Damage Evolution for some R/C Structures Subjected to Successive Earthquake Ground Motions

F. Acar
Ministry of Environment and Urban Development, Ankara, Turkey

15 WCEE
LISBOA 2012

SUMMARY:
A series of large earthquakes of magnitudes exceeding 7 (M_w) struck the Marmara Region, Turkey, during a nearly three-month period of time, in 1999. The distance between the epicenters was about 110 km. These repeated events provide a unique possibility to verify the effect of prior earthquake damage on seismic performance of R/C structures to future earthquakes. This study mainly addresses the problem of estimating the prior earthquake damage on the post-earthquake response of R/C structures. Inelastic time history and damage analyses of numerous SDOF and MDOF frame type structural systems have been carried out using synthetic accelerograms to determine whether the loading history has an effect on damage and dissipated hysteretic energy. The analysis tool employed for this purpose is the package named IDARC2D. It is observed that both damage progression and cumulative hysteretic energy dissipated along a path seem to depend on the number and amplitude of cycles constituting the path. However, final damage and accumulated hysteretic energy dissipated along a loading path are independent of the ordering of the same number and amplitude cycles along the path. There is a nonlinear relationship between the earthquake excitation intensity and damage attained in the end.

Keywords: synthetic ground motion, successive earthquakes, damage analysis, prior earthquake damage

1. INTRODUCTION

In 1999, two destructive successive ground shaking, with magnitudes exceeding 7.0, have been experienced nearly 3 months apart in the north-western region of a tectonically active country, Turkey. The distance between the epicenters of the successive ground motions, occurred on Aug. 17 and Nov. 12, 1999 in Marmara region, is about 110 km. Similarly, in a shorter period of time, between Sept. 21 and Sept. 26, 1999, Chi-Chi, Taiwan exposed to three major successive earthquakes of magnitudes (M_w) 7.6, 6.2 and 6.3, respectively, causing 2100 deaths with 8000 people injured (Seno, 1999). And lately, on Oct. 23 and Nov. 9, 2011, the eastern part of Turkey, Van and Edremit, experienced two destructive earthquakes of magnitudes (M_w) 7.2 and 5.6, respectively.

It was the first time that such strong successive earthquakes hit structures, in certain cities producing either accumulated extensive damage or collapse. These unusual building failures observed in Marmara region, especially surroundings of Düzce and Bolu cities after these two major successive earthquakes attracted special attention of earthquake engineering community (Sözen, 2000; Sucuoğlu and Yılmaz, 2001). It is stated that there may be no linear relation between the earthquake intensity and damage (Sözen, 2000). It is worthwhile to note that this event is a benchmark to shed light on accumulation of damage. The motivation of this study arisen from the observed unusual building failures in these successive earthquakes.

2. EVOLUTION OF SEISMIC DAMAGE BY SUCCESSIVE IMPACTS

The accumulation of damage may lead to collapse during the later successive events. But how the damage from each of the successive events could be predicted and what intensity of these events may cause to substantial increase in the following earthquake damage? Prior earthquake of what intensity substantially influences the damage sustained during the following major earthquake is another question. For this purpose effect of loading history on damage and dissipated hysteretic energy is investigated.

To accomplish this purpose, quasistatic, inelastic time history and damage analyses of SDOF systems have been conducted. Then, the inelastic time history and damage analyses of a five-storey building are performed. The building had experienced two major destructive earthquakes, namely Aug. 17, 1999 Marmara and Nov. 12, 1999 Düzce earthquakes. To assess the effects in the damage caused by the prior earthquake, these analyses have been carried out using the synthetic accelerograms comprised of base input provided by these two recorded successive ground motions. The analysis tool employed for this purpose is the package named IDARC2D, which use a slightly modified form of fatigue based Park and Ang (1985) damage index. The damage model incorporated in IDARC is composed of two parts: deformation and strength. The deformation damage is comprised of the first term, whereas the strength damage stems from the energy term of the model.

$$D = \frac{\phi_m - \phi_y}{\phi_u - \phi_y} + \beta \frac{\int dE}{M_y \phi_u} \tag{2.1}$$

where ϕ_m is the maximum curvature attained during the loading history, ϕ_u is the ultimate curvature capacity of the section, ϕ_y is the yield curvature, (β) is a model constant parameter, M_y is the yield moment and E_h is the dissipated energy in the section. Then, the biggest damage index of the end sections of a component is selected as the damage index of the component (Valles et al, 1996). Calibration of the damage index was performed by Stone and Taylor (1993), in which $0.11 \leq D < 0.4$ refers to repairable damage.

3. PRIOR DAMAGE EFFECTS ON THE RESPONSE OF SDOF SYSTEMS

It can be estimated that, the loading history may play vital role in the assessment of seismic performance and damage. This purpose has been accomplished through the use of (i) inelastic displacement reversals of various constant amplitudes, (ii) variable amplitude inelastic displacement reversals with increasing and decreasing order in the quasistatic analyses of SDOF systems. In these analyses, the test model of a typical beam specimen tested by Erberik is subjected to the same total displacement histories in which the sequence of the applied displacement altered without introducing additional cycles or altering amplitudes (Erberik, 2001).

