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DEVELOPMENT AND APPLICATION OF DAMAGE SPECTRA TO EVALUATE THE SEISMIC PERFORMANCE OF REINFORCED CONCRETE BUILDINGS IN GREECE

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Abstract. *Damage spectra for reinforced concrete buildings in Greece are presented in this paper based on a series of time-history nonlinear dynamic analyses for single-degree-of-freedom systems (Clough hysteresis model) with different deformation ductility and yielding capacities. The damage spectra are calculated for hundreds of horizontal ground motions recorded on rock-stiff soil in Greece since 1970's. Those damage spectra can be used in the seismic vulnerability assessment of existing reinforced concrete buildings in the country. To this end, the proposed damage spectra are evaluated via the damages observed in Athens as a result of the September 7, 1999 earthquake. The damage spectra confirm that low- to mid-rise RC buildings with lower ductility capacity experience heavy damage or collapse, as seen in the 1999 earthquake. The developed damage spectra can be also used for design purposes in the area. To this end, it is shown that the damage spectra can be used to determine what level of ductility capacity and yield strength is required to limit the expected damages to a certain accepted level according to the code provisions.*

1 INTRODUCTION

Quantification of damage potential of earthquakes can be a useful tool for those interested in seismic risk mitigation plans. A reliable estimation for such damage potential can have a wide range of application in the seismic vulnerability evaluation of existing buildings. One important application of this estimation is in scenario studies where the effects of a single earthquake, often historically significant ones, on present-day portfolios in a region are evaluated [1].

One way for quantifying the damage potential is using a damage index (DI) which has a value close to zero if the structure remains elastic, D1 damage grade of EMS-98 [2], and close to 1.0 when the structure reaches complete damage or collapse, D4 or D5 damage grade of EMS-98. Such index is known to be a function of earthquake parameters and structural properties as shown in Equation 1.

$$DI = f(M, R, \mu, T, F_y) \tag{1}$$

In Equation 1, M and R are the magnitude and source-to-site distance of the earthquake, respectively, μ is the global ductility of the structure, T is the period of vibration, and F_y is the yield strength. Several formulas are proposed in the literature to calculate the damage index ([3, 4, 5]). A very frequently-used relationship in different research works is the one proposed by Park and Ang [6] as shown in Equation 2.

$$DI_1 = \left({}^{u_{max}}\!/_{u_{mon}}\right) + {}^{\beta . E_H}\!/_{F_y . u_{mon}} \tag{2}$$

In this equation, u_{max} and u_{mon} are the maximum deformations under earthquake loads and monotonically increasing lateral loads, respectively. Moreover, E_H is the non-recoverable dissipated hysteretic energy, and β is a positive constant, which depends on structural characteristics and history of inelastic response. An advantage of the Equation 2 is that is has been calibrated with experimental data. However, in some cases, when the system remains in the elastic mode ($E_H = 0$), the equation gives DI values way bigger than zero which can be misleading towards the behavior evaluation of the building. To overcome this problem, a modified version of the DI_1 [7] defined as follows is used here in this paper.

$$DI_2 = \left({}^{(u_{max} - u_y)}\!/_{(u_{mon} - u_y)}\right) + {}^{\beta . E_H}\!/_{F_y . u_{mon}} \tag{3}$$

The variation of damage indices over a range of structural periods for a series of single-degree-of-freedom (SDOF) systems with different ductility and yield strength values forms “damage spectra” for a region [4]. The main objective of this paper is to present damage spectra for the existing reinforced concrete buildings in Greece based on the possible different structural characteristics of that building class. To this end, a range of period, ductility and normalized yielding strength (F_y/W) is considered to develop the DI values from Equation 3 based on series of nonlinear dynamic analyses of a SDOF system using the ground motion records of earthquakes that have happened in Greece since 1970. Those DI values are later used to develop damage spectra for the studied building class and used to assess their damage potential in future events. Finally, the accuracy of the developed damage spectra is evaluated using the damages that happened in RC buildings during the 1999 earthquake in Athens.

