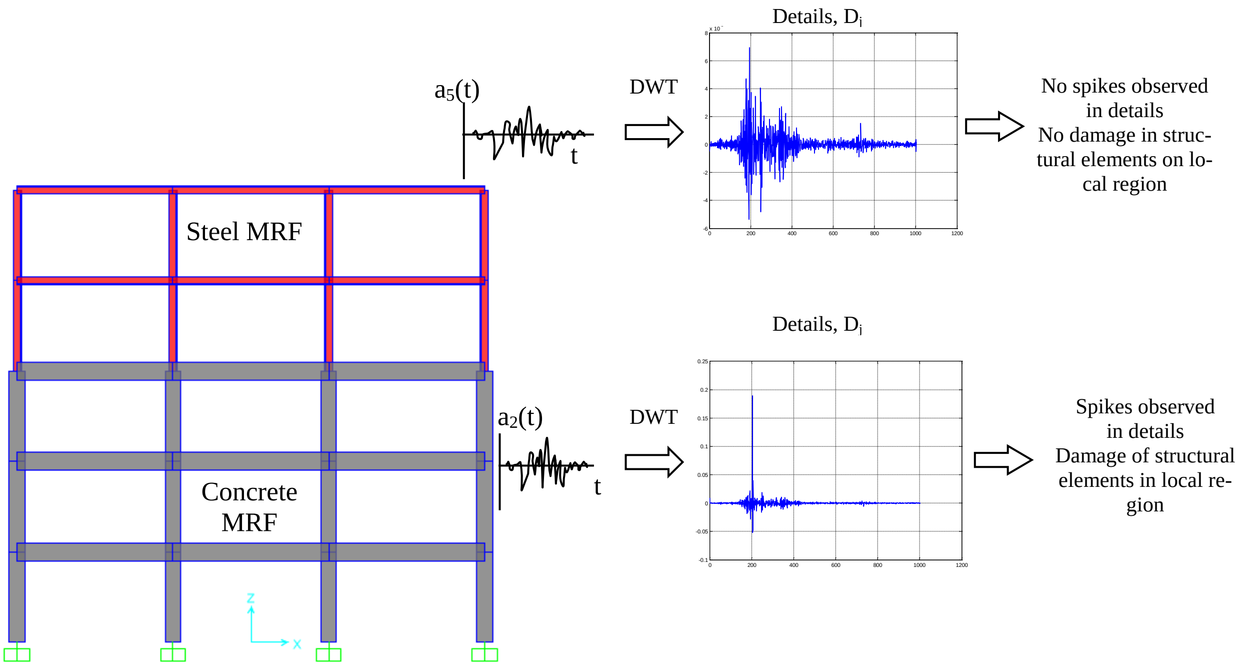

Figure 1: Steps for damage detection of mixed concrete/steel frame structures.

A question which arises: “How could one define the existence or not of spikes in the detail of output signal in order to come to a conclusion on whether a damage occurred or not?” To answer this question, two numerical indices were defined. The first is the *R1* value index. This index is the percentage of how many times the picks of the wavelet detail of output signal in each floor exceeds the proportion of maximum absolute value $p \cdot \max D$. The value of p,·is taken as 50%. If the calculated value of *R1* is small enough (*R1* $\leq$ 5%), then this is an indicator that spikes exist in the wavelet detail of signal. Otherwise, if *R1* > 5%, then no spikes caused by structural damage appear in the wavelet details and, consequently, no damage has occurred. The second index is the value of *R2* index. This index is the ratio of the maximum absolute value of the wavelet detail of output signal to the mean value of absolute signal. When the value of *R2* is high enough (*R2* > 30) this means that in the detail signal a spike exists so damage occurred in a local region of measurement. When the value of *R2* is lower than 20 this means that there is not a clear spike in the detail signal, so no damage occurred. In the grey zone between values from 30 to 10 once should combine and look at the *R1* value in order to conclude of damage in structure. The graphical representation of *R1* and *R2* numerical indicators are shown in Figures 2 and 3.

