COMPDYN 2011
3rd ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis, V. Plevris (eds.)
Corfu, Greece, 25–28 May 2011

DAMAGE DETECTION OF FRAME STRUCTURES SUBJECTED TO EARTHQUAKE LOADING

Nikos G. Pnevmatikos

Technological Educational Institution of Athens, Faculty of Technological Application, Department of Civil Infrastructure Works,
Ag. Spyridonos Str., P.O. 12210 Egaleo-Athens,Greece, Tel. : +30-211-7059910, Fax : +30-210-5385858
Email: nikos_pnevmatikos@hotmail.com

Keywords: Health monitoring, Damage detection, Discrete Wavelet analysis, Structural dynamics, Earthquake engineering.

Abstract. *This paper deals with an application of wavelet analysis for damage detection of frame structure subjected to earthquake excitation. 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 introducing by the non linear behaviour of columns and beams. In order the structural members go beyond the elastic limit and start yielding the earthquake excitation was scaled up with appropriate scale factor. Discrete wavelet analysis was performing in order to analyze the simulation response data for each floor because the dynamic behaviour of inelastic structures subjected to an earthquake is a non-stationary process.*

It was shown that structural damage, due to non linear behaviour of structural elements and the time when this damage occurred, can be clearly detected by spikes in the wavelet details.

The effect of noise is taken into account by adding a white Gaussian noise to the simulation response data and discrete wavelet analysis was performing again. It was observed that if the level of details and the order of wavelets are increased, spikes can be detected again and damage would be recognized. Results show the great promise of the wavelet approach for damage detection and structural health monitoring.

1 INTRODUCTION

Damage in the buildings is often observed during their service life. Damage may be caused due to excessive earthquake excitation, severe environmental condition, degradation of the materials properties, fatigue, cumulative crack growth, etc. Usually the existence and the location of the damage can be determined through visual inspection. However, in some cases visual inspection may not be feasible. To ensure structural safety and low maintenance cost, structural health monitoring, SHM, is an efficient strategy to monitor the system performance and make a corresponding maintenance decisions.

Damage detection is a part of damage identification which includes the estimation of the severity of damage, determination of the location of damage and prediction of the remaining service life. One 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 Doeblin et al. [2] and Carden and Fanning, [3]. Other works based on change in modal parameters is the work of Humar et al. [4] and khoo et al., [5].

Structural health monitoring techniques based on changes in dynamic characteristics have success when the damage is substantial. Improved research directions for damage detection including the use of innovative signal processing, new sensors, are described in the work of Chang et al., [6]. Neural network approaches can be used for damage detection. Wu et al., [7], trained a neural network to recognize the behaviour of the undamaged structure as well as the behaviour of the 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. Tsou, and Shen, [8], applied neural network to discrete structural systems. Masri et al., [9], train a neural network with measurements from 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, [10], Chandrashekhar and Ganguli, [11], used fuzzy logic for determination of damage location. Friswell and Mottershead, [12], use a combination of sensors and analytical model of structure for damage detection. Parameters of the model that are related to damage are updated so that the dynamic characteristics of the model correspond to the measurements sensors, Papadimitriou and Ntotsios, [13]. Reigh and Park, [14], utilised methods of localized flexibility in order to determining the damage and its location in a structure. Panetsos et al, [15], describe the Egnatia Odos Bridge Management system (EOBMS) which used for deterioration prediction and maintenance, repair cost.

Engelhardt et al., [16], were investigated the Crack and flaw identification in elastodynamics using Kalman filter techniques. Soyoz and Feng, [17], used an extended Kalman filtering (EKF) method in order to instantaneously identify elemental stiffness values of a structure during damaging seismic events based on vibration measurement. This method is capable of dealing with nonlinear as well as linear structural responses. Sakelariou and Fasois, [18], introduced a stochastic output error for damage detection and assessment (location and quantification) in structures under earthquake excitation. De Roeck and Reynders, [19], present a number of recent innovations to extend the borders of what is realistically feasible with the current system identification and damage detection methods.

Medda and DeBrunner, [20], proposed a novel technique that employs the use of compactly supported sub-band space-frequency and time-frequency analysis using local vibration characteristics.

Another tool for damage detection is wavelet-based damage detection which has been considered by several researchers over the last decade, Staszewski, [21]. Newland, [22], have used wavelets to vibration analysis. He applied a wavelet analysis to study the vibration of buildings caused by underground trains, road traffic and earthquake excitations. Taha et al., [23], presents a view of wavelet transform and its technologies. They discuss specific needs of health monitoring addressed by wavelet transform. Masuda et al, [24], use orthonormal discrete wavelets transform to detect the degradation of stiffness due to fatigue. They applied the method to the laboratory-scale experiments to detect the sudden changes in the structural parameters. Kim and Melhem, [26], provide a review of the research that has been conducted on damage detection by wavelet analysis. Hou et al., [27], proposed a wavelet-based approach for structural damage detection. Their model consists of multiple breakable springs which is may suffer either for irreversible damage when the response exceeds a limit value nor the number of cycles of motion is accumulated beyond their fatigue life. In any case, occurrence of damage and the time when it occurs can be clearly determined in the details of the wavelet decomposition of these data. Hera and Hou, [28], applied wavelet analysis for detection and locating damage for a four-story prototype benchmark building provided by ASCE Task Group on Health Monitoring, Johnson et al., [29]. They were found that structural damage due to sudden breakage of structural elements and the time when it occurred can be clearly detected by spikes in the wavelet details. In the work of Khatam et al., [30], wavelet analysis is used for damage identification in beams subjected in harmonic loading. The damaged region can be determined by the spatial distribution pattern of the observed spikes. Yaghin and Hesari, [31], use Wavelet Analysis in crack detection at the arch concrete dam. Noh et al., [32], use the Wavelet Coefficient Energies in order to perform structural damage diagnosis for non stationary response signals. Nair and Kiremidjian, [33], have shown that the energies of the wavelet coefficients at appropriate scales can be used as damage sensitive features. A wavelet based, distortion energy approach is presented by Bukkapatnam et al., [34], as a method, for quantifying and locating the damage to structural systems. Another application of the wavelet transform for damage detection based on optical measurements is presented in the work of Patsias and Staszewski, [35].

In this paper the method of spikes in the wavelet details, from discrete wavelet analysis, is used in order to detect the damage in the frame structure. Damage in the structure was introduced by the non linear behaviour of the members. In order the members go slightly beyond the yielding point, and small damage occurred, the earthquake excitation was scaled up with appropriate factor. The analyzing data were obtained by non linear dynamic analysis of plane frame. Since the dynamic behaviour of inelastic structures during an earthquake is a non-stationary process wavelet analysis is more appropriate tool than conventional Fourier analysis.

2 BACKGROUND OF 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 wavelet shape according to the features of the signal. The basis function in wavelet analysis is defined by two parameters: scale and translation. This property leads to a multi-resolution representation for non-stationary signals.