2 APPLIED METHODOLOGY

2.1 Ground motion records and structural properties

The ground motion records used to develop the damage indices for the RC buildings are selected from the European Strong-Motion Data [8]. To this end, earthquakes with a magnitude (M_s) equal or bigger than 5 which occurred in Greece since 1970 are used in this paper (Table 1).

Date	Epicentre	M_s
17.01.1983	Kefallinia island	7.1
06.08.1983	Off coast of Magion Oros peninsula	6.7
18.11.1997	Strofades	6.7
13.05.1995	Kozani	6.6
13.10.1997	Kalamata	6.4
22.01.2002	Off coast of Karpathos	6.2
20.06.1978	Volvi	6.2
21.12.1990	Griva	6.1
23.05.1994	South Aegean	6.1
13.09.1986	Kalamata	5.8
16.10.1988	Kyllini	5.8
18.11.1992	Tithorea	5.8
18.03.1993	Kallithea	5.7
27.02.1987	Near NW coast of Kefallinia island	5.6
23.06.2001	Off coast of Rhodes	5.6
30.04.1985	Anchialos	5.4
17.09.1972	Kefallinia island	5.4
10.06.2001	Chios	5.4
19.03.1983	Heraklio	5.4
05.11.1997	Itea	5.4
23.01.1992	Kefallinia island	5.4
14.07.1993	Patras	5.4
16.06.1990	Filippias	5.3
25.10.1984	Kranidia	5.3
19.03.1991	Near SE coast of Crete	5.3
22.05.1988	Etolia	5.1
07.09.1985	Gulf of Kiparissiakos	5.1
16.09.2001	Kallirro	5.1
25.02.1994	Komilion	5.1
10.03.1981	Preveza	5.1
26.03.1993	Pyrgos	5.1
26.04.1996	Rhodos island	5.1

Table 1: List of earthquakes used in the nonlinear dynamic analysis

Consequently, 110 ground motion records recorded at various stations, located on rock or stiff soil, are chosen to perform the nonlinear dynamic analyses for a series of SDOF systems. The distribution of magnitude with source-to-site distance for those ground motion records are shown in Figure 1.

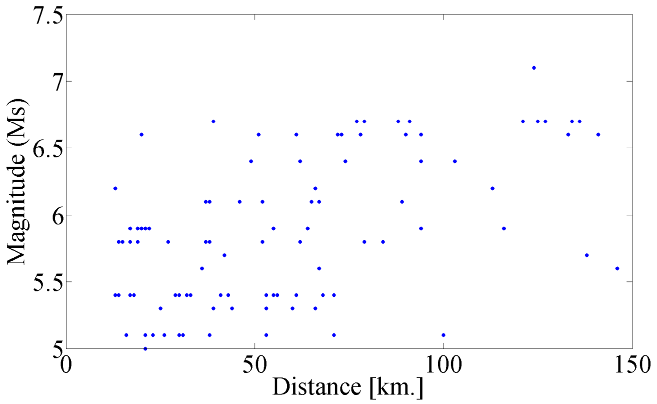

Figure 1: Distribution of the magnitude and source-to-site distance of the considered ground motion records

2.2 Structural properties of the SDOF

Taking into account that the damage spectra in this paper are being developed for RC buildings, Clough hysteresis model [9] is considered in the nonlinear dynamic analyses of the SDOF systems, performed with the computer program IDARC [10]. The structural properties of the SDOF systems are shown in Table 2.

Ductility	Period	Fy/W
2-5	0.3-1.0	0.05-0.10

Table 2: Range of the structural properties used for the RC buildings

2.3 Development of the damage spectra

As stated earlier, a damage spectrum consists of the variation of damage index values for a series of SDOF systems with various structural vibration periods. Using Equation 3, a damage index is developed from each of the 110 ground motion records shown in Figure 1 over the range of structural properties shown in Table 2. Such nonlinear dynamic analyses leads to approximately 7040 damage index values which are functions of various parameters as shown in Equation 1. An attenuation relationship is then defined (Equation 4) to estimate the variation of damage spectra with earthquake magnitude and source-to-site distance, for each ductility, yield strength, and period value.

$$log(DI_2) = C_1 + C_2.M_s + C_3.log(R) \tag{4}$$

C_1, C_2, and C_3 are regression parameters which are calculated from the regression analyses of the 7040 damage indices for different M_s and R values.