Explicitly, the actual response of structural systems can be obtained by inelastic time history analysis. Hence, to assess the effects of load paths on damage of structural systems subjected to successive earthquakes, an inelastic time history and damage analyses of SDOF systems are carried out using a total of four real earthquake records. Each synthetic ground motions comprises one of the ground motion acceleration records and preceded or followed by its various times amplitude-compressed record acting as a pre or post-event. The sequence of the records constituting the path is altered so as to force the structural system to follow a different loading history. These analyses are performed using a cantilever column specimen tested by Pujol (2002).

3.1. SDOF Systems Subjected To Constant And Variable Amplitude Loadings

Seismic loads induce several inelastic displacement reversals at relatively large ductility levels combined with many smaller cycles. The nonlinear quasi-static and damage analyses of the same beam specimen have been performed to evaluate whether the load path has an effect on the total damage. The main variable in the quasistatic analyses was the amplitude of the displacement reversals. In the analyses, the models are designated using two letters and several numerals: the letter 'CH' or 'VH' is the abbreviation of the imposed loading histories of 'Constant amplitude' or 'Variable amplitude'. The numerals 1, 2 and 3 indicate the cycles of 10mm, 20mm and 30mm amplitudes, respectively. The beam specimens suffered severe damages during the tests (Erberik and Sucuoğlu, 2004). Therefore, the stiffness degradation, strength deterioration and pinching parameter values considered are 7.0, 0.7 and 5.0, respectively.

Each constant amplitude loading pattern, labelled as CH-111, CH-222 and CH-333, contained three subsequent cycles with 10mm, 20mm and 30mm amplitudes. The loading histories, hysteretic relationships and progression of the total damage are plotted in Figure 3.1.

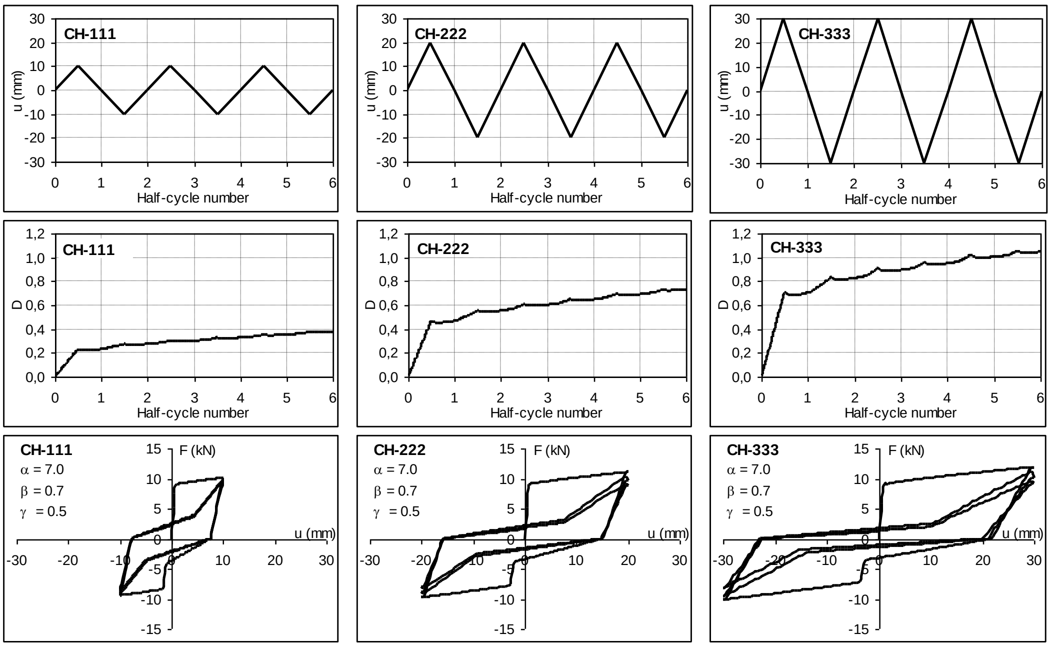

Figure 3.1. Constant amplitude loading histories, damage curves and force-displacement relationships

The variable loading histories considered in these analyses contain variably sequenced cycles of the same number and amplitude. The loading paths are consisting of three cycles of 10mm, 20mm and 30mm amplitudes sequenced in increasing, decreasing or mixed order. The models labeled in accordance with order of cycles as VH-123, VH-132 and VH-321 for which the numerals referring to the size of the cycle amplitudes.