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

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

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

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

$$a=2^{j} \quad b=2^{j}k \quad j,k\in Z \qquad (2)$$

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

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

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

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

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

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

and the approximation at level J is defined as:

$$A_J=\sum_{j>J} D_j \qquad (6)$$

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

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

The 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 DETECTION OF DAMAGE USING WAVELETS

When the structure subjected to the earthquake excitation the envelop of the hysteretic behavior of base shear versus the roof displacement is similar to figure 1. If the excitation is strong enough and push the structure in region c or b then damage in structures is obvious since large displacements and rotations can be observed with visual inspection, and no damage detection technique is needed to verify it. If the excitation is not too small, structure behaves elastic and no permanent displacement are observed or no damage occurs. In between the two extreme above cases, the structure can be go slightly no linear, region a, and small damage that is difficult to observe by visual inspection, can be occurred.

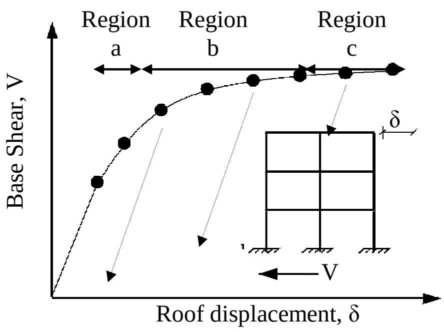


Figure 1. Global behavior envelop curve of a structure.

The above global behaviour of structure is a result of the behaviour of each element that consist the structure. The frame element has its own nonlinear characteristics based on section and material. A generalized force-displacement characteristic of frame element (or hinge properties) is shown in figure 2. Region AB, corresponds to a linear behaviour and point B represents yielding of the element. The ordinate at C corresponds to nominal strength and abscissa at C corresponds to the deformation at which significant strength degradation begins. The drop from C to D represents the initial failure of the element and resistance to lateral loads beyond point C is usually unreliable. The residual resistance from D to E allows the frame elements to sustain gravity loads. Beyond point E, the maximum deformation capacity and gravity load can no longer be sustained. This formulation is according to FEMA 356 for force deformation behaviour of structural element subjected to monotonic loading. This nonlinear behaviour can be used during nonlinear direct integration time history analysis.

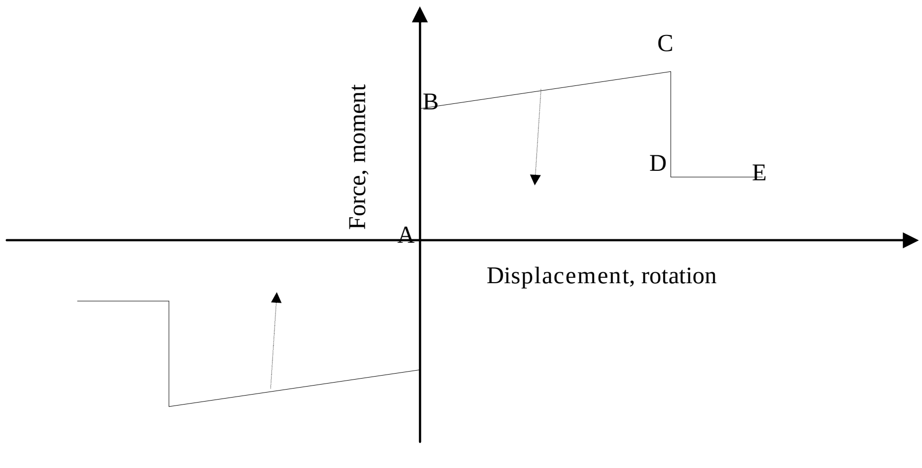


Figure 2. Generalized Force-Displacement Characteristic of a Degrading Frame Element.

As the structural elements reach the region DE or the end of the region BC the damage is clear by visual inspection since large displacement and rotation is occurred. If the element is in a linear elastic branch AB no damage is occurred. Finally if the element goes slightly beyond the yielding point, B, then small damage occurs and is difficult to be observed by visual inspection. Visual detection of damage becomes more difficult considering that structural elements are covered by other material or is difficult to access them.

Once the plastic hinge is occurred during the excitation, the frequency of the system is also change. This change in frequency has as a result the change in frequency in the response signal. From the other hand if a signal which changes its frequency is analyzed by discrete wavelet transform spikes will be observed in the details. This is clearly indicated in figure 3.

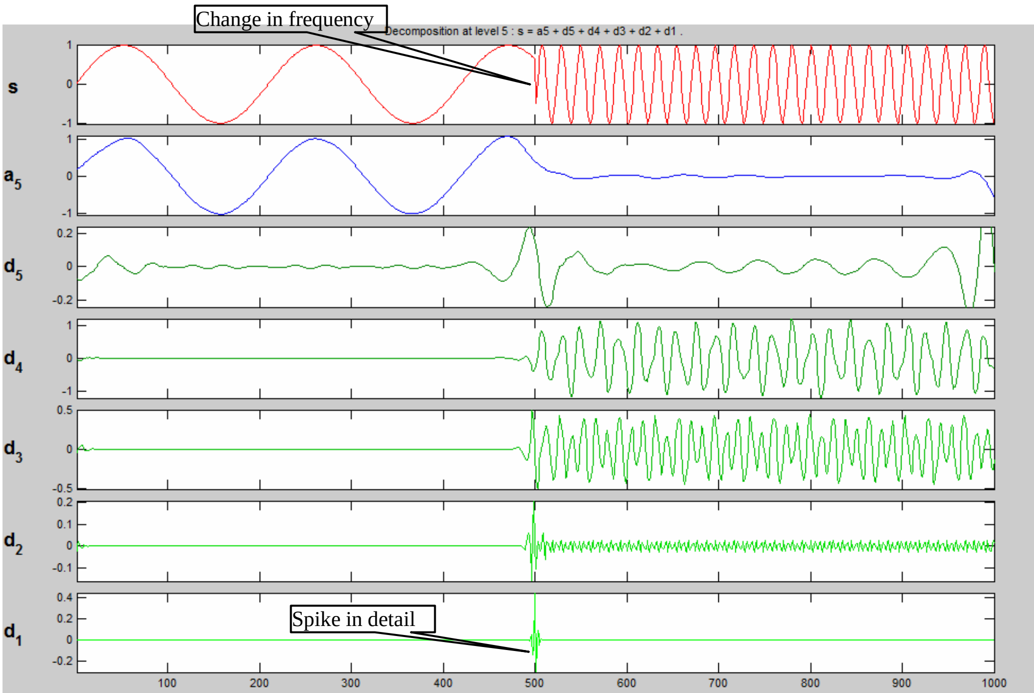


Figure 3. Spike in the detail of a signal which consists of two different frequencies.

Combining the above two characteristics (plastic hinge-chance of frequency, chance of frequency-spikes in details) the strategy that used in order to detect the damage in frame structures is as follow: The response signal is analyzed by discrete wavelet analysis and the details of the signal are obtained according to equation (4). If spikes will be observed in the details of the response signal this means that the structural element goes beyond the yielding point and damage is occurred. The time moment that the spikes appear in the details, represent the time were a plastic hinge is created. If no spikes would be observed in the detail of the response signal the structure would remain elastic and no damage would be happen. The above cases are shown schematically in figure 4.