3 RESULTS

Table 3 to 6 show the values for the three coefficients C_1, C_2, and C_3 for the range of the structural properties considered in this study (Table 2).

	Fy/W=0.05			Fy/W=0.1		
T	C1	C2	C3	C1	C2	C3
0.3	-1.91	0.88	-1.96	-2.06	0.64	-1.12
0.4	-1.45	0.65	-1.45	-0.75	0.37	-1.03
0.5	-0.51	0.48	-1.39	-2.39	0.69	-1.29
0.6	-0.44	0.42	-1.31	-0.36	0.31	-1.31

0.7	-0.74	0.39	-1.06	-1.26	0.28	-0.54
0.8	-1.38	0.51	-1.17	-1.53	0.35	-0.68
0.9	-1.32	0.39	-0.79	-1.64	0.98	-3.50
1	-1.50	0.36	-0.60	-1.86	0.29	-0.47

Table 3: Values of coefficients C1, C2, and C3 for RC buildings with a ductility value of 2

	Fy/W=0.05			Fy/W=0.1		
T	C1	C2	C3	C1	C2	C3
0.3	-2.35	0.94	-2.08	-2.37	0.64	-1.12
0.4	-1.76	0.66	-1.46	-1.06	0.37	-1.03
0.5	-0.81	0.48	-1.39	-2.69	0.70	-1.29
0.6	-0.82	0.44	-1.35	-0.67	0.32	-1.31
0.7	-1.11	0.42	-1.10	-1.57	0.29	-0.54
0.8	-1.68	0.51	-1.17	-1.82	0.35	-0.68
0.9	-1.62	0.40	-0.79	-1.97	0.97	-3.42
1	-1.80	0.36	-0.60	-2.16	0.30	-0.47

Table 4: Values of coefficients C1, C2, and C3 for RC buildings with a ductility value of 3

	Fy/W=0.05			Fy/W=0.1		
T	C1	C2	C3	C1	C2	C3
0.3	-2.52	0.96	-2.16	-2.55	0.64	-1.12
0.4	-1.94	0.66	-1.46	-1.24	0.37	-1.03
0.5	-0.99	0.48	-1.39	-2.87	0.70	-1.29
0.6	-1.00	0.44	-1.35	-0.84	0.32	-1.31
0.7	-1.28	0.42	-1.10	-1.74	0.29	-0.54
0.8	-1.86	0.51	-1.17	-2.00	0.35	-0.68
0.9	-1.79	0.40	-0.79	-2.15	0.97	-3.39
1	-1.98	0.36	-0.60	-2.34	0.30	-0.47

Table 5: Values of coefficients C1, C2, and C3 for RC buildings with a ductility value of 4

	Fy/W=0.05			Fy/W=0.1		
T	C1	C2	C3	C1	C2	C3
0.3	-2.52	0.91	-2.08	-2.67	0.64	-1.12
0.4	-2.06	0.66	-1.46	-1.36	0.38	-1.03
0.5	-1.11	0.48	-1.39	-3.00	0.70	-1.29
0.6	-1.12	0.44	-1.35	-0.97	0.32	-1.31
0.7	-1.41	0.42	-1.10	-1.87	0.29	-0.53
0.8	-1.98	0.51	-1.17	-2.12	0.35	-0.68
0.9	-1.92	0.40	-0.79	-2.28	0.96	-3.37
1	-2.10	0.36	-0.60	-2.46	0.30	-0.47

Table 6: Values of coefficients C1, C2, and C3 for RC buildings with a ductility value of 5

Using the coefficient values in Tables 3 to 6 for Equation 4, the attenuation of the damage spectra with R is demonstrated in Figures 1 and 2, for the lower and upper bound values of earthquake magnitude and structural properties considered in this paper.