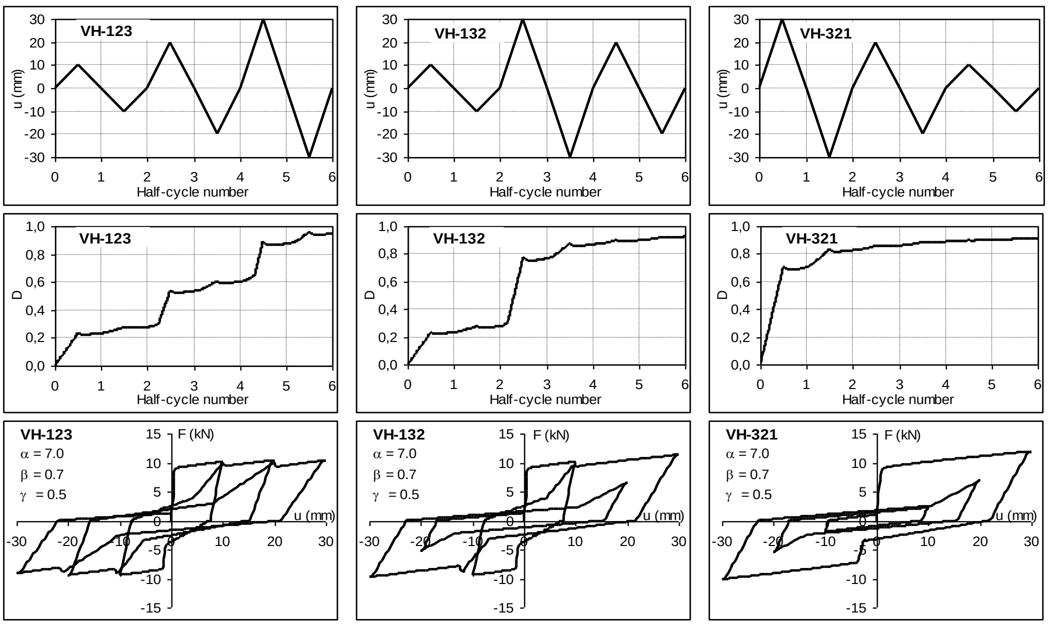

Figure 3.2. Variable-amplitude loading histories, damage curves and force-displacement relationships

Loading histories, corresponding damage curves and force-displacement relationships are presented in Figure 3.2. The comparison of the damage curves indicate that, despite variably ordering of the cycles in the histories, the discrepancies revealed between the total damage level achieved at the end of the analyses are negligibly small. The analytical evidence indicates the independency of the cumulative energy dissipation and total damage from the order of amplitudes along displacement paths consisting of the same number and amplitude of cycles.

3.2. SDOF Systems Subjected To Variable Amplitude Cyclic Loading Generated From Earthquake Response

Structures are subjected to variable-amplitude cyclic loading, and the response varied from cycle to cycle throughout the earthquake. To imitate the actual seismic behavior of the structural components imposed by successive ground motions, the quasi-static analyses of the specimen are performed under the simulated displacement response of ground motions with the prior earthquake and successive earthquake. Two specimens (VH-2 and VH-3) were subjected to variable-amplitude displacement histories, which were generated from the displacement responses of nonlinear, stiffness degrading SDOF systems under recorded ground motions. VH-2 and VH-3 loading patterns were obtained from the SDOF displacement response to 12 Nov. 1999 Düzce earthquake, Bolu-L comp (Erberik, 2001).

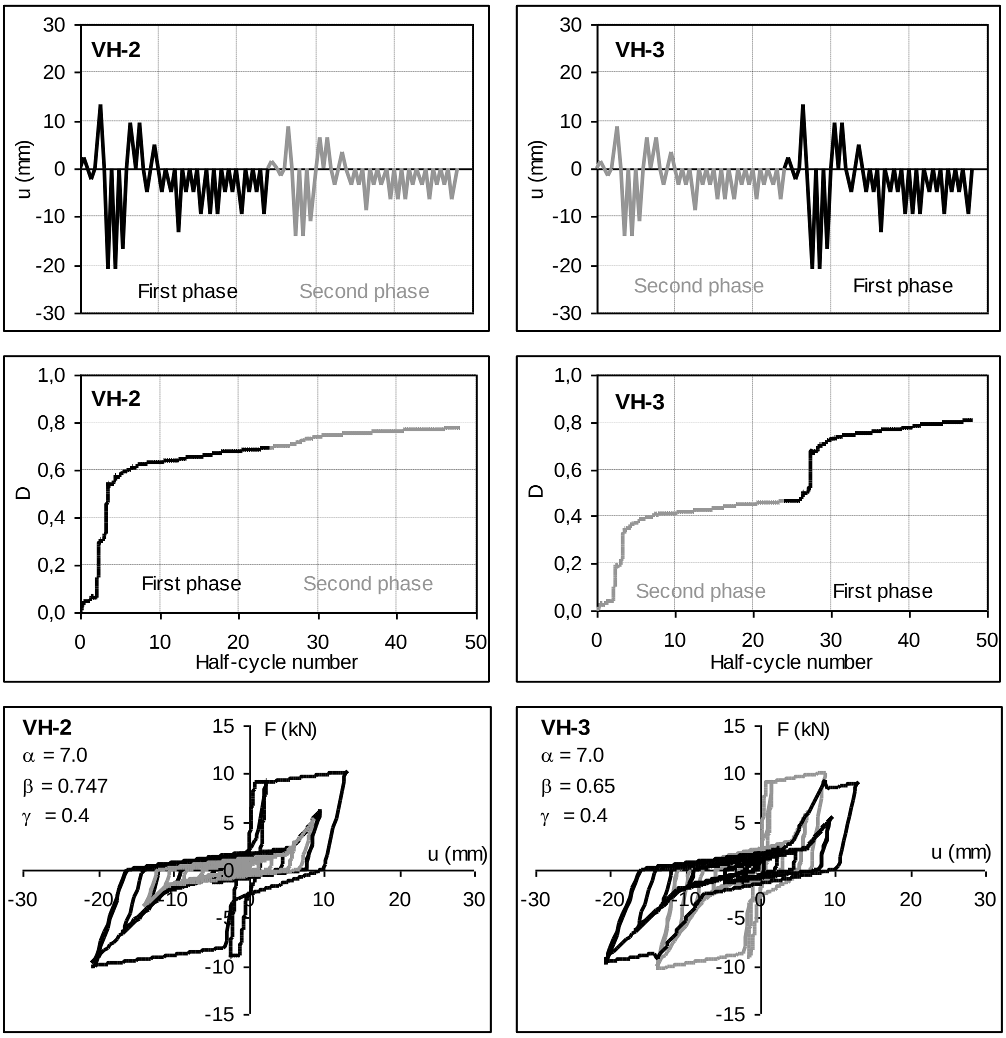

Figure 3.3. Loading histories, damage curves, force-displacement relationships of specimens VH-2 and VH-3