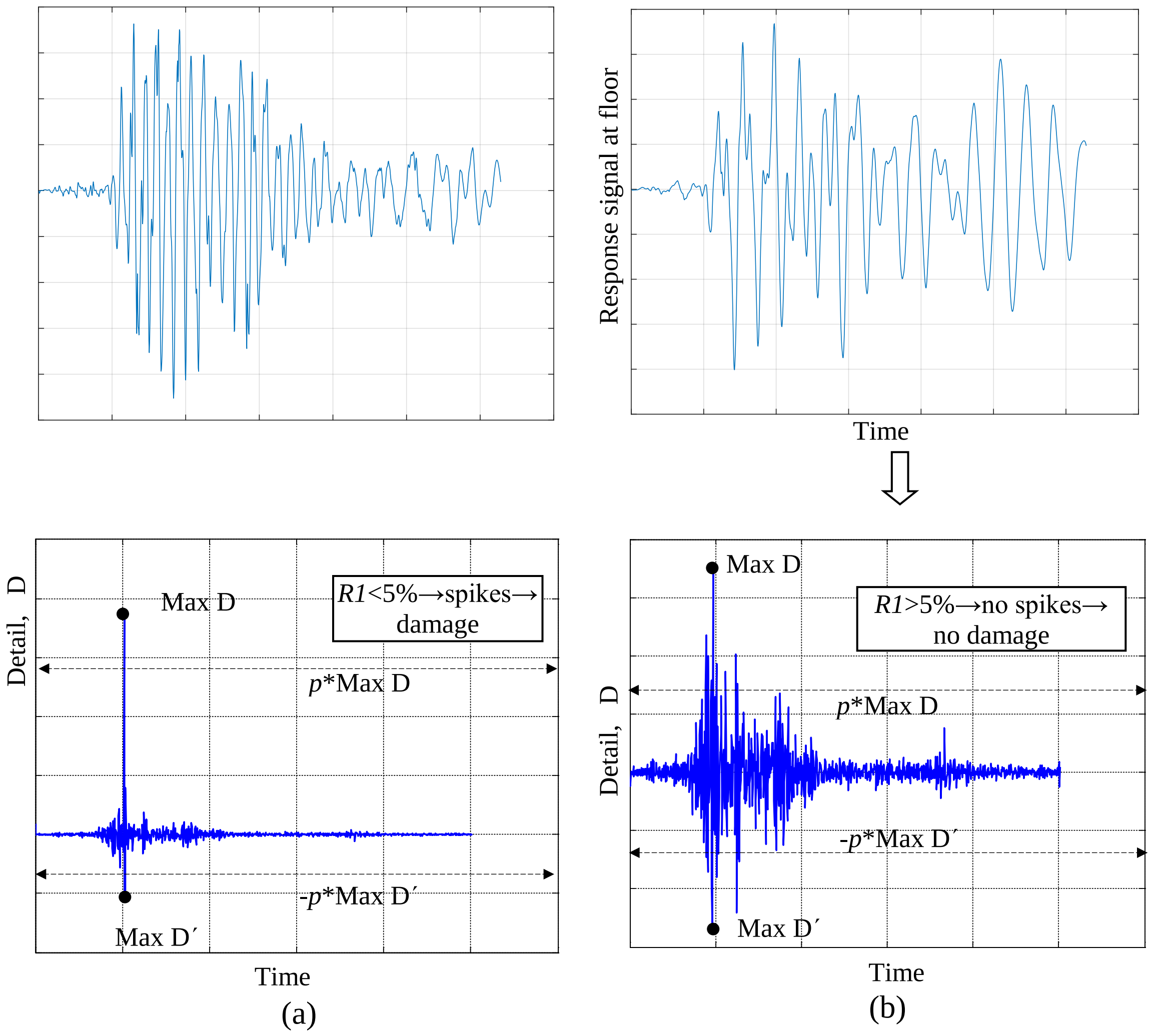

Figure 2: Graphical representation of *R1* numerical index and limits of *R1* value for damaged structure (a) and healthy structure (b).