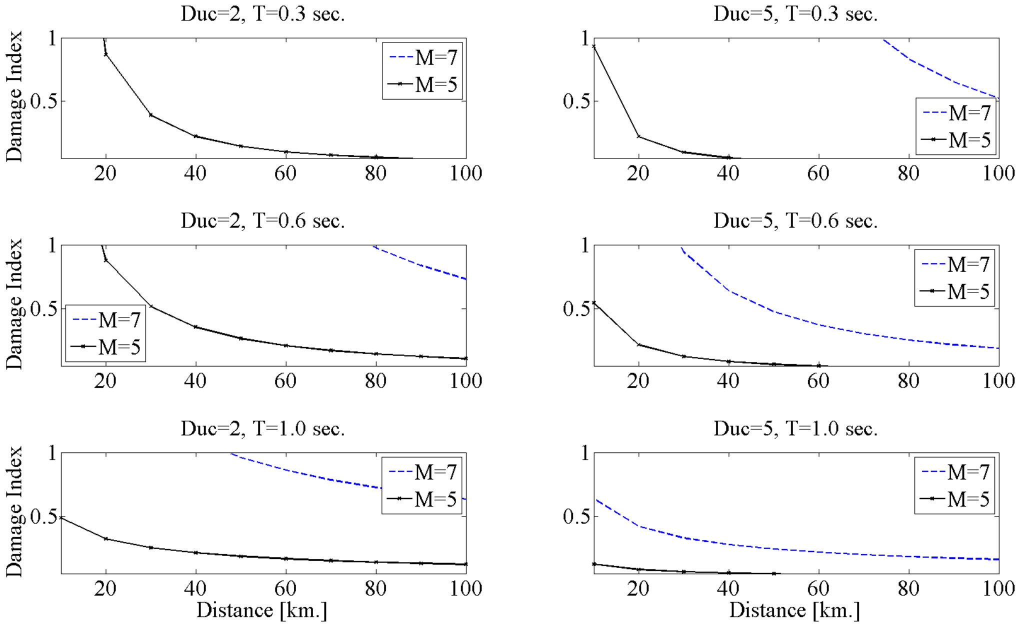

Figure 2: Attenuation of the damage spectra with source-to-site distance for structures with *Fy/W=0.05*

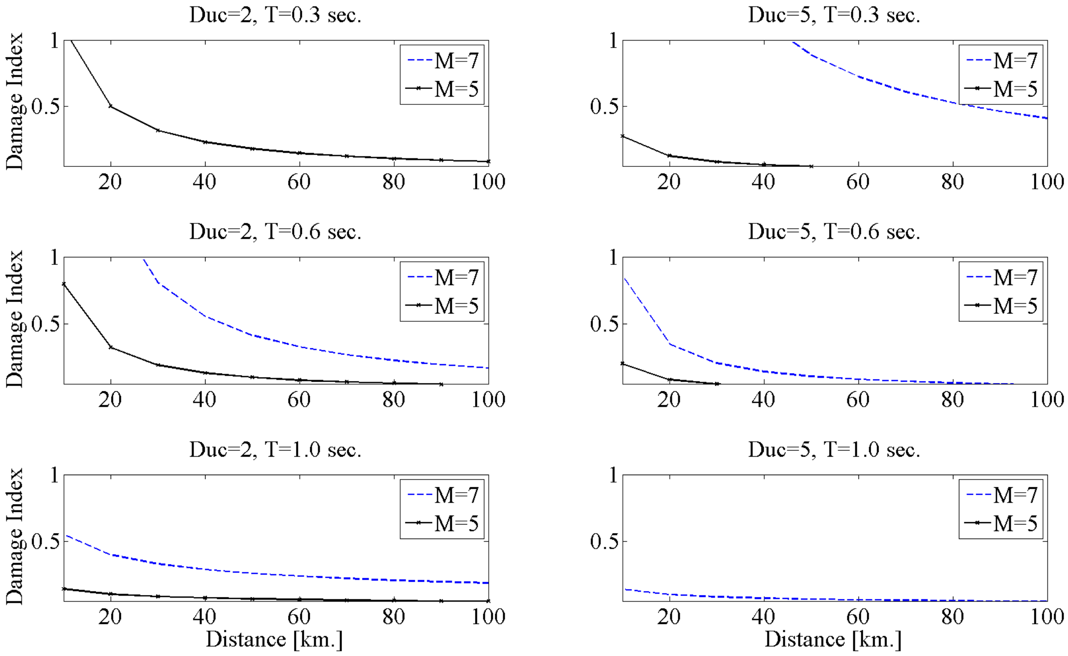

Figure 3: Attenuation of the damage spectra with source-to-site distance for structures with *Fy/W=0.1*