When any structural element yields, this phenomenon is imprinted as spikes in the details of wavelet analysis of the acceleration response signal. This can be used in opposite direction, suppose that is not easy to see the situation of the structural element and the only measured data that is available is the acceleration response signal of the structure. If spikes are observed in the wavelet analysis of the signal, then yielding (damage) has been occurred.

4 NUMERICAL EXAMPLES

The above damage detection strategy has been applied to one single, one two and one eight story frame structure with the properties shown in figure 5. The frames were subjected to earthquake excitations. The nonlinear dynamic analysis and the response of the frames have been done using the software programme SAP2000nl, [36]. The wavelet analysis of the response signal has been done by the MATLAB software, [37], using the wavelet toolbox. Four order Daubechies wavelets and five levels of the details have been used for the wavelet analysis of response signal.

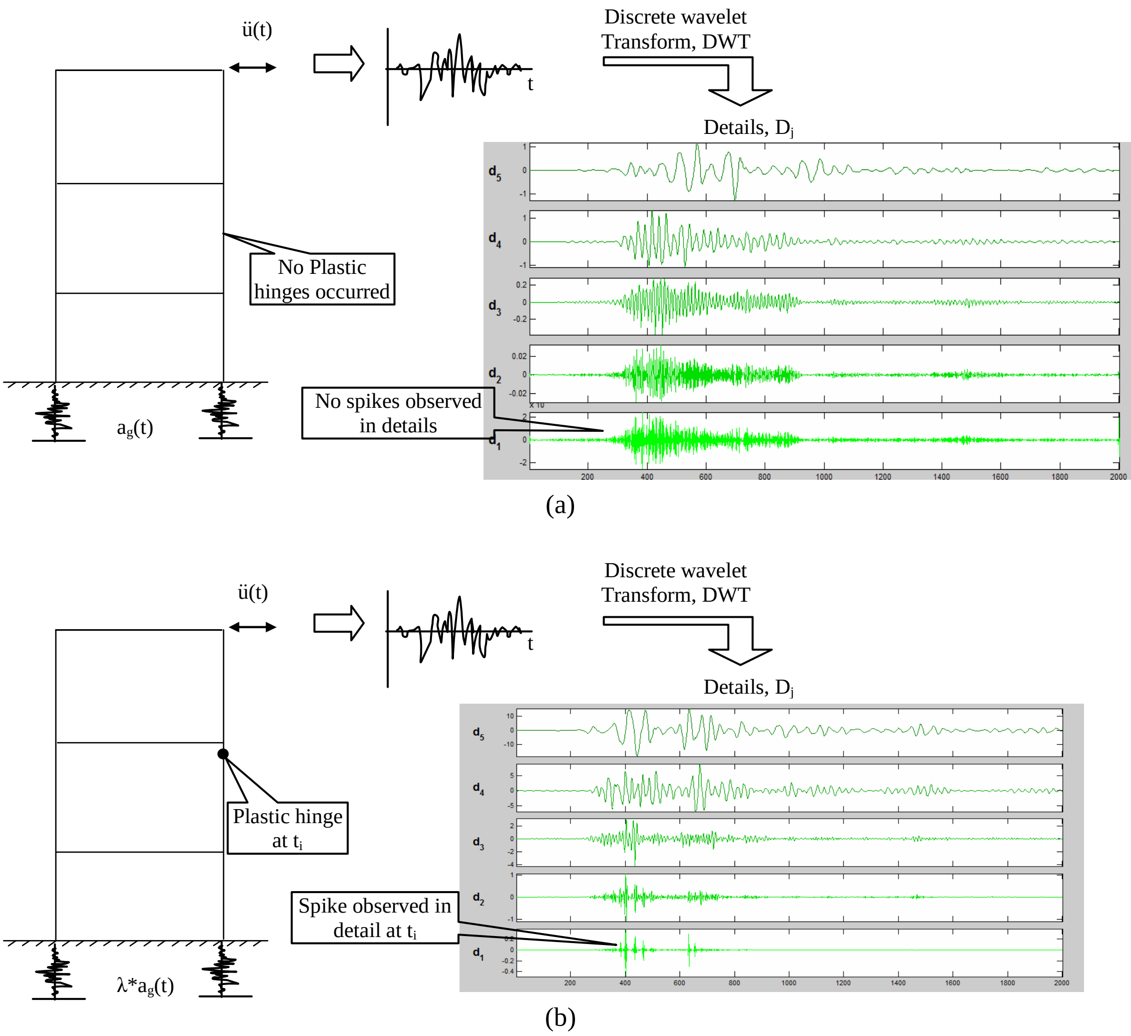


Figure 4. Procedure for detection the existence of plastic hinges in the structure. (a) no plastic hinges occurred no spices are observed, (b) plastic hinges occurred at time t_i spices are observed at t_i.

The single story frame subjected to Athens earthquake signal and no hinges has occurred. The response acceleration on the top of the frame were analyzed by wavelet analysis and the results of the approximations and details of the signal are shown in figure 6(a). It is clear, in the details of signal, d_1, no spikes are observed and consequently no damage occurred. This is verified by the nonlinear dynamic analysis where no plastic hinges occurred during the Athens earthquake excitation. The earthquake signal is scaling up gradually and dynamic non linear analysis is performing again until plastic hinges will be observed. When the factor λ becomes equal to 4 the first plastic hinges were created. For this case, the response signal at the top of the frame is analyzed again, by discrete wavelet analysis and the details are shown in figure 6(b). From the result of the wavelet analysis it is seems that spikes are observed in the details of signal. This indicates that damage has been occurred in frame. This is verified by the results of the dynamic nonlinear analysis of the frame where a plastic hinges, damage, occurred to the frame when subjected to Athens earthquake record scaled up four times. It is also remarkable, that the time (t=4.05 s) when the first plastic hinges occurred, at the base of frame, is the same when the first spike is observed in the details of the signal. After a while at time (t=4.07 s) the plastic hinges at the beam of the frame occurred and spike at time (t_i=4.07 s) was also observed. The moment-rotation diagram of plastic hinge at the base of the frame is shown in figure 7. Nevertheless the rotation of the element is too small, after yielding, this nonlinearity, or small damage, can be captured by the detail of the response signal.