The imposed loading histories and analytical damage curves and force-displacement relationships of the specimen models are shown in Figure 3.3. The variation in displacement given by dark trace is labeled as 'first phase'. In the displacement histories, the gray part labeled as 'second phase' corresponding to the pre and post-event, was obtained by scaling the strong part of the displacement amplitude by two-thirds. The gray part is considered to act as a pre and post-event to the main shock.

Table 3.1. Total Damage And Total Damage Values For The Specimens VH-2 And VH-3

Loading Pattern	Damage Index							**E_{hyst} (kNmm)**
	$(D_T)_{def}$ (1)	$(D_T)_{str}$ (2)	**D_1 (3)**	**D_2 (4)**	**D_T (1+2) or (3+4)**	**D_2 / D_1 (%)**	**D_2 / D_T (%)**	
VH-2	0.372	0.405	0.696	0.081	0.777	11.6	10.4	750
VH-3	0.372	0.437	0.344	0.465	0.809	74.0	57.5	929

Graphical representation of the damage progression, plotted in Figure 3.3 indicate that the damage sustained by the second phase of the loading history, VH-2, is considerably small compared to the damage stemming from the first phase of the history. The numerical values of the first phase damage, second phase damage and total damage are shown in Table 3.1. The ratios of the second phase damage (D_2) to the preceding first phase damage (D_1) and total damage (D_T) are 11.6 percent and 10.4 percent, respectively. In other words the contribution of the damage raised from the second phase to the total damage is considerably small, and remain around one-tenth of the total.

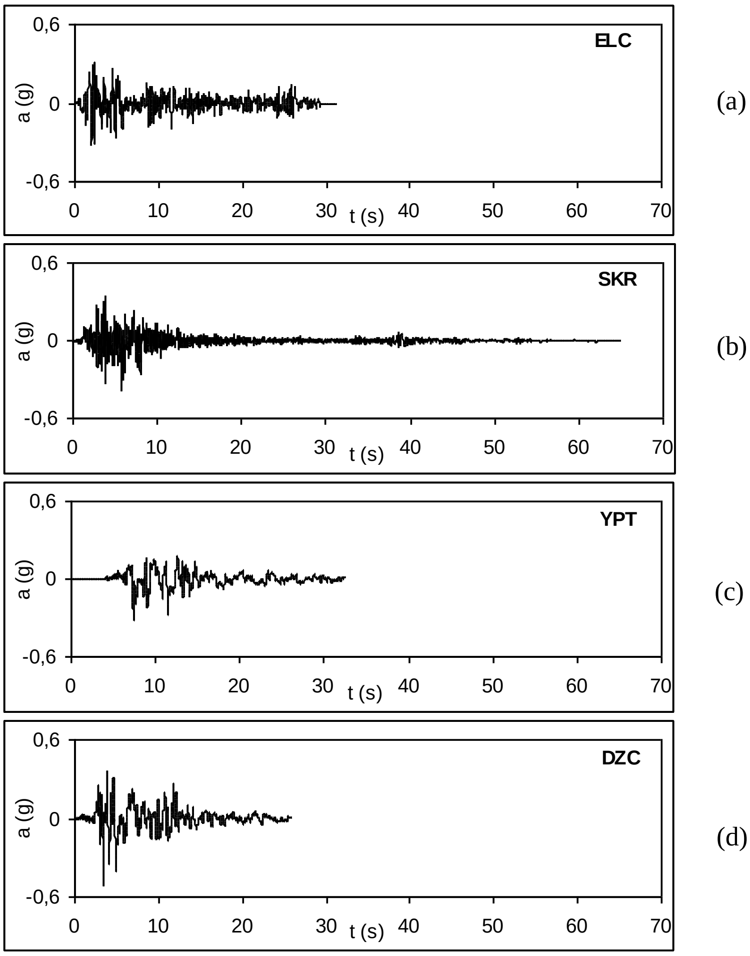

Figure 3.4. The ground motions used in this study. **a)** El Centro 1940, NS comp., **b)** Aug. 17, 1999 Marmara Earthquake, Sakarya Station, EW comp., **c)** Aug. 17, 1999 Marmara Earthquake, Yarımca Petrochemical Complex Station, NS comp., **d)** Nov. 12, 1999 Düzce Earthquake, Düzce Station, NS comp.

3.3. SDOF Systems Subjected To Successive Earthquake Ground Motions

Inelastic time history and damage analyses of SDOF systems subjected to generated synthetic accelerograms. Four randomly selected ground motions are employed to accomplish this purpose. The first one is the north-south component of the ground motion recorded at El Centro, in 1940 (Fig. 3.4).

