Development and Application of Damage Spectra for RC Buildings in Europe

A. Karbassi & P. Lestuzzi
Ecole Polytechnique Fédérale de Lausanne, Switzerland

B. Mohebi
Imam Khomeini International University of Qazvin, Iran

SUMMARY:
Damage spectra for existing reinforced concrete buildings in Europe are presented in this paper. To this end, a series of time-history nonlinear dynamic analyses for single-degree-of-freedom systems with different deformation ductility values and yielding capacities are performed. The structural properties considered are natural period, ductility, and normalized yielding strength (F_y/W). The hysteresis model is based on Takeda's model. The computer program IDARC is used to perform the non-linear dynamic analyses, using more than 500 ground motions records on rock-stiff soil and more than 200 records on soft and very soft soil from earthquakes in different parts of Europe since 1970's. Subsequently, those damage spectra are verified through an numerical approach using a four-storey RC frame. The developed damage spectra can also be useful to determine the level of ductility capacity and yield strength required to limit the expected damages to a certain accepted level according to the EURO-code provisions.

Keywords: Damage Index, Reinforced Concrete, Seismic Vulnerability, Earthquake Scenarios

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 (Coburn and Spence 2002).

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 (Grünthal 1998), 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 1.1.

$$DI = f(M, R, \mu, T, F_y) \tag{1.1}$$

In Equation 1.1, 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 (Ghobarah et al. 1999; Bozorgnia and Bertero 2003; Massumi and Moshtagh 2010). A very frequently-used relationship in different research works is the one proposed by Park and Ang (1985) as shown in Equation 1.2.

$$DI_1 = \left({}^{u_{max}}/_{u_{mon}}\right) + {}^{\beta . E_H}/_{F_y . u_{mon}} \tag{1.2}$$

u_{max} and u_{mon} in this equation 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 1.2 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 (Kunnath et al. 1992) defined as follows is used here in this paper.

$$DI_2 = \left({(u_{max} - u_y)} \big/ {(u_{mon} - u_y)} \right) + {\beta . E_H} \big/ {F_y . u_{mon}} \tag{1.3}$$

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 (Bozorgnia and Bertero 2003). The main objective of this paper is to present damage spectra for the existing reinforced concrete buildings in Europe based on the possible different structural characteristics of that building class. To this end, a range of period values from 0.3 to 1.0 sec., ductility values from 2 to 5, and normalized yielding strength (F_y/W) from 0.05 to 0.2 are considered to develop the DI values from Equation 1.3. A series of nonlinear dynamic analyses for SDOF systems are performed using more than 700 ground motions records from earthquakes in different parts of Europe since 1970’s. Those DI values are later used to develop damage spectra for the studied building class. Finally, the accuracy of the developed damage spectra is evaluated using damage pattern of a four-storey RC frame subjected to 17 earthquakes out of the ground motion database used to develop the DI’s in the first place.

2. METHODOLOGY

2.1. Selection of the ground motion records

The ground motion records used to develop the damage indices for the RC buildings are selected from the European Strong-Motion Data (Ambraseys et al. 2002). To this end, earthquakes with a magnitude (M_s) between 4.5 and 7.5which occurred in Europe since 1970 are used here. Consequently, 580 ground motion records recorded at various stations, located on rock or stiff soil, and another 200 recorded on soft and very soft 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 Figures 1 and 2.

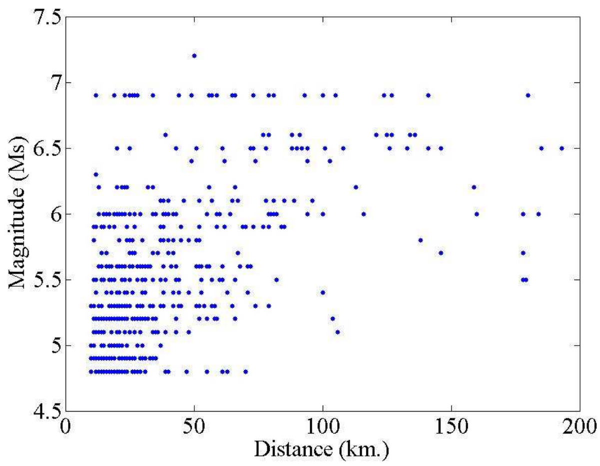

Figure 1. Distribution of the magnitude and distance of ground motion records on rock and stiff soil