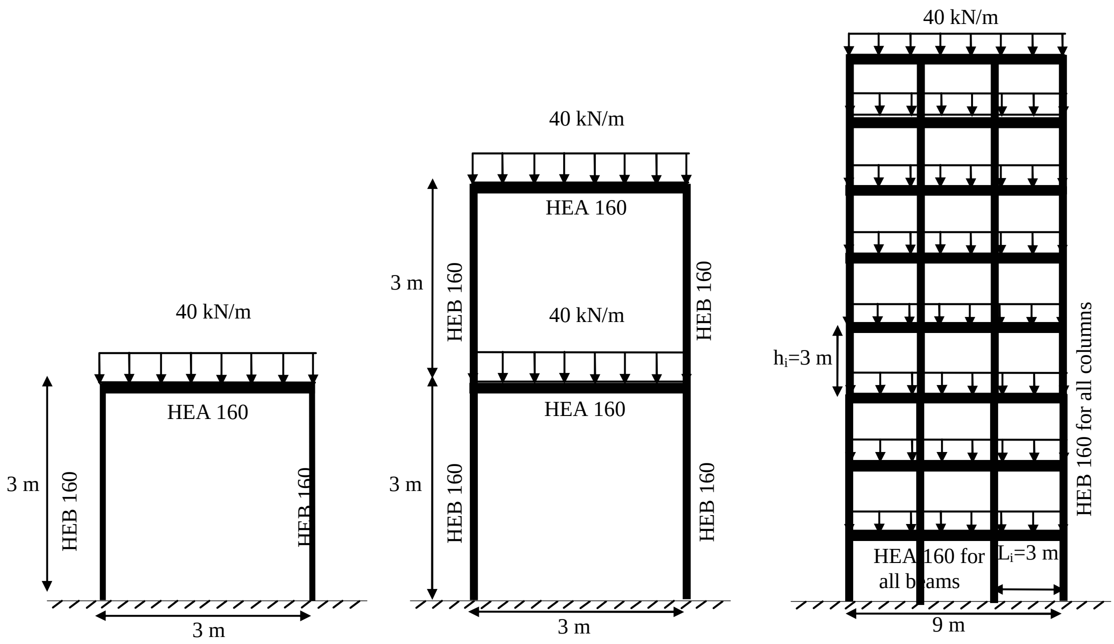
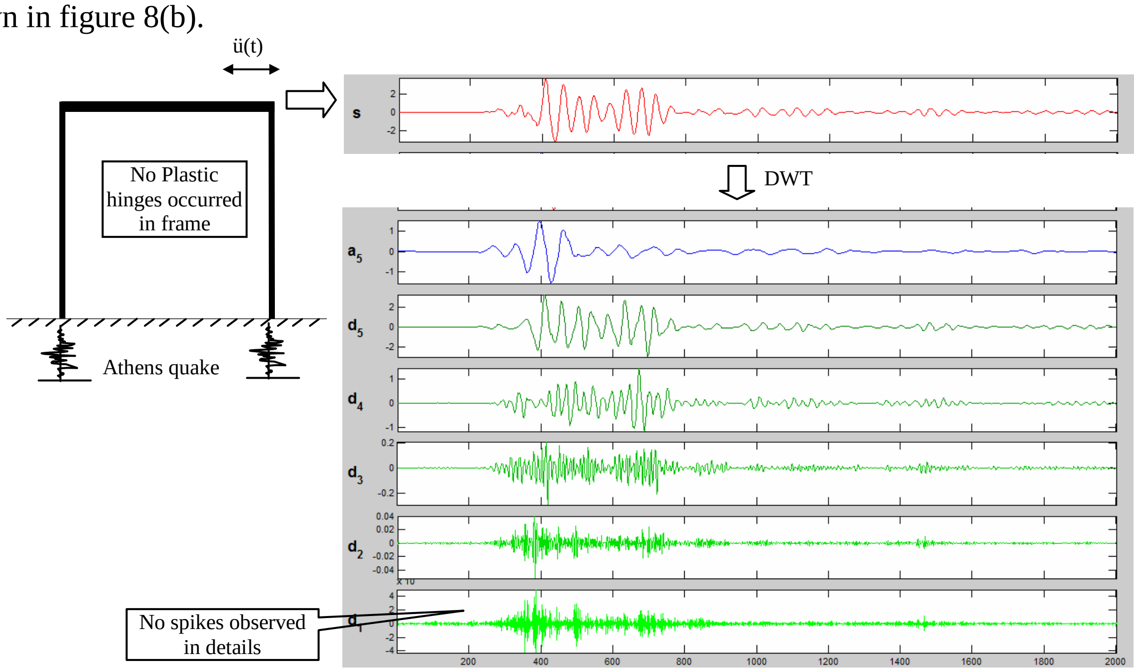
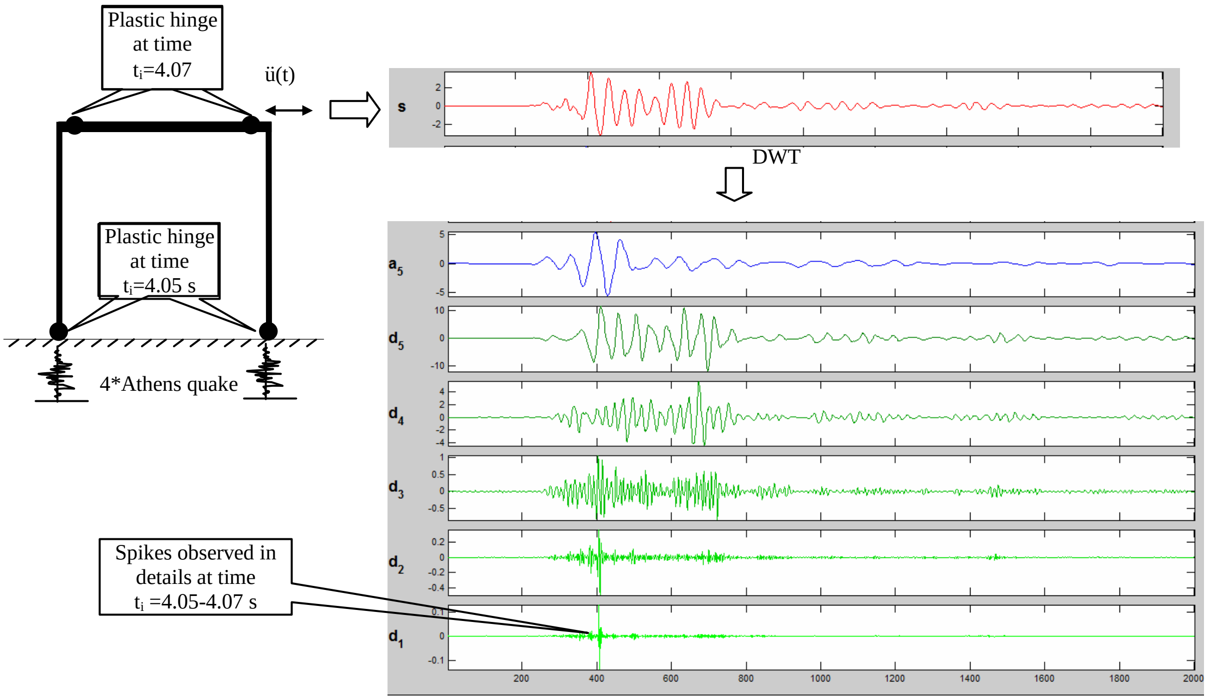


Figure 5. The examined frames, their load, geometrical and sections properties.

The two story frame subjected to the same earthquake signal and the results are shown in figure 8(a). No plastic hinge has occurred in the frame and no spikes were observed in the details of the response signal at the second floor. The earthquake is scaling up with the factor λ equal to 4 and the results are shown in figure 8(b). For this case the results from the non linear analysis show that plastic hinges at the beam of the first floor have occurred at the time t= 3.91 s, while, the plastic hinge at the column have occurred at time t= 4.22s. At the same times, the first two spikes have been observed in the details of the response signal as it is shown in figure 8(b).