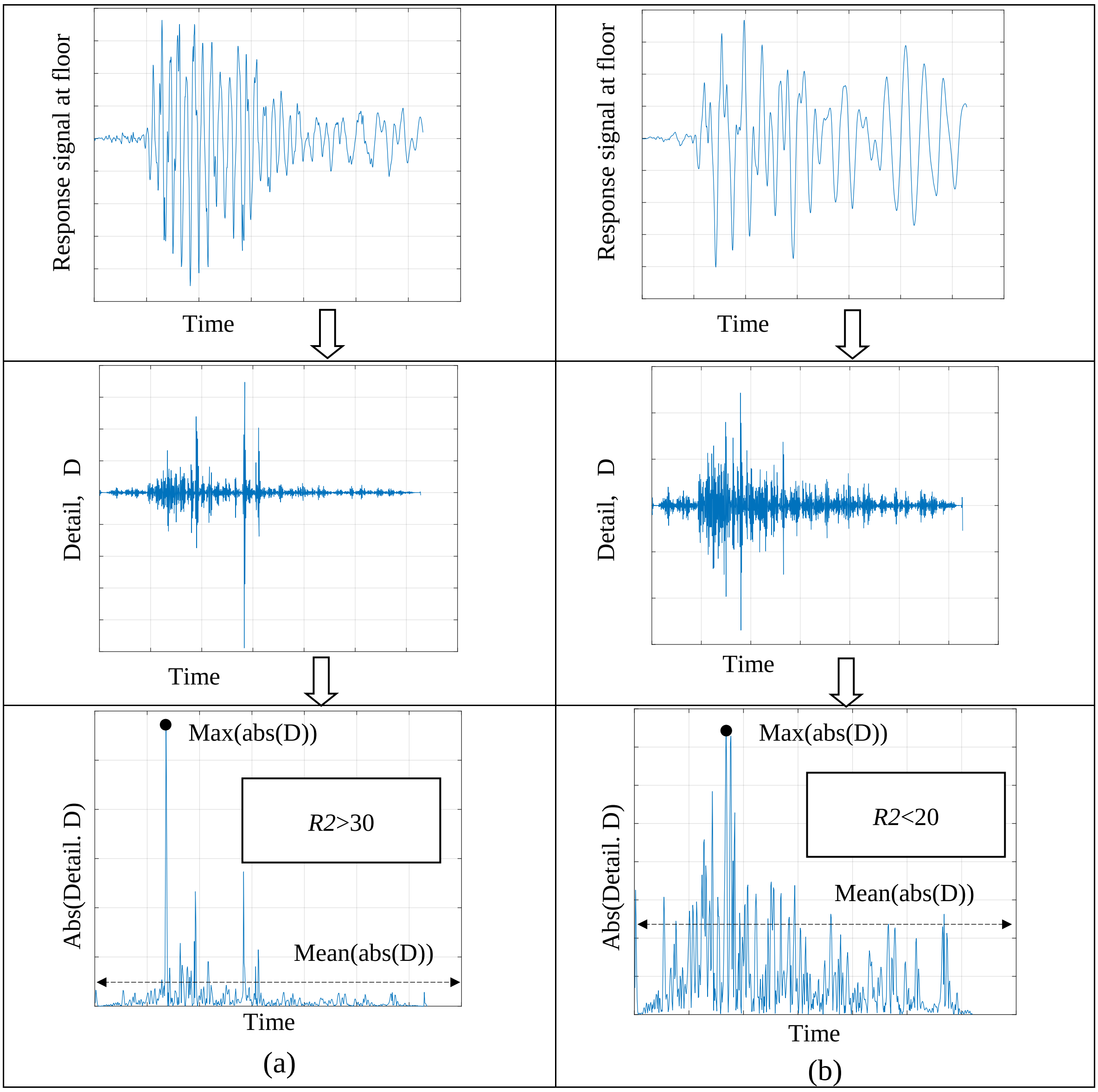

Figure 3: Graphical representation of R2 numerical index and the corresponding limits for damaged structure (a) and healthy structure (b).

4 NUMERICAL CASE STUDY

The above damage detection strategy has been applied to a five story three bay concrete/steel mixed framed structure shown in Fig. 1. The frame has three bays with 5m span each, while the typical story high is 3m. The dead and live loads are 40kN/m and 15kN/m, respectively, and they are applied on the beams as distributed loads. The materials used for the lower part are C20/25 concrete with B500C reinforcement steel. The upper steel part consists of S275 structural steel. Details about materials properties, sections and modelling of frame are in the work of Pnevmatikos *et al.* [38].

The frames were subjected to Santa Barbara (1978) earthquake excitation. The non-linear dynamic analysis and the response of the frames has been completed using the software programme SAP2000nl. The wavelet analysis of the response signal has been done using MATLAB software, and specifically using the wavelet toolbox. Fifth order Daubechies wavelets and eight levels of the details have been used for the wavelet analysis of the response signal. Other types of wavelets which are sensitive to damage detection can also be used.