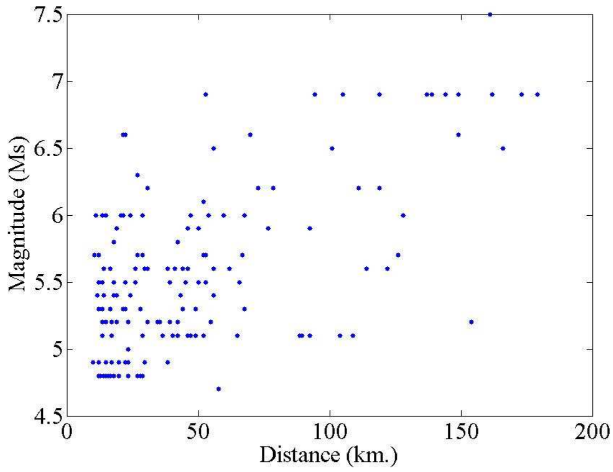

Figure 2. Distribution of the magnitude and distance of the ground motion records on soft soil

2.2. Structural properties of the SDOF

Taking into account that the damage spectra in this paper are being developed for RC buildings, the hysteresis model developed by Takeda et al. (1970) is considered in the nonlinear dynamic analyses of the SDOF systems, performed with the computer program IDARC (Reinhorn et al. 2010). The structural properties of the SDOF systems are shown in Table 2.1.

Table 2.1. Range of the structural properties used for the RC buildings

Ductility	Period	Fy/W
2-5	0.3-1.0	0.05-0.20

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 1.3, a damage index is developed from each of the ground motion records shown in Figures 1 and 2 over the range of structural properties shown in Table 2.1. The damage index values are functions of various parameters as shown in Equation 2.1. An attenuation relationship is then defined (Equation 2.1) to estimate the variation of damage spectra with earthquake magnitude and source-to-site distance, for each ductility, yield strength, and period value.

$$log(DI_2) = C_1 + C_2.M_s + C_3.log(R) \quad (2.1)$$

C_1, C_2, and C_3 in Equation 2.1 are regression parameters which are calculated from the regression analyses of the damage indices for all M_s and R values.

3. RESULTS

Using the coefficient values calculated for Equation 2.1, examples of the attenuation of the damage spectra with R is demonstrated in Figures 1 and 2. Figure 3 shows the attenuation of DI values for a building with a ductility of 3 and a period of vibration of 0.3 sec, for both a low and up-bound value of the earthquake magnitude.

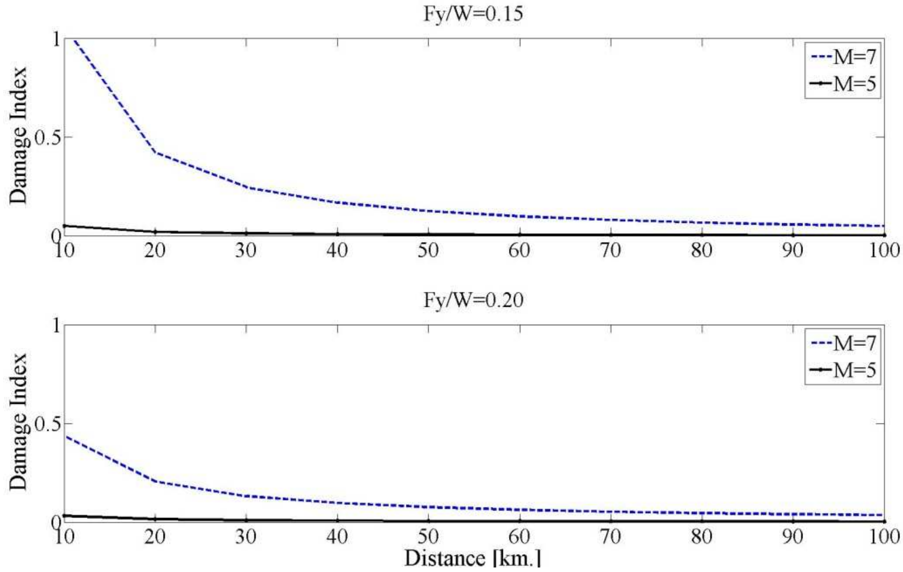

Figure 3. Attenuation of the damage spectra with source-to-site distance
for structures with ductility=3 and T= 0.3 sec.

Figure 4 shows the attenuation of DI for the same structural ductility as in Figure 3, but for a building with a period of vibration of 1.0 sec. It should be noted that the maximum of the “y axis” in this figure has been changed to better present the small DI values in this case.