(a)



(b)

Figure 6. The approximation a5, and the details d1-d5 of the response acceleration signal, s, at the top of the frame subjected to (a) Athens earthquake signal and (b) four times scale up Athens earthquake signal.

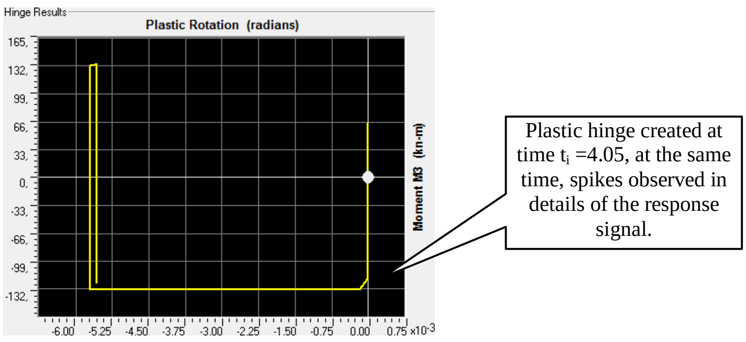
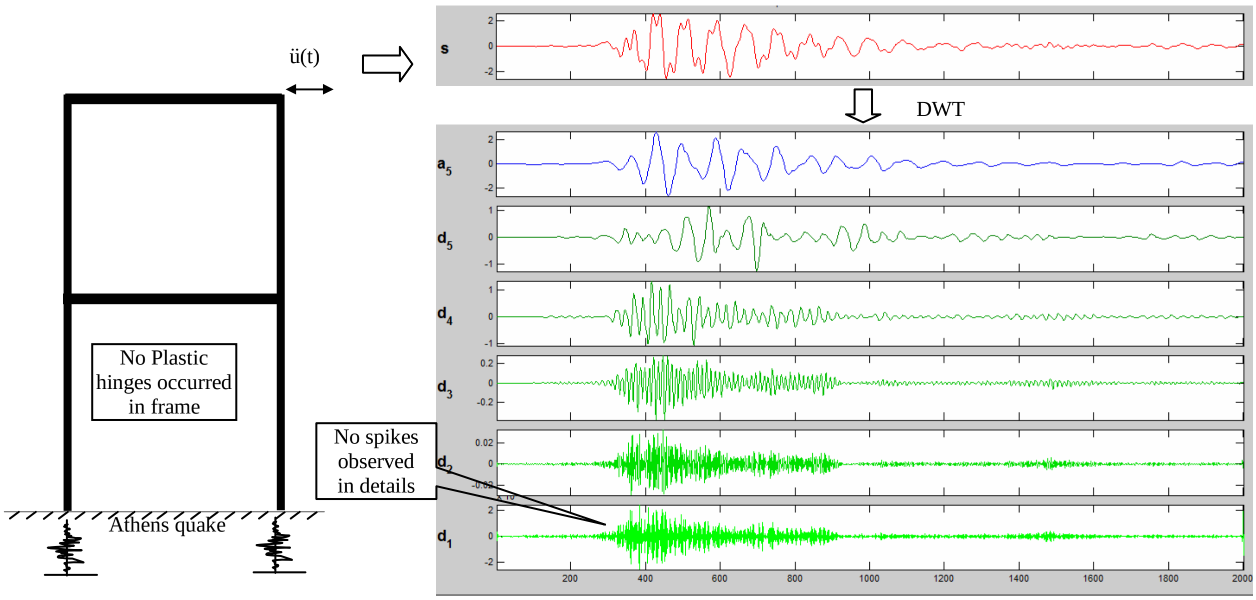
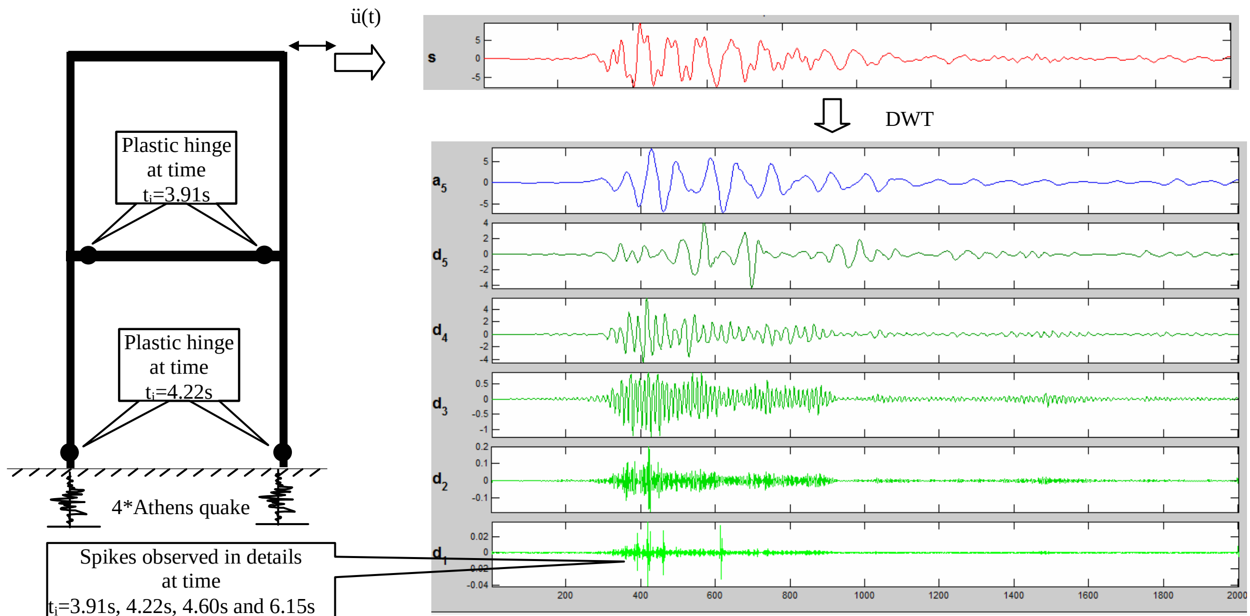


Figure 7. Moment-rotation hysteretic curve for base column of the single frame subjected to four time scale Athens earthquake record.

In the details of response signal it is also observed spikes at the times, t= 4.60s and t= 6.15s. These spikes correspond to the times when the hinges at the beam reach the yielding point for the third and fourth time as can be seen in figure 9. In this figure it is seems that the hinge starts from zero and have an elastic behavior until 3.91s where reach, for first time, the yield point. It remains in the post yield region until 3.98s and then rebounds, because of the change in direction of earthquake, and reaches again the yield point, for the second time, at 4.22s and remains in the post yield region until 4.30s. Then rebounds and reach, for the third time, the yielding point at time 4.60s, and remains in post yield region until 4.66s, then rebounds again and behaves elastically. Finally the hinge reach, for forth time, the yield point at time 6.15s, remains to the post yield region until the 6.22s and then rebounds and behave elastically until the end of the earthquake. All the times, where the plastic hinge reach the yielding point, (t= 3.91s, t= 4.22s, t= 4.60s, t= 6.15s), are observed as spikes in the wavelet analysis of the acceleration response signal in figure 8(b).