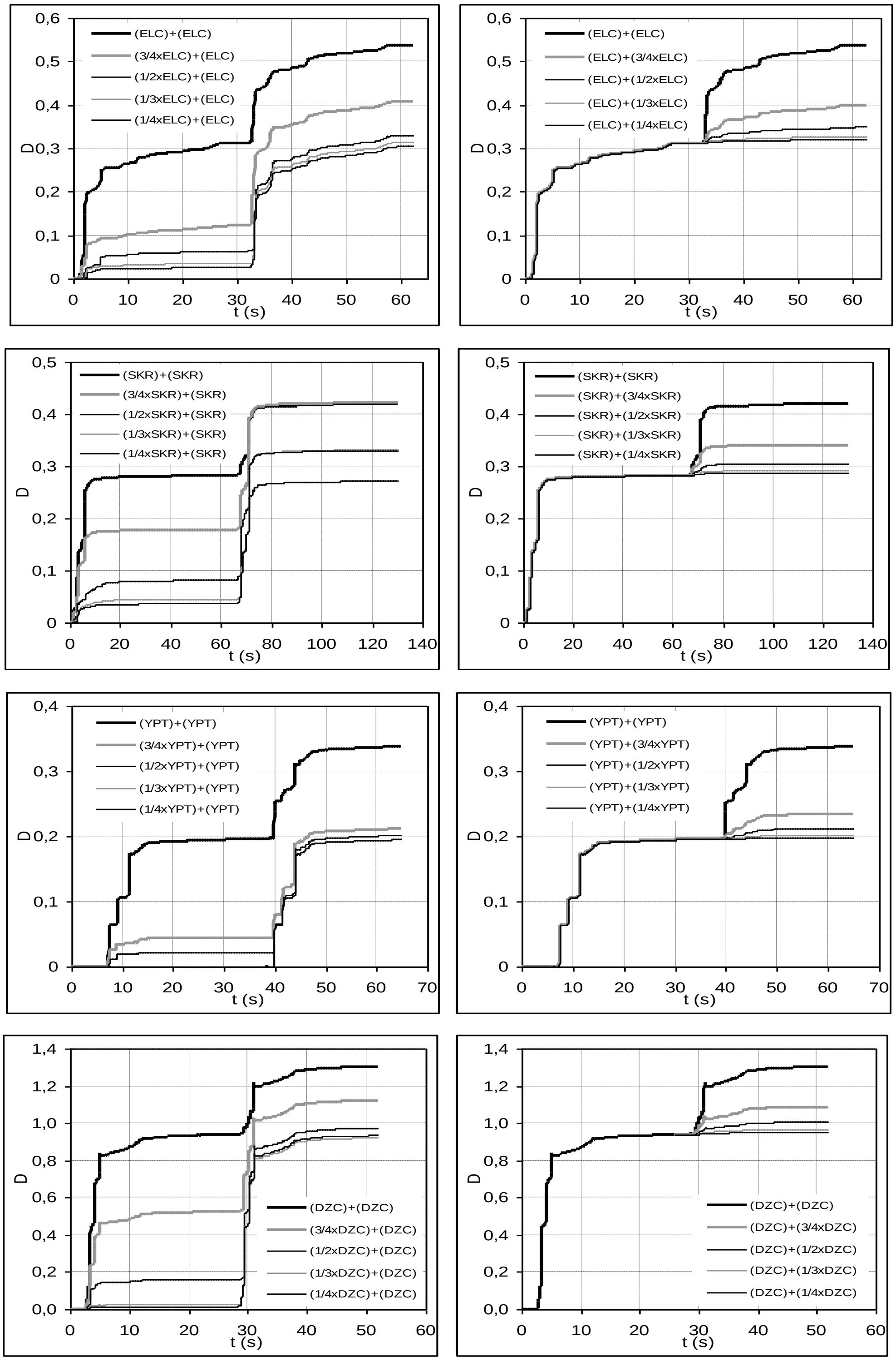

Figure 3.5. Damage curves for a SDOF subjected to the synthetic acceleration histories comprising El Centro 1940, NS component and its various amplitude **a)** El Centro 1940, NS comp., **b)** Aug. 17, 1999 Marmara Earthquake, Sakarya Station, EW comp., **c)** Aug. 17, 1999 Marmara Earthquake, Yarımca Petrochemical Complex Station, NS comp., **d)** Nov. 12, 1999 Düzce Earthquake, Düzce Station, NS comp.

The second and third records are the original records of the 17 August 1999 Marmara Earthquake, Sakarya Station east-west component and Yarımca Petrochemical Complex (YPT) Station, north-south component, respectively. The second record is a long (65 sec.) duration record with the main shock and relatively small shock. The forth record is the transverse component of the ground motion recorded at the Düzce Station during the 12 November 1999 earthquake (see Fig. 3.4). For the sake of simplicity these ground motions are referred as ELC, SKR, YPT and DZC, respectively.

The amplitude of the seismic events preceding or following the main ground motion is equal or lower than the amplitude of main history acting. However, the prior or successive earthquakes with intensity of the same and three-fourth scaled of the ground motions have been taken into account. In order to simulate the successive earthquake excitations, these records have been preceded or followed by an equal or smaller amplitude artificial-records without quiescent period. The various amplitude artificial records acting as prior or successive earthquakes have been generated from the original main records. The synthetic accelerograms have been constituted from two phases: an original ground motion record and a pre or post-event obtained by scaling the amplitude of the original ground motion record by one, three-fourth, a half, one-third or one-fourth, successively (see Fig. 3.5).