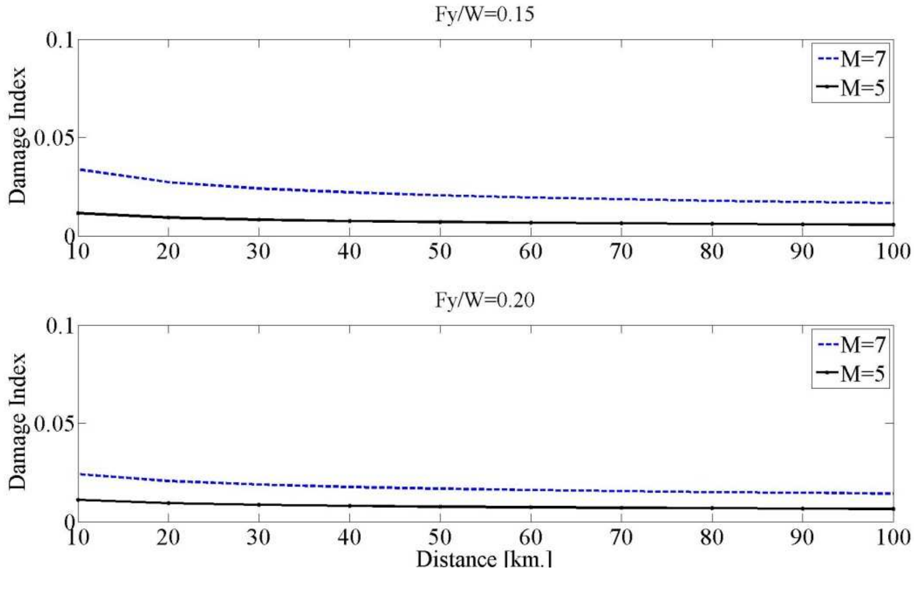

Figure 4. Attenuation of the damage spectra with source-to-site distance
for structures with ductility=3 and T= 1.0 sec.

As seen from Figure 3, low-rise RC buildings with 3 to 4 storeys (T_1=0.3 sec.) with moderate strength values (Fy/W=0.15) are vulnerable to big-magnitude earthquakes (M>6) at close distances. The increase of the building strength, as expected, reduces such seismic vulnerability. However, even with higher strength values, those short-rise buildings are expected to experience moderate damage (0.25<DI<0.5) from big-magnitude earthquakes at mid-range distances from the site. High-rise RC buildings with a ductility of 3, on the other hand, are shown to experience none or very little damage (DI<0.05) from earthquakes at any distance. It is important to state that because the near-fault effects have not been considered in the nonlinear dynamic analyses to develop the indices, the results for the damage indices are not valid in those cases.

4. VERIFICATION OF RESULTS

4.1. Numerical model

The damage spectra obtained in the previous section are verified through the comparison of the results with the damage pattern in a 4-storey RC frame shown in Figure 5. The structural properties of the RC frame are shown in Table 4.1.

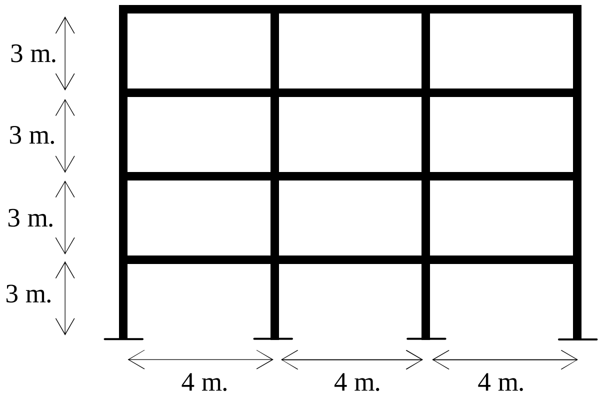

Figure 5. 4-storey RC frame used to verify the damage spectra

Table 4.1. Structural properties of the 4-storey RC frame

Ductility	Period	Fy/W
3.7	0.95	0.17

The nonlinear dynamic analysis for the RC frame is performed for 16 ground motion records shown in Table 4.2, from the European Strong-Motion Data (Ambraseys et al. 2002). These records are different from those that were used in the previous section to develop the regression parameters in Equation 2.1.

Table 4.2. List of M-R for the ground motion records used in the nonlinear dynamic analysis of the RC frame

Record no.	M_s	R (km.)
1	4.7	21
2	5.1	18
3	7.2	53
4	5	10.2
5	7.7	55.9
6	6.6	34.5
7	6.5	44.1
8	5.8	54
9	5.8	64
10	6.1	23.6
11	5.4	22.5
12	6.3	20.1
13	5.4	21.5
14	6.8	28.6
15	6.8	24
16	5.6	21.2

Figure 6 shows the results of the damage indices for the 4–storey frame from the damage spectra in Section 3 in comparison to the damage indices that are obtain directly from the nonlinear dynamic analysis of the RC frame subjected to the ground motion records in Table 4.2.