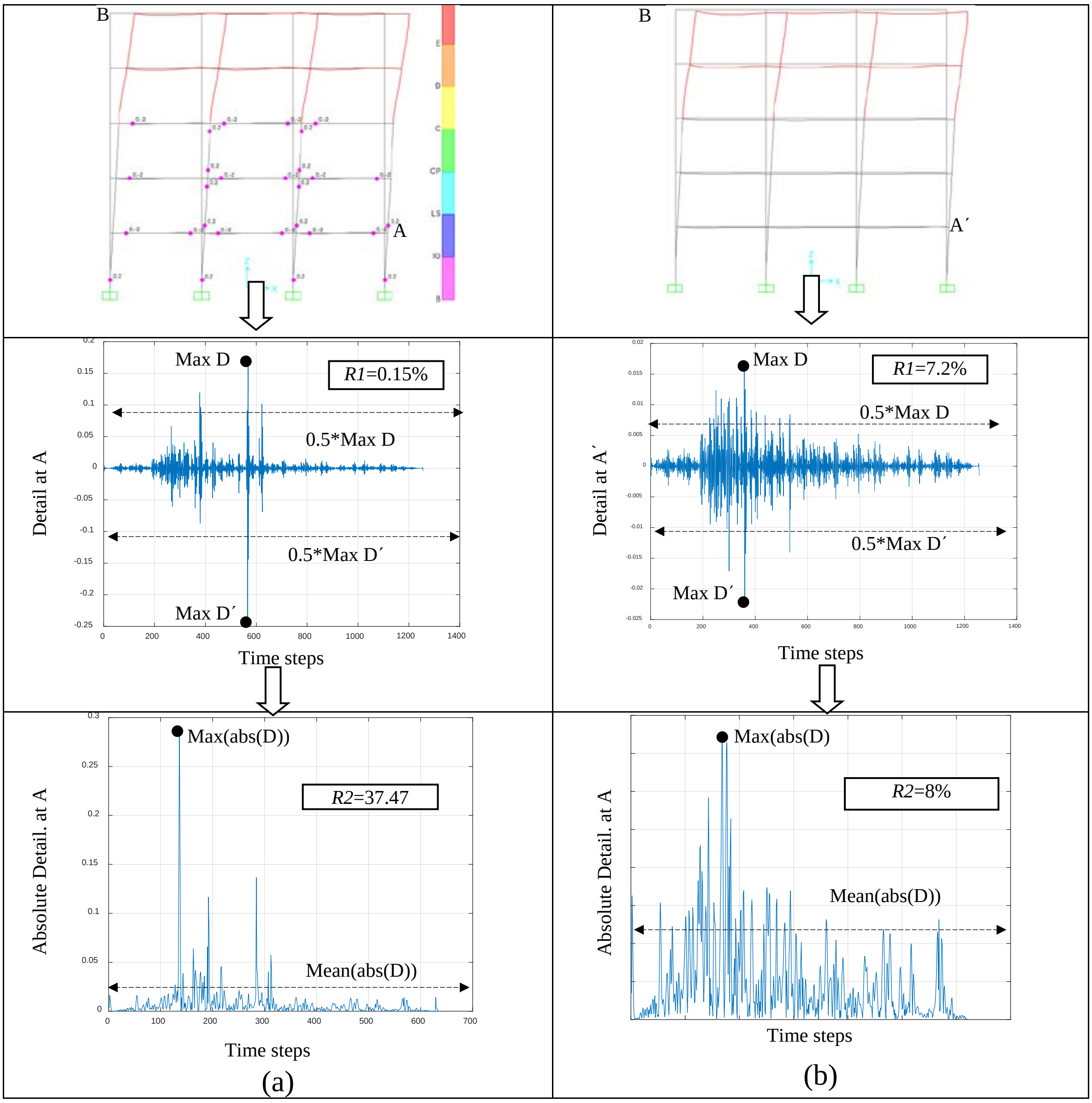

Figure 4: Numerical indicators *R1* and *R2* values obtained from response measured at 1st floor for healthy and damaged frame.

The earthquake excitation was scaled up in order plastic hinges appears in structural members. In figure 4 the response of frame with scale factor equal to 1 and 2.8 is shown. It is shown that in the column (a), is the healthy frame with no damage while in column (b) is the frame with slight damage where the sections reach the yield point. The damage detection procedure is applied when the structure has low level of damage otherwise the damage can be visual inspected. The *R1* and *R2* values for each case were calculated and shown in figure 4. It is clear that the *R1* and *R2* values for healthy and damage structure follow the limits that presented in figure 2 and 3.

The *R1* and *R2* values were obtained from the response at point B (5th floor) from both frames. It was found that they satisfy the criteria of healthy frame for both cases which are presented in figure 2 and 3. It is worth to note that the *R1* and *R2* values at point B (5th floor) from damaged structure satisfy the criteria of healthy structure because at 5 floor no damage was observed. In lower floors, for example third floor, of damaged frame the *R1* and *R2* values satisfy the limits of damaged structure presented in Figures 2 and 3. This is because at this area of structure is damage since plastic hinges occurred.

Continues wavelet analysis was also performed. In Figure 5 the chance of frequencies during the time of excitation in 3D space and in contour plot as well as the cone of influence is shown for damage and healthy structure at second floor.

