# ANALYSIS OF SEISMIC BEHAVIOR OF A BUILDING FROM TURKEY USING REAL EARTHQUAKE RECORDS

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## ABSTRACT

*This paper exhibits the application of signal processing techniques in the field of earthquake engineering. A moderately damaged reinforced-concrete building during the June 27, 1998 Ceyhan earthquake of Turkey, is analytically investigated by means of site assessed damages. Structural model of the building is established and structural responses are initially calculated by nonlinear dynamic analysis using raw (noisy) acceleration data. Later, noise is suppressed and baseline is eliminated using a commonly used technique, and structural computations are renewed. As an alternative to the commonly used technique, a wavelet-based method is employed and nonlinear dynamic analysis is repeated. Finally for each outcome, variations of significant structural responses such as top story displacement; base shear and moment-curvature relationships of structural members are computed and results are compared on the basis of best indication of the site-observed damages. The wavelet-based method performed promising results.*

## 1. INTRODUCTION

Determination of the structural safety of existing buildings subjected to earthquake loads is a major issue especially in the seismic prone regions of the world. Current earthquake resistant design codes of many countries enforce similar dynamic analysis procedures for evaluating the seismic performance of reinforced-concrete (RC) buildings, which basically depend on numerical modeling of the structural system under the effect of recorded ground motions [1-3]. However, two major objectives should be taken into consideration during processing the earthquake records: (i) the response of the instrument to the strong motions may create baseline (a shift from the DC value) which is needed to be corrected; (ii) random noise component should be suppressed. Otherwise these effects may cause misleading or physically unrealistic results. Commonly, earthquake engineers apply baseline correction to acceleration data and then use a band-pass filter in which the corner frequencies are decided depending on the physics of the related earthquake event. Since the displacement of the ground due to seismic shaking is computed by double integration of the digitally recorded accelerations in time [4, 5], due to the hysteretic phenomenon of the transducers, ground tilting or other instrumental effects, such computations usually cause shifts in the baseline of the time series resulting unrealistic permanent displacements. Note that the data should be processed properly such that real earthquake signals should be preserved during baseline correction and noise elimination [6]. On the other hand, band pass filters may result in significant phase distortions in the signal, which is not acceptable especially when the inelastic response spectra of a building are taken into account as illustrated in [7]. A wavelet-based technique can be remedy for such problems.

In this paper, a three story RC residential building which has suffered moderate damage during the June 27, 1998 *Ceyhan-Turkey* earthquake is analytically investigated by means of structural responses and the observed damage. Nonlinear dynamic analyses are carried out for the building by employing the raw form of the recorded earthquake acceleration-time series as an initial case. Later standard baseline correction and filtering is applied to the recorded acceleration signals and nonlinear structural responses are recalculated. As a third case, a wavelet-based procedure is implemented to the earthquake records and similar computations are repeated. Finally, structural demands obtained under the effects of these three earthquake signals are compared considering the site-observed damages in the building.

In section 2 strong motion records and data processing techniques are explained. Modeling and the description of the building are provided in section 3. Section 4 includes the nonlinear dynamic analyses for the building and the paper is concluded in section 5.

## 2. STRONG MOTION RECORDS AND PROCESSING PROCEDURES

The magnitude $M_L$=5.9 *Ceyhan* earthquake of Turkey shook the province of *Adana* and the surroundings on June 27, 1998. The strong motion was recorded by many accelerograms within the strong motion network of Turkey. Fig. 1 shows the acceleration-time series of the east-west component of the earthquake recorded in *Ceyhan-Turkey* as well as the velocity and displacement time series calculated by one and double integration in time. Significant amounts of baseline offsets and permanent deformations up to 1 m at the end of the event can clearly be seen in the velocity and displacement time series of raw motions. Therefore, a baseline correction and noise removal process is needed.

### 2.1 Band-pass Filtering

Pre-processing started by removing the mean of the acceleration signal. Then, a fourth order Butterworth band-pass filter with corner frequencies of $f_{HP}$=0.75Hz and $f_{LP}$=60Hz are applied to the signal so that the permanent deformations are isolated. Fig. 2 shows the processed version of ground motions. The permanent deformation in displacement data which was visible in previous figure is corrected after band-pass filtering.