As seen in both Figures 2 and 3, low-rise RC buildings with 3 to 4 storeys (T_1=0.3 sec.) are completely vulnerable (DI>0.6) to big earthquakes (M>6) even at far distances. The increase of ductility, as expected, somewhat reduces such vulnerability. However, for different values of ductility, those short buildings would experience complete damage (DI>1.0) for near-to-source events and moderate damage (DI>0.5) for far-to-source ones. Mid-rise RC buildings (T_1=0.6 sec.) especially those with higher yield strength (F_y/W=0.1) and higher ductility show better behaviour as they experience slight damage (DI<0.5) even for a near-to-source event. Finally, high-rise buildings (T_1=1.0 sec) only suffer moderate to extensive damage in lower ductilities and lower yield strength. It should be noted that such conclusions are applicable to regular buildings which have high enough mass participation factor for their first mode of vibration.

4 DISCUSSION OF RESULTS

To evaluate the damage spectra developed in this paper, the damage spectra for the 1999 earthquake in Athens is compared with the observed damages from that event which happened on September 7, 1999 at 14:56 local time (11:56 GMT) with a magnitude M_w=5.9, close to the city of Athens in Greece.

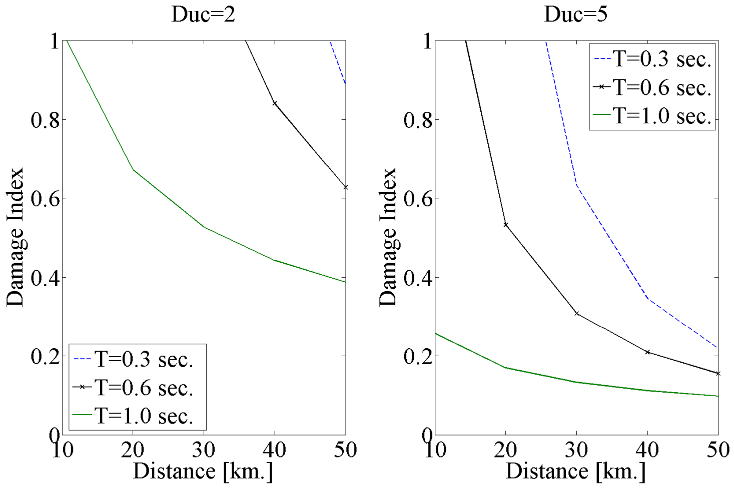

Figure 4: Attenuation of the 1999 Earthquake damage spectra with source-to-site distance for structures with *Fy/W=0.05*

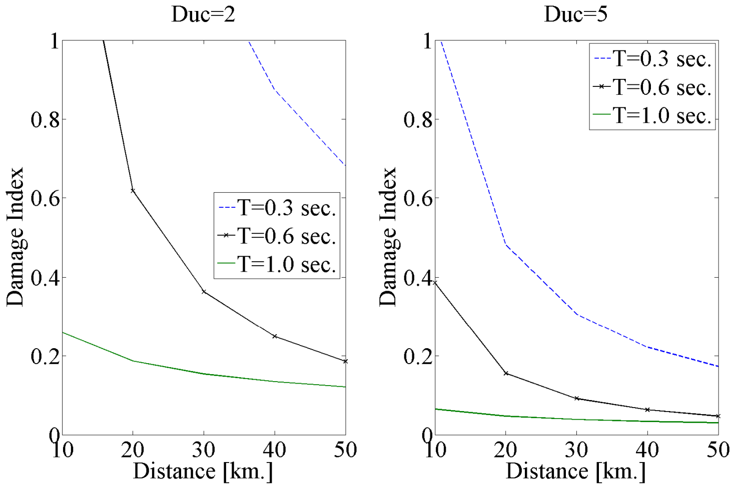

Figure 5: Attenuation of the 1999 Earthquake damage spectra with source-to-site distance for structures with *Fy/W=0.1*

It is reported that two- to five-storey RC buildings with low ductility capacity experienced the highest damage in the meizoseismal area at an epicentral distance between 10 to 20 km [11, 12]. Those were the buildings built according to the 1959 code [13], without ductility provisions, or illegally built ones with poor construction which would not fulfill the minimum requirements of the 1959 code.