(a)



(b)

Figure 8. The approximation a5, and the details d1-d5 of the response acceleration signal, s, at the top of the frame subjected to (a) Athens earthquake signal and (b) four times, scale up, Athens earthquake signal.

The moment curvature curve for the base column is shown in figure 10. In this figure seems that the hinge reach the yield point at time 4.22s, which is the same time when the beam yields for second time. It is observed that when any structural element starts yielding for first time or rebounds and yields again for the subsequence times this phenomenon is imprinted as spikes in the wavelet analysis of the acceleration response of the signal.

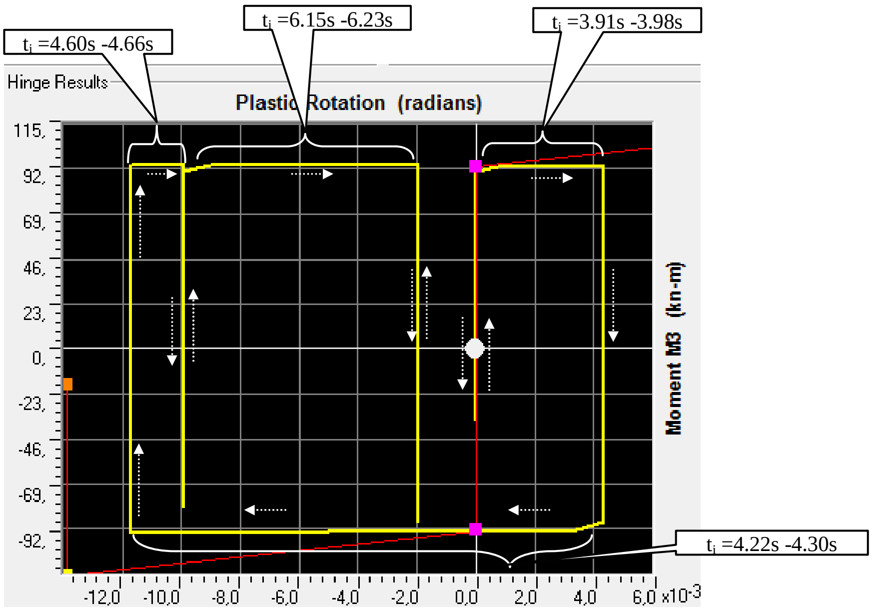


Figure 9. Moment-rotation hysteretic curve for fist floor beam of the two story frame subjected to four time scale Athens earthquake record.

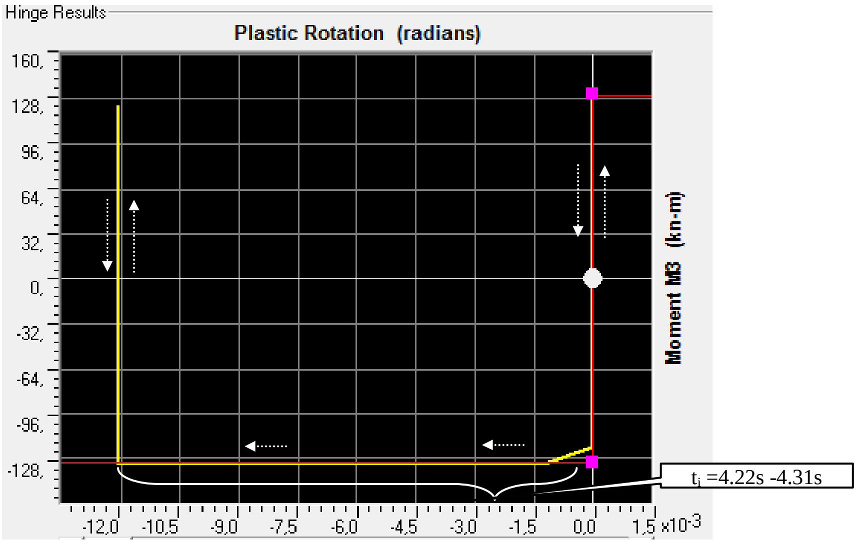


Figure 10. Moment-rotation hysteretic curve for base column of the two story frame subjected to four time scale Athens earthquake record.

Similar results are obtained in eight story building. In figure 11 are shown the locations of plastic hinges, (damage), the wavelet analysis of the response acceleration of the eighth floor of the frame subjected to Athens earthquake signal scaled with the factors 1 and 8 respectively. When the building subjected to the Athens earthquake signal no plastic hinges have appeared and no spikes in the details of the response signal were observed. When the earthquake was scaled up by a factor of 8, then plastic hinges, (damage), were created at the beams, between the time period 3.80s-4.11s. Plastic hinges were also created at the base columns at time 3.84s. In the details of the wavelet analysis of the response signal spikes are observed at the same period of the hinges creation.