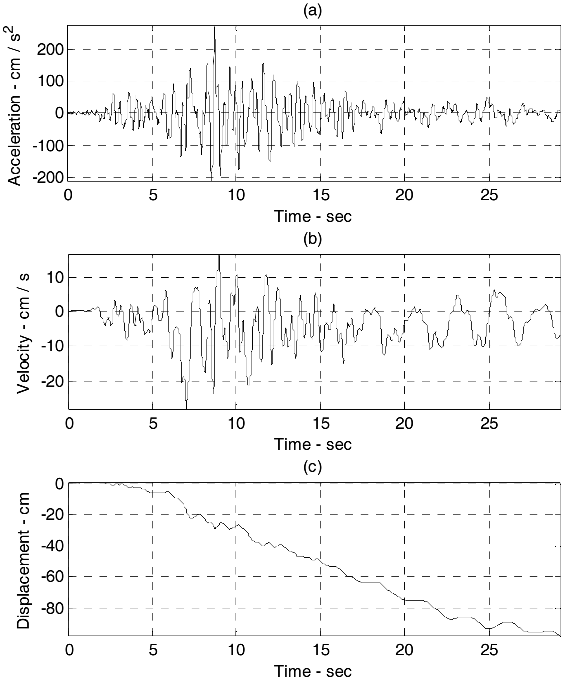

Figure 1 – Original earthquake record; (a) Acceleration, (b) Velocity, (a) Displacement.

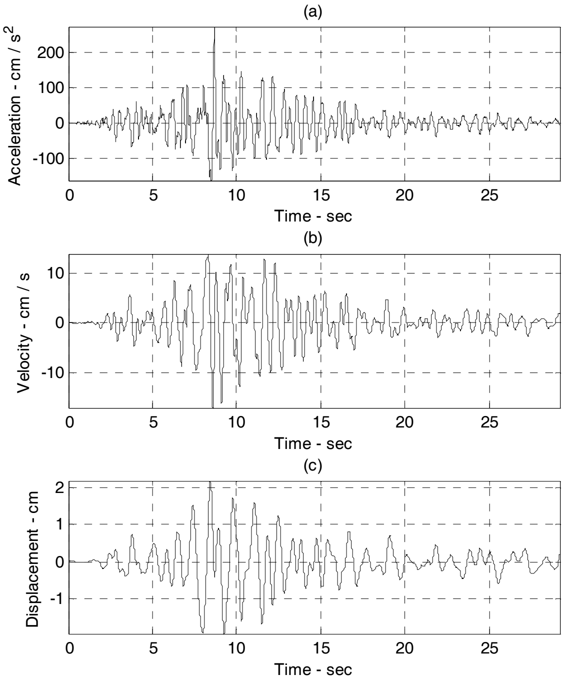

Figure 2 – Band-pass filtered correction: (a) Acceleration, (b) Velocity, (a) Displacement.

### 2.2 Wavelet-based Baseline Correction and Noise Reduction

Recently, Wavelet Transform (WT)-based baseline corrections are reported in literature [8-10 ]. WT can be considered as a filter bank of band-pass filters which decomposes the signal into approximation and detail coefficient utilizing different frequency regions [11]. Setting the highest scale approximation and detail coefficients to zero removes monotonically varying baseline since these coefficients correspond to the lowest frequency where most of the baseline wandering occurs. Similarly, setting the highest-frequency coefficients to zero provides de-noising.

In this study, translation invariant stationary discrete WT with Daubechies-5 wavelet is used [12]. Original acceleration signal is decomposed into approximation and detail coefficients up to 9 scales. The approximation coefficients of the last scale represent the coarsest, low-frequency components of the signal which were assumed to correspond to the baseline wanderings. After the correction, one and double time integration of the acceleration signal provides velocity and displacement that have zero values at the end of the earthquake event. This is consistent with the nature of an ending motion. Fig. 3 shows the WT-based processed acceleration data and its one and double integrations.

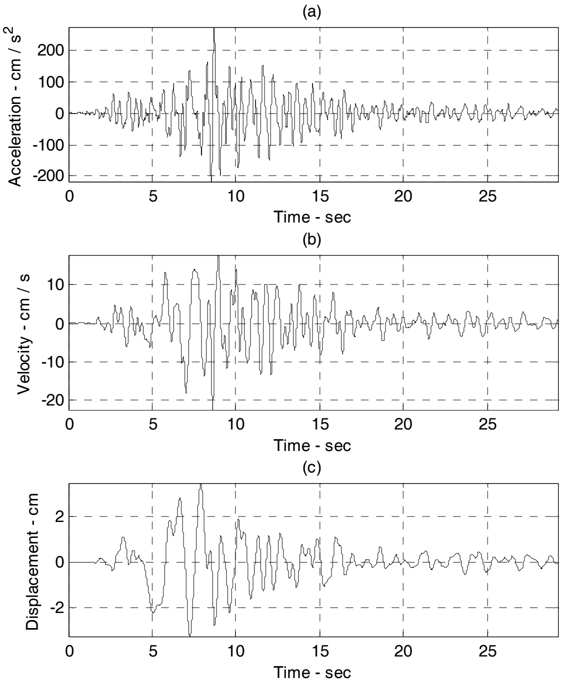

Figure 3 – WT-based correction: (a) Acceleration, (b) Velocity, (a) Displacement.