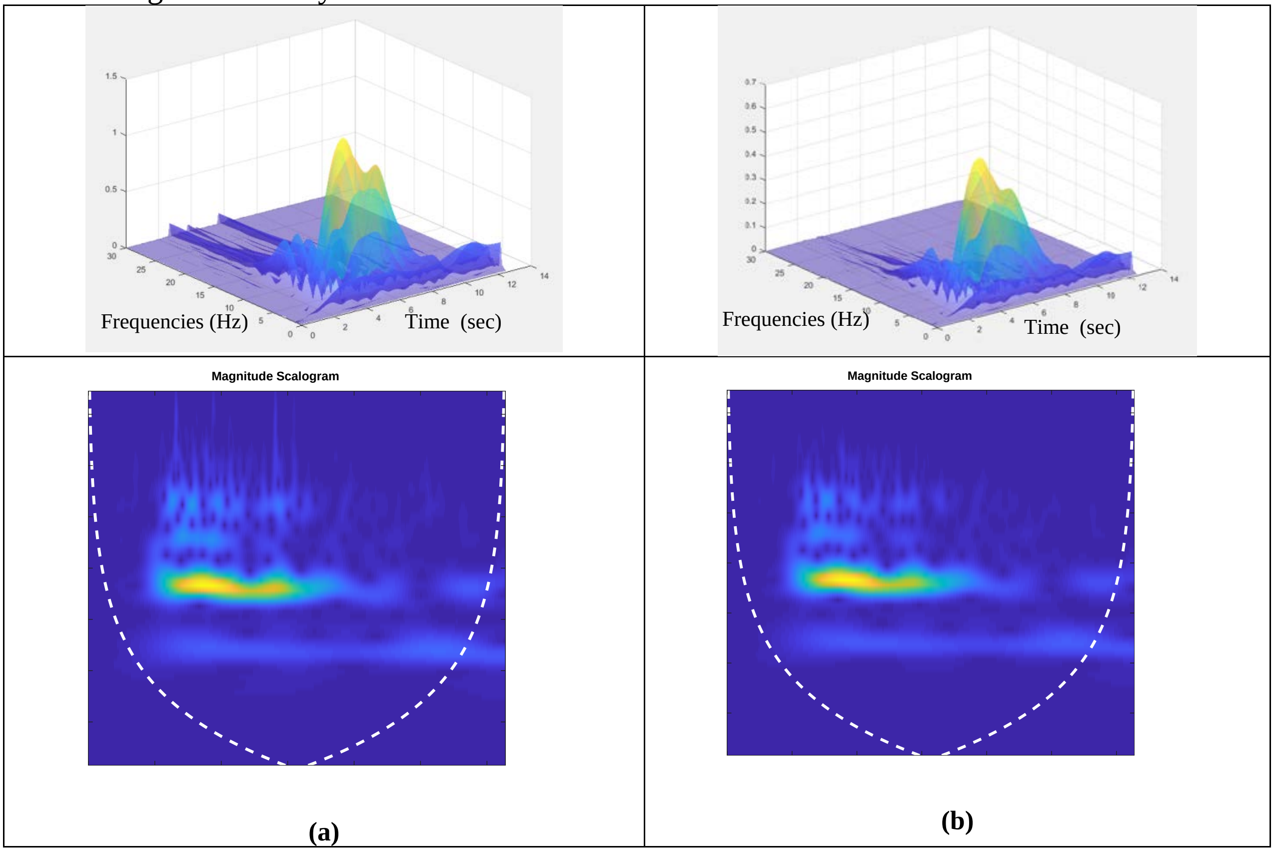

Figure 4: Continue wavelet transform from response measured at 1st floor for healthy (b) and damaged (a) frame.

5 CONCLUSIONS

A procedure of discrete and continues wavelet analysis for damage detection of a mixed concrete /steel framed structure subjected to earthquake excitation has been performed. Discrete wavelet analysis is a good tool to analyze the non-stationary dynamic behaviour of inelastic structures and capture the damage that occurs in buildings. It was shown that structural damage of a story level, can be detected by spikes in the wavelet details. Tow numerical indicator *R1* and *R2*, and their limits in order the structure to be healthy or damaged were proposed.

This procedure helps engineers in two ways. Firstly, after an earthquake event, engineers concentrate their inspection on a specific building, from all the instrumented buildings, which they have the *R* values between the damage limits. Secondly, they need to uncover specific floors from the chosen building in order to perform a detailed visual inspection of the structural elements located at this floor. This approach can also be used as an alarm procedure helping engineers proceed with the visual inspection at the appropriate region of the building. The numerical results of mixed concrete/steel framed shows the effectiveness of the wavelet approach for damage detection in structures subjected to earthquake excitation.

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