The analyses have been performed using the cantilever column test specimen, labelled as C10-1-2.25N, tested by Pujol (2002). The column properties can be summarized as follows. The cross section of the specimen was 152 mm wide and 305 mm deep and the shear span was 686 mm. The effective depth (*d*) was 254 mm, for a shear span to effective depth ratio (*a/d*) of 2.7. The axial load applied to the specimen was 136 kN ($0.08 f_c A_g$). The stiffness degradation, strength deterioration and pinching parameter values used are 5.0, 0.2 and 0.448, respectively.

Figure 3.5 contains plots of several composite ground motion histories and corresponding damage progression curves. The plots were arranged mutually for the sake of simple comparison. Fig 3.5 reveals that the damage increases rapidly at the time values corresponding to sudden increases in the reversal. Note here that damage inflicted on the SDOF system by the pre-event is not proportional to its intensity. A comparison of the damage progression curves and numerical data presented show that the same intensity of loading history acting as pre and post-event does not lead to the same amount of damage. There is a nonlinear relationship between the earthquake excitation intensity and the damage attained in the end. In addition, it should be noted that increase in the pre-event amplitude results in decrease in the damage inflicted by the main shock. On the other hand, increase in the post-event amplitude does not lead to proportional increase in the damage attained in the end. It results in the relatively greater rate of damage progression. The post-events with one-fourth, one-third and even a half of the main shock amplitude do not lead to substantial damage. The data show the path independency of the total damage from the order of amplitudes along loading paths consisting of the same number and amplitude of cycles (Acar, 2004).

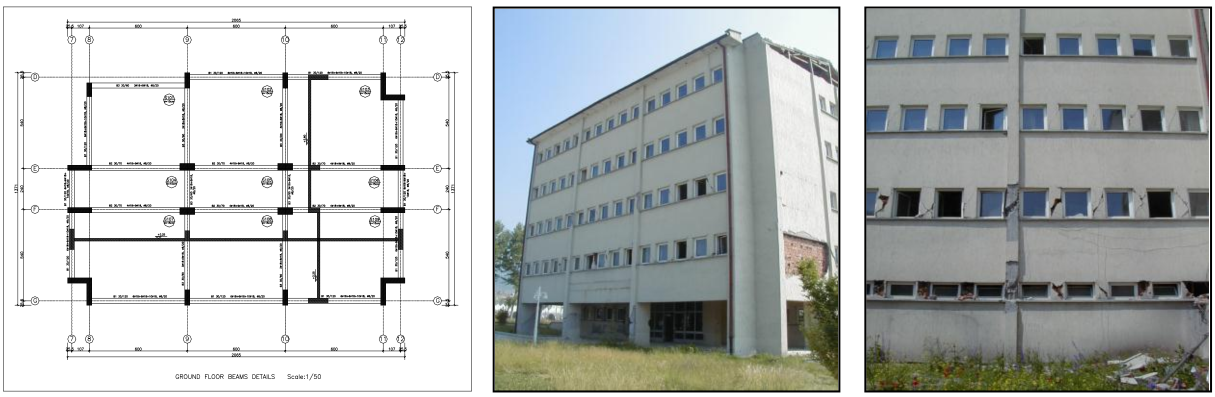

Figure 4.1. Ground floor plan and observed damage state after Nov.12, 1999 Düzce Earthquake

4. DAMAGE OF THE R/C BUILDINGS SUBJECTED TO REPEATED EARTHQUAKES

To assess the effects of prior earthquake damage on the response of MDOF frame type reinforced concrete structures to future earthquakes, inelastic time history and damage analyses of a five-story case study building have been conducted. The building had experienced two major destructive earthquakes, namely Aug. 17, 1999 Marmara and Nov. 12, 1999 Düzce earthquakes. The analyses have been carried out using the artificial ground motion accelerograms comprised of base input provided by these two recorded ground motions. The case study building, located approximately 39 km away from the epicenter of the second event, was a public building and used as the branch office of the Ministry of Public Works and Settlement at Bolu. Sample floor plan and the photographs of the exterior perspective and backside of the building taken after the earthquake are shown in Figure 4.1.