Although, the results are similar to the classical band-pass filtering case, as seen in Fig. 4, the wavelet-based processed signal follows the original data closer without any phase distortion. Plus, since WT does not require stationarity, it is appropriate to use WT-based method for earthquake data (which is a typical non-stationary signal).

The power spectra (using Welch method) of the original, band-pass filtered and WT-based processed data are given in Fig. 5 for visual evaluation. Note that while the classical method requires several trials and specialist intervention which is time-consuming and subjective, WT-based method requires simple manipulations on a few numbers of approximation and detailed coefficients which can be automated.

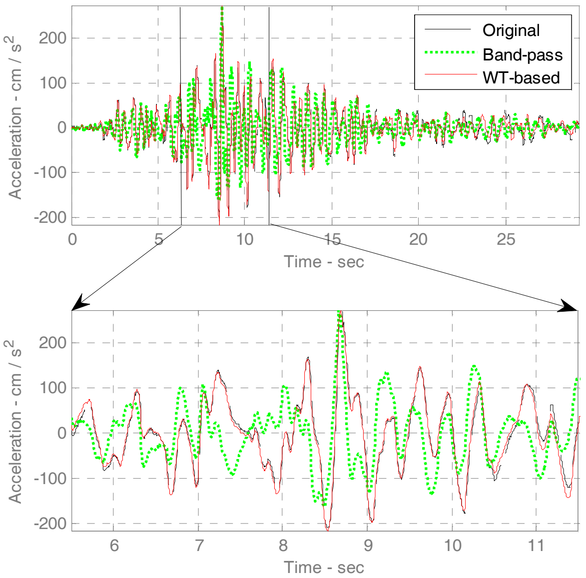

Figure 4 – Comparison in time; original, band-passed (BP), and WT-based processed data (top figure) and their zoomed version (bottom figure) to show phase distortions.

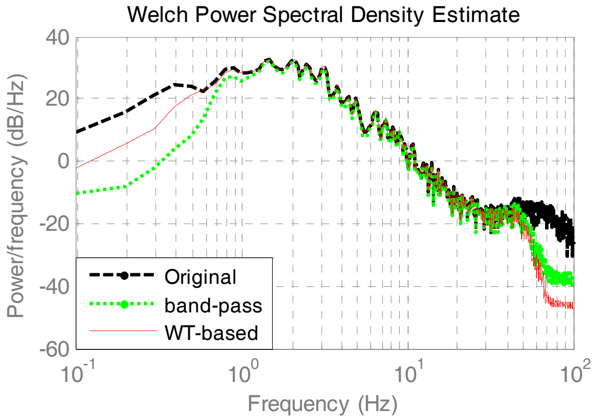

Figure 5 – The power spectra of the original (dash), band-pass filtered (dot) and WT-based processed (solid) data.

## 3. DESCRIPTION OF THE BUILDING

### 3.1. General Characteristics of the Building

A three story RC residential building having 2.7m of height at each stories, which has suffered moderate damage in *Ceyhan* city is analytically investigated by means of structural responses and the observed damage. Based on lab experiments, the structural materials are determined as C10 (characteristic compressive strength $f_{ck}$=9.4 N/mm$^2$ concrete and S220 (characteristic yield strength $f_{yk}$=220 N/mm$^2$) type of structural steel. Structural system of the building consists of regular RC frames infilled with hollow clay brick with 15cm thickness. Beams and columns have the dimensions of 20/30 cm/cm and 15cm×35cm respectively. There was no confinement of transverse reinforcement neither in beams nor in columns. Floors are constructed with one- or two-way slabs with a 10cm of thickness. The structural model of the building is given Fig. 6.