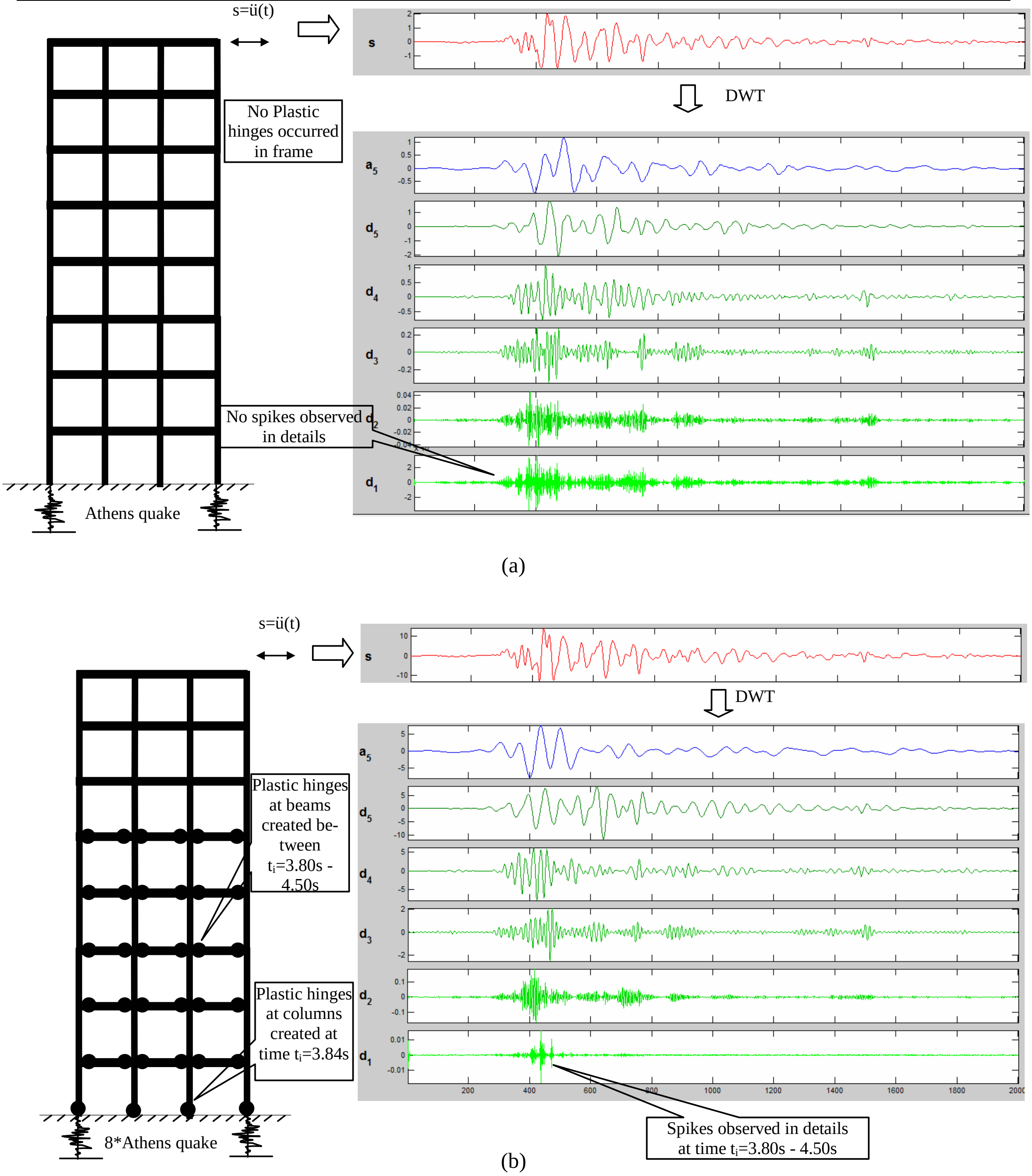


Figure 11. The approximation a5, and the details d1-d5 of the response acceleration signal, s, at the top of the frame subjected to (a) Athens earthquake signal and (b) eight times scale up Athens earthquake signal.

5 NOISE INFLUENCE

In the previous examples, the response data were obtained by the computer program without contain noise. In practice the presence of noise in measurement signals is unavoidable. In the work of Hera and Hou (2004) is shown the effect of noise to the wavelet approach. The effectiveness of the wavelet approach for structural health monitoring depends on the measurement noise level and the damage severity. The lower the level of noise is, the easier to detect the damage. As far as the damage level concerns, the higher the damage severity is, the easier to detect the damage by wavelet analysis. In this study the measurement noise was modelled as a Gaussian process with signal to noise ratio equal to 15%. A measurement noise was added to the acceleration response signal and then wavelet analysis was performed again. In order to detect spikes in the details of noise signal, the level of details and the order of the wavelet were increased. In this case, the level of details decomposition in the wavelet analysis was increased to twelve, (12), instant of five, (5), which was in the examples for signals without noise. The order of the wavelet which is used is also increased. For the noise signal the Daubechies wavelet of twelve order was used instant of fourth order which was used for the signals without noise.

Another factor that plays important role in the analysis of the noise signal is the sampling rate. The higher the sampling the better it is. In the numerical example the response signal without noise was obtained by non linear dynamic analysis where the sampling interval was 0.01 s. While, for the noise response signal was obtained by non linear dynamic analysis where, the sampling interval was decreased to 0.0001 s.

The wavelet analysis of the noise response acceleration signal, of the single story building is shown in figure 12. In this figure, are shown the approximation and the details of the response acceleration signal, s, contaminated with noise. In the detail level 9, a spike it is observed for time period between 4.00 to 4.10 s which is in agreement for the case of single story frame without noise.

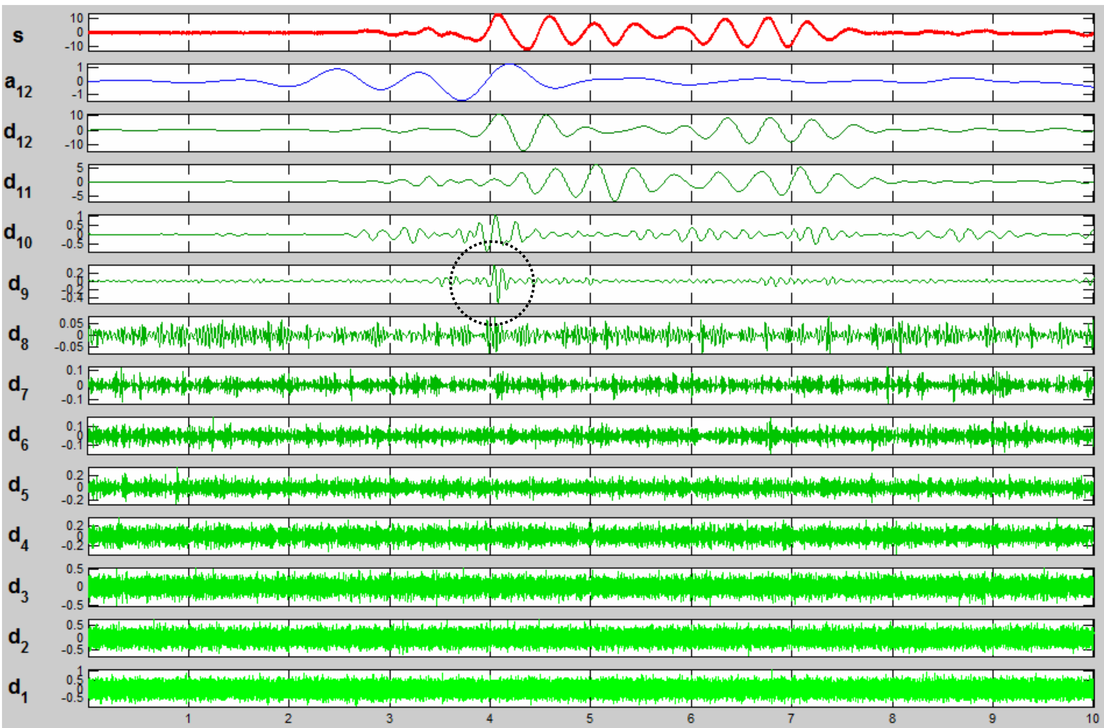


Figure 12. The approximation a12, and the details d1-d12 of the response acceleration signal, s, contaminated with noise, at the top of the single story frame subjected at four times scale up the Athens earthquake signal.

6 CONCLUSIONS

A discrete wavelet analysis for damage detection of frame structure subjected to earthquake excitation has been done. Wavelet analysis is a good tool to analyze the non-stationary dynamic behaviour of inelastic structures. It was shown that structural damage, which was introduced by non linear behaviour of structural elements, and the time that this occurred can be clearly detected by spikes in the details of discrete wavelet analysis of the response signal.

These spikes can also be observed in the case where the response signal contaminates noise. In order to detect the spikes of the noise signal the level of details and the order of the wavelet must be increased. The numerical results show the great promise of the wavelet approach for damage detection in structures subjected to earthquake excitation.

REFERENCES

[1] Kirmser PG. (1944). The effect of discontinuities of the natural frequency of beams. Proceedings American Society for Testing Materials, Philadelphia, PA. 44, 897-904

[2] Doebling, S. W., Farrar, C. R., Prime, M. B., and Shevitz, D. W. (1996). Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review. *Rep. LA-l3070-MS,* Los Alamos National Laboratory, Los Alamos, N.M.