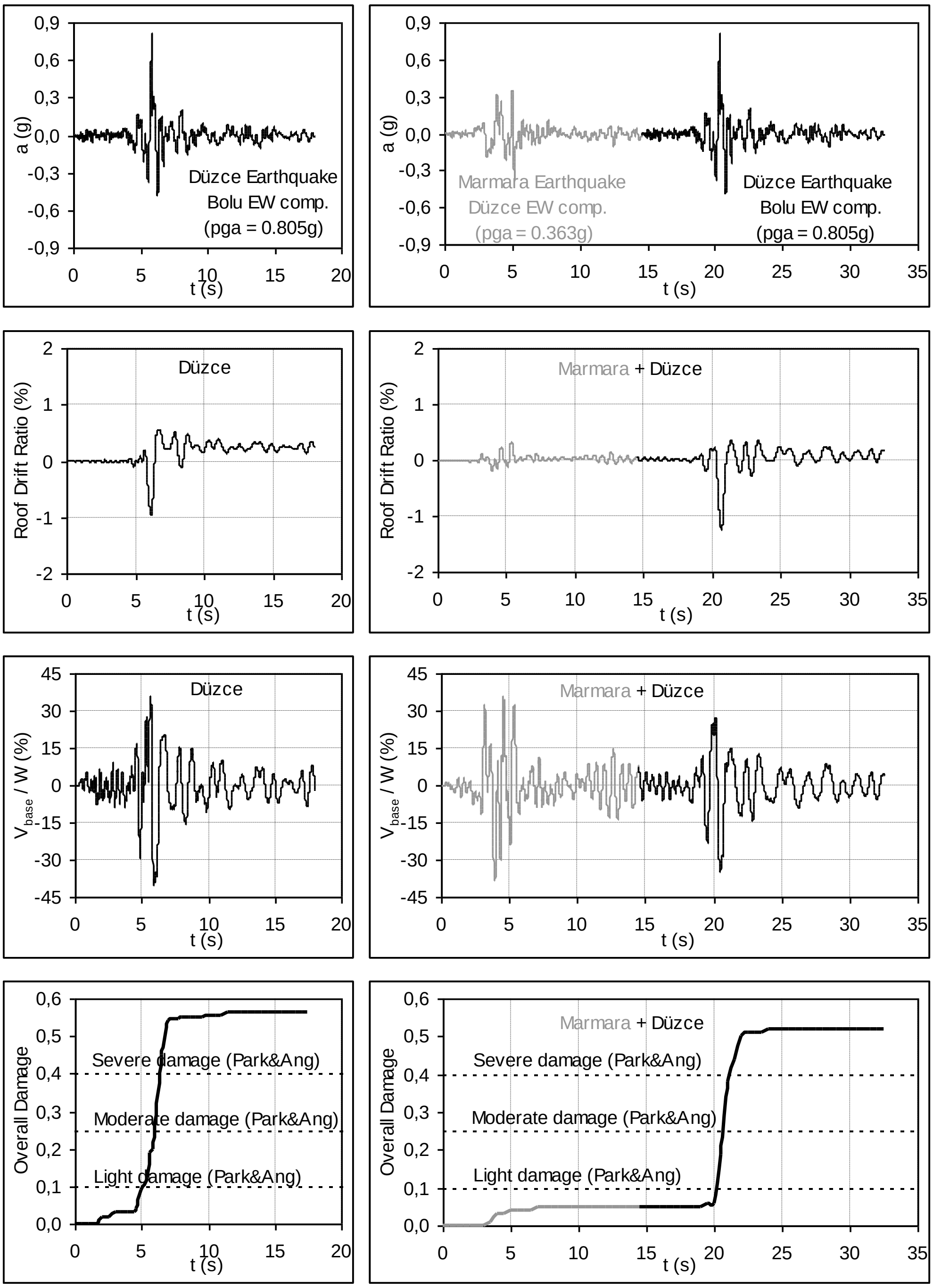

Figure 4.2. Ground acceleration histories, roof drift ratio variations, base shear ratio variations and damage curves for transverse (east-west) direction of the building

It has three bays both in the longitudinal (north-south) and transverse (east-west) directions of the building. The infill walls are not taken into consideration in the analytical models. S220 reinforcement was used as longitudinal and transverse reinforcement. The average compressive strength was found to be 20 MPa. Although some design and construction mistakes such as short columns, deep beams and inadequate confinement at joints had been made, the building is a well designed and built. It was well maintained before the second event and might have sustained light or non-damage during the first event. Note here that damage in this building by the second event was rather heavy. The damage consisted primarily of shear failures at the top of columns of the lowest three stories (see Fig. 4.1). Flexural cracks were visible in almost all beams. Some of the ground story beams had diagonal shear cracks (Çağnan, 2001).

The building is modeled as a series of plane frames linked by rigid horizontal elements. Each frame is in the same vertical plane, and no torsional effects are considered. Since the floors are considered infinitely rigid, identical frames are simply lumped together. Input data is prepared for each of the typical frames. Two-dimensional frame models of the building were prepared in both longitudinal and transverse directions. The structural system has three bays in both principal directions. Except for one rectangular column located in the corner, the system is symmetric in plan in both directions as shown in Figure 4.1. The structural system having ordinary properties is evaluated as moderately deteriorating system. Hence the hysteretic model deterioration parameter values proposed for such systems have been used in the analyses.

Ground acceleration histories, roof drift ratio variations, base shear ratio variations and damage curves for transverse (east-west) direction model of the building are presented in Figure 4.2. The analytical damage results are compared with the observed structural damage. Analytical damage analyses results are interpreted considering the observed damage state of the structures. A good match was observed between the damage states found analytically and observed after the Düzce earthquake.

Inspection on the roof drift ratio, base shear ratio and damage curves in Figure 4.2 revealed that there is rapid increases at times corresponding to the sudden increases in the amplitude of both single and synthetic ground motions. The overall damage inflicted to the system by the Marmara earthquake remains below the light damage level, meaning non-damage would occur at the first event of the synthetic ground motion. It has been demonstrated that although the prior earthquake damage does not substantially affect the maximum drift response in future larger earthquakes, it has significant effects on the damage due to succeeding earthquake. It can be stated that a structural system with a prior damage suffers less damage in an earthquake in comparison with the one without a prior damage.

Prior earthquake damage reduces the lateral stiffness of the structure significantly; letting the structure take less lateral load. This accompanies with increase in the fundamental period. The softening of the systems can be observed also from the distances in between the tips of the roof drift ratio and base shear ratio traces given in Figure 4.2. The prior earthquake damage significantly influences the damage of MDOF frame type structures from succeeding earthquakes. Although it seems illogical, a structural system with a prior damage suffers less overall damage in an earthquake in comparison with the one without a prior damage. It has been demonstrated that the inelastic time history and damage analysis is competent to indicate the damage state of the structural systems.