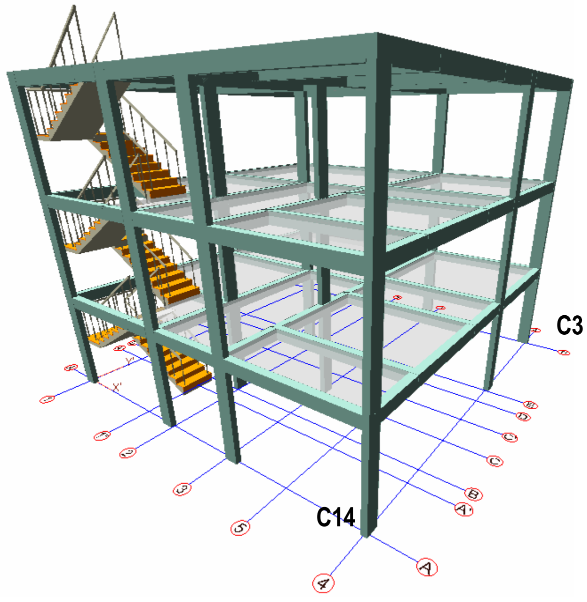

Figure 6 – Structural model of the building.

### 3.2. Modelling of the Structural System

Structural system, which is established in DRAIN-2DX computer program [13], is modeled as planar frames consisting of nonlinear elements connected at nodes of beams and columns. It is assumed that, stiffness-degrading hysteretic model represents the nonlinear behavior of structural members under the effect of dynamic loading. Frames are connected to each other with elastic tension/compression link elements representing the rigid diaphragm effect. The nonlinear characteristics of columns and beams are calculated considering the actual amounts of rebars. Non-structural infill walls' contribution in the structural responses is also considered by their introduction into the structural model as defined in [14]. Modulus of elasticity for infill walls and concrete are used as 1000 N/mm$^2$ for hollow clay bricks and 24000 N/mm$^2$ for C10, respectively.

The numerical solution of the dynamic equation of motion

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = -\mathbf{M}\ddot{\mathbf{u}}_{\mathbf{g}} \qquad (1)$$

will result in obtaining the structural response of the system by means of the structural deformations in which **M** is the mass matrix; **C** is the damping matrix; **K** is the stiffness matrix; **u** is the displacement vector; $\dot{\mathbf{u}}$ and $\ddot{\mathbf{u}}$ are the time derivatives of the displacement vector representing velocity and acceleration respectively and $\ddot{\mathbf{u}}_{\mathbf{g}}$ is the vector of ground accelerations.

According to the reconnaissance team's damage assessment report, there were diagonal shear cracks and spalling off concrete in column C3; shear cracks in the nodal zone of column C14; severe X-type of shear cracks in the brick walls on D/1~2, 2/B~D and 3/E~F building axes and permanent deformations in the staircase. The building neither benefited an engineering service during the construction stage nor followed any version of the earthquake code regulations.

## 4. NONLINEAR DYNAMIC ANALYSES

Employing the original (Raw) records, BP filtered motions and WT-based processed acceleration-time signals, nonlinear dynamic analyses are carried out for the building. Table 1 shows a summary of the structural responses of the building and the demands of columns C3 and C14, where $U_{top}$ is the absolute maximum roof displacement; $V_b$ is the absolute maximum base shear of the building; $M_y$ and $\chi_y$ are the yielding moment capacity and corresponding curvature and $M_{max}$ and $\chi_{max}$ are the maximum bending moment and corresponding curvature demands, respectively.

Table 1 – Comparison of the structural responses utilizing the original records (Raw), band-pass filtered motions (BP) and wavelet-based processed acceleration signals (WT).

| | $U_{top}$ | $V_b$ | C3 | | | | C14 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $M_y$ | $\chi_y$ | $M_{max}$ | $\chi_{max}$ | $M_y$ | $\chi_y$ | $M_{max}$ | $\chi_{max}$ |
| | cm | kN | kNm | $10^{-2}$/m | kNm | $10^{-2}$/m | kNm | $10^{-2}$/m | kNm | $10^{-2}$/m |
| Raw | 6.09 | 144.6 | 22.96 | 0.76 | 7.95 | 5.5 | 10.81 | 2.9 | 24.63 | 6.1 |
| BP | 4.68 | 125.2 | 22.96 | 0.76 | 5.87 | 3.4 | 10.81 | 2.9 | 21.20 | 3.9 |
| WT | 5.78 | 143.6 | 22.96 | 0.76 | 7.91 | 5.5 | 10.81 | 2.9 | 25.11 | 6.2 |

When the shear force resisting capacity of the entire building of 132.3 kN is considered, it is analytically shown that Raw and WT motions demand more than the capacity, which is consistent with the observed damage. The BP motion seems to give no damage to the structure. Furthermore, as shown in Fig. 7, top-story displacement values are extremely larger for each motion than the code limit, which is 2.03cm at roof level.