[3] Carden, E.P. and Fanning, P. (2004). Vibration based condition monitoring: a review. Structural Health Monitoring, 3, 355–377.

[4] Humar, J., Bagchi, A. and Xu, H.P. (2006). Performance of vibration-based techniques for the identification of structural damage. Structural Health Monitoring, 5, 215–241.

[5] Khoo, L.M., Mantena, P.R. and Jadhav, P. (2004). Structural damage assessment using vibration modal analysis. Structural Health Monitoring, 3, 177–194.

[6] Chang, P.C., Flatau, A. and Liu, S.C. (2003). Review paper: health monitoring of civil engineering. Structural Health Monitoring, 2, 257–267.

[7] Wu, X., Ghabossi, J., and Garrett, J. H. (1992). Use of neural networks in detection of structural damage. Computers and Structures, 42(4), 649-659.

[8] Tsou, P., and Shen, M. H. H. (1994). Structural damage detection and identification using neural networks. American Institute of Aeronautics and Astronautics Journal (AIAA), 32(1), 176-183.

[9] Masri S.F., Nakamura M., Chassiakos A. G. and Caughey T. K. (1996). Neural network approach to detection of changes in structural parameters. Journal of engineering mechanics, 122 (4), 350-360.

[10] Vanik, M. W., and Beck, J. L. (1997). A Bayesian probabilistic approach to structural health monitoring. Proceedings, International Workshop on Structural Health Monitoring: Current Status and Perspectives, Stanford University, Stanford, CA. 140-151.

[11] M. Chandrashekhar and Ranjan Ganguli. (2009). Structural Damage Detection Using Modal Curvature and Fuzzy Logic. Structural Health Monitoring, 8; 267-282.

[12] Friswell M.I. and Mottershead J.E. (1995) Finite Element Model Updating in Structural Dynamics, Kluwer Academic Publishers Group

[13] Costas Papadimitriou, Evangelos Ntotsios **(**2009). Structural model updating using vibration measurements. Proceedings Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, ECCOMAS, COMPDYN, M. Papadrakakis, N.D. Lagaros, M. Fragiadakis (eds.), Rhodes, Greece, No CD 83

[14] Reigh, G. W., and Park, K. C. (1997). Localized system identification and structural health monitoring from vibration test data. Proceedings, American Institute of Aeronautics and Astronautics, AIAA, Reston, Va.

[15] Panagiotis Panetsos, Sergios Lambropoulos, Konstantinos Papadimitriou, Spyros Karamanos, Vassilios Lekidis, Christos Karakostas, (2006), Bridge health monitoring for egnatia odos bridge management system, Third European Workshop on Structural Health Monitoring, Organizers,Alfredo Guemes, Rafael Gallego Univ. Politecnica Madrid, Univ. Granada Granada, Spain.

[16] Marek Engelhardt Z Georgios E. Stavroulakis and Heinz Antes. (2006). Crack and flaw identification in elastodynamics using Kalman filter techniques, Computation Mechanics, 37; 249–265.

[17] Serdar Soyoz and Maria Q. Feng. (2008). Instantaneous damage detection of bridge structures and experimental verification. Structural Control Health Monitoring, 15;958–973.

[18] J. S. Sakellariou, S. D. Fassois. (2006). Stochastic output error vibration-based damage detection and assessment in structures under earthquake excitation. Journal of sound and vibration, 127; 1048-1067.

[19] Guido De Roeck and Edwin Reynders. (2009). Exploring the limits and extending the borders of structural health monitoring. Proceedings Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, COMPDYN, ECCOMAS, M. Papadrakakis, N.D. Lagaros, M. Fragiadakis (eds.), Rhodes, Greece, No CD 166.

[20] Alessio Medda and Victor DeBrunner, Near-field Sub-band Beamforming for Damage Detection in Bridges Structural Health Monitoring, 2009, 8, 313–329.

[21] Staszewski WJ. (1998). Structural and mechanical damage detection using wavelets. Shock Vibration Digest, 30(6);457–472.

[22] Newland D. E., (1993). An introduction to random vibrations, spectral and wavelet analysis. Longman Singapore publishers Pte Ltd.

[23] Reda Taha, M.M., Noureldin, A., Lucero, J.L. and Baca, T.J. (2006). Wavelet transform for structural health monitoring: a compendium of uses and features. Structural Health Monitoring, 5, 267–295.

[24] Masuda, A., Nakaoka, A., Sone, A., and Yamamoto, S. (1995). Health monitoring system of structures based on orthonormal wavelet transform. Seismic Engineering, 312; 161-167.

[25] Masuda, Y. Hashimoto and A. Sone. (2003). Experimental verification of wavelet-based structural damage identification method. Structural Health Monitoring From Diagnostics & Prognostics to Structural Health Management. Edited by F.K. Chang, DEStech Publications, pp.517-524.

[26] Hansang Kim, Hani Melhem. (2004). Damage detection of structures by wavelet analysis. Engineering Structures, 26; 347–362.

[27] Z. Hou, M. Noori, and R. St. Arnand. (2000). Wavelet-based approach for structural damage detection. Journal of Engineering Mechanics, 126(7); 677-683.

[28] Adriana Hera and Zhikun Hou. (2004). Application of Wavelet Approach for ASCE Structural Health Monitoring Benchmark Studies. ASCE Journal of Engineering Mechanics, 130(1); 96-104.

[29] Johnson, E. A., Lam, H. F., Katafygiotis, L. S., and Beck, J. L. (2004). Phase I IASC-ASCE structural health monitoring benchmark problem using simulated data. ASCE Journal Engineering Mechanics, 130(1); 3–15.

[30] Khatam, H., Golafshani, A.A., Beheshti-Aval, S.B. and Noori, M. (2007). Harmonic class loading for damage identification in beams using wavelet analysis. Structural Health Monitoring, 6, 67–80.

[31] M.A. Lotfollahi Yaghin and M.A. Hesari. (2008). Using Wavelet Analysis In Crack Detection at The Arch Concrete Dam Under Frequency Analysis With FEM. Research India Publications, Journal of Wavelet Theory and Applications, 2(1);61–81.

[32] Noh, H. Y., Nair, K., Lignos, D. G., Kiremidjian, A. (2009). Application of Wavelet Coefficient Energies of Stationary and Non-stationary Response Signals for Structural Damage Diagnosis. 7^{th} International Workshop on Structural Health Monitoring, Stanford, CA, September 9-11, 2009.

[33] K. Krishnan Nair, Anne S. Kiremidjian. (2009). Derivation of a Damage Sensitive Feature Using the Haar Wavelet Transform. ASME, Journal of Applied Mechanics, , 76(6); 610151-9.

[34] S. T.S. Bukkapatnam, J. M. Nichols, M. Seaver, S. T. Trickey and M. Hunter. (2005). A Wavelet-based, Distortion Energy Approach to Structural Health Monitoring, Structural Health Monitoring; 4; 247-258.

[35] S. Patsias and W. J. Staszewskiy. (2002). Damage Detection Using Optical Measurements and Wavelets, Structural Health Monitoring, 1; 2-22.

[36] www.csiberkeley.com.

[37] http://www.mathworks.com.