Figures 4 and 5 show the attenuation of the damage spectra for the 1999 Earthquake for two different ductility values and two levels of yield strength. As seen in both figures, low- and mid-rise RC buildings (T=0.3 sec and 0.6 sec.) with low ductility capacity have DI values greater than 1.0 at epicentral distances lower than 20km. Both figures indicate that the structural damages rapidly decrease with the distance from the source.

According to the reports, no major damage was stated for bridges [11]: this is the fact seen in both Figures 4 and 5, as structures with higher periods (T =1.0 sec and bigger) have low DI values even at a close distance to the source.

The 1999 earthquake in Greece occurred at an epicentral distance of about 18 km from the historical center of Athens. The damage spectra for such a source-to-site distance are shown in Figure 6 for different ductility values. It is assumed here that the period of vibration is directly in proportion with the number of storeys (T=0.1N). In case of a similar scenario as the one in 1999, low- to mid-rise structures with low ductility capacity will experience near to collapse or complete damage. Figure 6 can also be also helpful in the design of new RC buildings in the area as it clearly states the required ductility and yield strength values for a defined accepted level of damage. For example, a 6-storey building needs to have a minimum ductility value equal to 3 ($F_y/W=0.1$) or 6 ($F_y/W=0.05$) to experience DI's lower than 0.5. Similar to the case for the 1999 Earthquake, damage spectra can be calculated for any code's design earthquake with a specific return period (magnitude), for any site (source-to-site distance) in Greece.

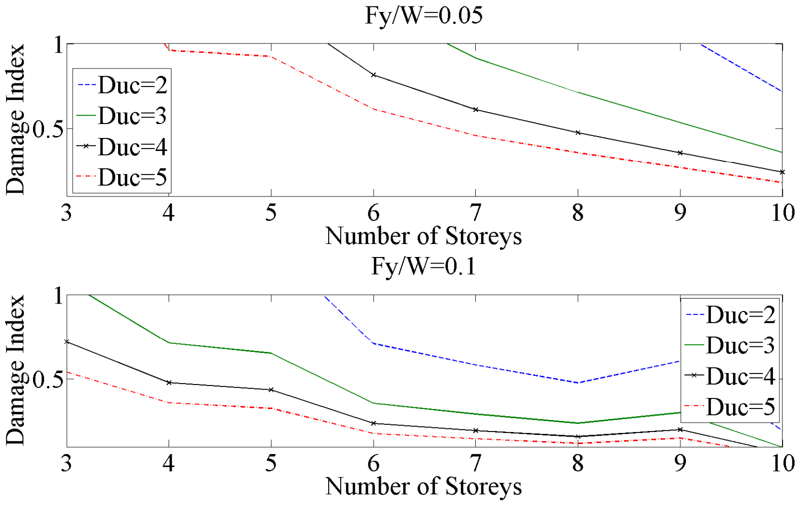

Figure 6: Damage spectra for 1999 Greece earthquake at a source-to-site distance of 18 km

5 CONCLUSIONS

- An attenuation relationship of damage spectra for RC buildings in Greece is presented in this article based on a series of nonlinear dynamic analyses using 110 ground motions records from various earthquakes which happened in the country since 1970.

- Various damage spectra can be developed from the attenuation relationship based on desired structural properties such as ductility capacity, yield strength, and the vibration period of the RC buildings.
- The calculated damage spectra show good correlation with the observed damage of the 1999 Earthquake in Greece.
- Low-rise RC buildings show high vulnerability to big earthquakes (M_s>6) even at far distances. In such situations, high ductility values (μ>5) are required to keep the DI lower than 0.5.
- Structures with longer period of vibration (e.g., bridges) show very low damage index values in a scenario similar to the 1999 earthquake. This is in accordance with the field observation from that earthquake.
- The developed damage spectra here can be also used in the seismic design of new RC buildings in Greece: to determine the required ductility capacity and yield strength for the credible earthquake in a region based on code requirements.

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