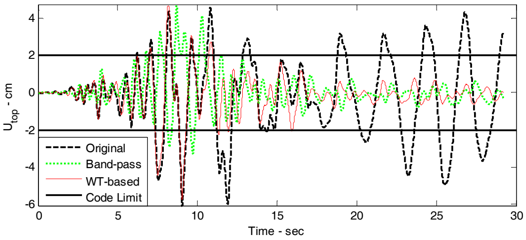

Figure 7 – Comparison of the variation of roof displacement.

When the structural demands for C3 is evaluated, it is understood that none of the motions cause yielding in terms of bending moment, however yielding occurs depending on the extreme amount of rotations; consistent with field observations. The C14 column is suffering damage due to both exceeding the yielding moment and curvature limits. From the numerical values, it might be expressed that wave forms and phases are successfully captured in WT procedure when compared to the original records. However, the phase distortions occurring during the BP processing, affect the nonlinear analysis results yielding almost 40% less curvature demands.

## 5. CONCLUSIONS

The effects of the noise content in the recorded earthquake acceleration time series on the structural responses are investigated in this paper. Two different processing procedures are performed on the EW component record of June 27, 1998 *Ceyhan-Turkey* earthquake and the obtained time series are applied to the structural model of a moderately damaged building during the event. It is shown that the first processing technique (BP) has successfully handled the baseline shift problem and removed the high frequency noise content however caused phase distortions which led unrealistic structural results when compared to the actual damage observed within the building. When the second processing technique (WT) is considered site-assessed damages are captured more realistically and the characteristics of the strong motion record are preserved. It is concluded that the WT procedure gives promising results and should be applied to other earthquake records which reflect different characteristics of site and source properties.

## REFERENCES

[1] Ministry of Public Works and Settlement, “Turkish earthquake resistant design code,” Ankara, Turkey, 2007.

[2] European Committee for Standardisation, “Eurocode 8: design of structures for earthquake resistance,” Brussels, Belgium, 1998.

[3] Applied Technology Council, “Seismic evaluation and retrofit of concrete buildings,” Report No: ATC-40, Redwood City, CA, USA, 1996.

[4] D. Boore, “Effect of baseline corrections on displacements and response spectra for several recording of the 1999 Chi-Chi, Taiwan earthquake,” *Bulletin of the Seismological Society of America*, vol. 91, pp.1199–1211, 2001.

[5] W. A. Chao, Y.M. Wu and L. Zhao, “An automatic scheme for baseline correction of strong-motion records in coseismic deformation determination,” *Journal of Seismology*, vol. 14(3), pp.495-504, 2010.

[6] M. D. Trifunac, “Zero baseline correction of strong-motion accelerograms,” *Bulletin of the Seismological Society of America*, vol. 61(5), pp. 1201-1211, 1971.

[7] D. M. Boore and S. Akkar, “Effect of causal and acausal filters on elastic and inelastic response spectra,” *Earthquake Eng. and Structural Dynamics,* vol.32, pp. 1729-1748, 2003.

[8] O. Sayadi, M. B. Shamsollahi, “ECG baseline correction with adaptive bionic wavelet transform,” *9th Int. Symp. on Signal Proc. and Its App.*, Sharjah, UAE, 12-15 Feb. 2007.

[9] A. A. Chanerley, N. A. Alexander, B. Halldorsson, R. Sigbjornsson, R. Perryman, “Baseline correction made easier using an automated method based on the wavelet transform,” *9th U.S. National and 10th Canadian Conference on Earthquake Engineering*, Toronto, Canada, 25-29 Jul. 2010.

[10] S. Rampp, J. Prell, H. Thielemann, S. Posh, C. Strauss, J. Romstock, “Baseline correction of intraoperative electromyography using discrete wavelet transform,” *J. of Clinical Monitoring and Comp.*, vol. 21, pp. 219-226, 2007.

[11] S. Mallat, *A Wavelet Tour of Signal Processing* (2nd Ed.). Academic Press, CA, USA, 1998.

[12] D. L. Donoho, “De-noising by soft thresholding,” *IEEE Trans. Inf. Theory*, vol. 34, no.3, pp. 613-627, 1995.

[13] V. Prakash, G.H. Powell and S. Campbell, *DRAIN-2DX Base Program Description and User Guide*. SEMM Report, UCB/SEMM-93/17, U. of California-Berkeley, USA, 1993.

[14] G. Al-Chaar and G. Lamb, *Design of Fiber-Reinforced Polymer Materials for Seismic Rehabilitation of Infilled Concrete Structures*. ERDC/CERL TR-02-33, US Army Corps of Engineers, USA, 2002.