5. CONCLUSIONS

The study reveals that structural damage depends on the ductility level of constant amplitude reversals. Damage rapidly increases during the first pulse of the constant amplitude loading history. Regardless of ductility, this damage constitutes the major part of the total damage. Later, damage progression seems to follow almost a linear path with relatively very small rates. Damage increases almost in proportion to the increase in the cycle amplitudes. The number of load cycles has an effect on the level of damage sustained by a R/C component. Increase in the amplitude of the constant amplitude cycles diminishes the number of cycles up to failure.

The structural damage progression and cumulative hysteretic energy dissipation for simple systems are path dependent and not linear. The resultant structural damage and accumulated hysteretic energy dissipated along a path seem apparently to depend on the number and amplitude of cycles constituting the path. However, the resultant of the cumulative hysteretic energy dissipation and the total damage sustained along a loading path are independent from the ordering of the same number and amplitude cycles along the path.

The relationship between the earthquake excitation intensity and the resultant damage attained in the end is not linear. Increase in the amplitude leads to asymptotical increase in damage. A ground motion acting as a prior and successive event leads to substantially different damage. Prior earthquake damage does not have considerable effect on the maximum drift response in future larger earthquakes. A frame type structure with a prior damage suffers less overall damage in an earthquake in comparison with the one without a prior damage. The prior earthquake damage has significant effect on the SDOF system response to subsequent future earthquakes. Increase of the prior earthquake intensity leads to less damage due to the succeeding main earthquake.

The prior earthquake damage significantly influences the damage of MDOF frame type structures caused by succeeding ground motion. Although it seems illogical, a structural system with a prior damage suffers less overall damage in an earthquake in comparison with the one without a prior damage.

REFERENCES

Acar, F. (2004). Low-cycle fatigue effects in the damage caused by the Marmara earthquake of August 17, 1999, *Ph.D. Thesis*, Department of Civil Engineering, Middle East Technical University, Turkey.

Çağnan, Z. (2001). Three Dimensional Nonlinear Dynamic Analysis of a Reinforced Concrete Frame Building in Bolu, *M.S. Thesis*, Department of Civil Engineering, Middle East Technical University, Ankara, Turkey.

Erberik, M.A. (2001). Energy Based Seismic Evaluation of Degrading Systems, *Ph.D. Thesis*, Department of Civil Engineering, Middle East Technical University.

Erberik, A., Sucuoğlu, H. (2004). Seismic Energy Dissipation in Deteriorating Systems Through Low-cycle Fatigue, *Earthquake Engineering and Structural Dynamics*, **Vol. 33**, pp. 49-67.

Middle East Technical University Earthquake Engineering Research Center (2012). *Engineering Report of Nov. 9, 2011 Van-Edremit Earthquake*, METU-EERC Report No:2012-01, Ankara, Turkey.

Park, Y.-J., and Ang, A. H.-S. (1985). Mechanistic Seismic Damage Model for Reinforced Concrete, *Journal of Structural Engineering, ASCE*, **Vol. 111, No. 4**, Apr. 1985, pp. 722-739.

Pujol, S. (2002). Drift Capacity of Reinforced Concrete Columns Subjected to Displacement Reversals, *Ph.D. Thesis*, Purdue University, IN.

Seno, T. (1999). Report on the Surface Ruptures of the Chi-Chi (Taiwan) Earthquake on Sept. 21, 1999, *Earthquake Research Institute, Geodynamics Division, University of Tokyo, Japan*, at http://www.eri.u-tokyo.ac.jp/seno/taiwan.report.eng.html

Sözen, M.A. (2000). Measured Ground Shaking and Observed Damage: Do Recent Events Confirm a Direct Connection?, *Earthquake Engineering Frontiers in the New Millennium : Proceedings of the China-Us Millennium Symposium on Earthquake Engineering*, Beijing, pp.43-56.

Stone, W.C., Taylor, A.W. (1993). Seismic Performance of Circular Bridge Columns Designed in Accordance with AASHTO/CALTRANS standards, *NIST Building Science Series 170*, National Institute of Standards and Technology, Gaithersburg MD.

Sucuoğlu, H., Erberik, M.A. (2004). Energy-based Hysteresis and Damage Models for Deteriorating Systems, *Earthquake Engineering and Structural Dynamics*, **Vol. 33**, pp. 69-88.

Sucuoğlu, H., Gülkan, P., Yılmaz, Ç., Bakır, S., Özcebe, G., Ersoy, U., Tankut, T., Gür, T., Yılmaz, T., Erberik, A., Akkar, S. (2000). *Engineering Report of Marmara and Düzce Earthquakes*, METU-EERC Report, Ankara, Turkey.

Sucuoğlu, H., and Yılmaz, T. (2001). Düzce, Turkey: A City Hit by Two Major Earthquakes, *Seismological Research Letters*, **72(6)**, 679-689.

Valles, R.E., Reinhorn, A.M., Kunnath, S.K., Li, C., and Madan, A., (1996). IDARC 2D: A Program for the Inelastic Damage Analysis of Buildings, *Technical Report NCEER-96-0010*, State University of New York at Buffalo.