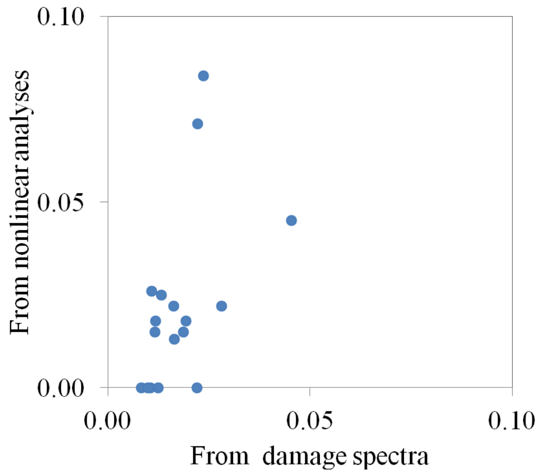

Figure 6. Comparison of results from damage spectra and direct nonlinear dynamic analysis

As seen in Figure 6, the damage indices in most cases fall close to the 1:1 line. It should be noted that the damage index values should be seen in a qualitative manner. In other words, the exact value of the damage index is less important than the amount of damage according to the span in which the index value falls. For this reason, it is necessary to present an interpretation of damage level for each damage index span. Examples of those interpretations can be found in Park et. al. (1987).

4.2. Earthquake case study

The L'Aquila earthquake occurred in central part of Italy on April 6, 2009. The earthquake was rated 6.3 on the surface magnitude scale and happened near the capital of Abruzzo, which together with surrounding villages suffered most damage.

The damage spectra from the previous section are used here to assess the damage in existing RC buildings with a low ductility (μ=2) and F_y/W=0.05, as a result of a similar earthquake with the same magnitude at different distances (Figure 7).

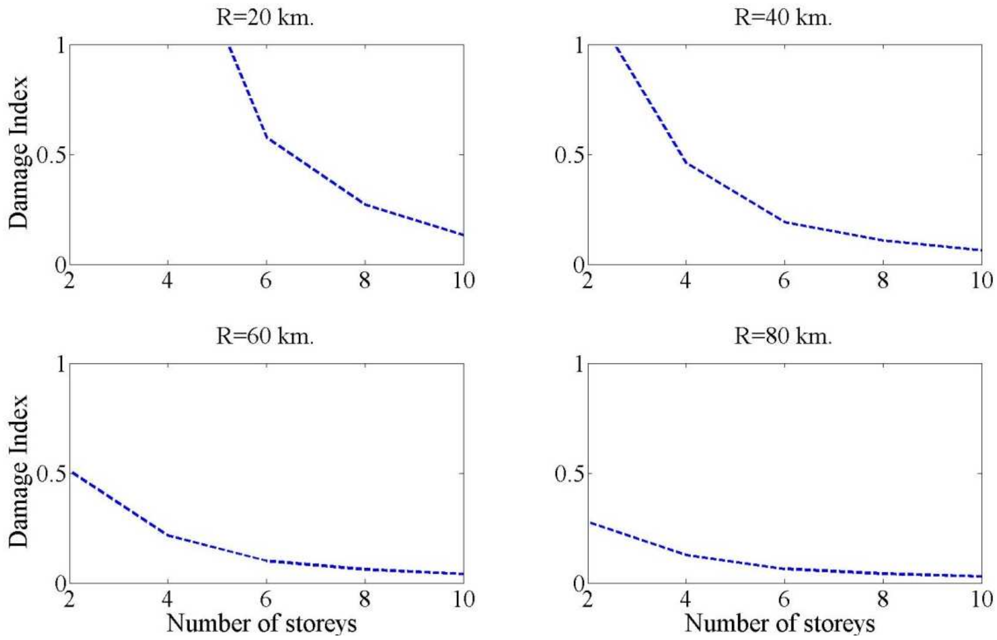

Figure 7. Variation of damage indices with building height for L'Aquila earthquake μ=2 and F_y/W=0.05

It is assumed here that the period of vibration is directly in proportion with the number of storeys (T=0.1N). As seen in Figure 7, the low ductility and strength of such buildings cause them to suffer heavy damage at a close distance to the source.

5. CONCLUSIONS

An attenuation relationship of damage spectra for RC buildings in Europe is presented in this article based on a series of nonlinear dynamic analyses using 700 ground motions records from various earthquakes which happened 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. To verify the calculated damage spectra in this paper, the results are compared with the dynamic analysis of a 4-storey RC frame subjected to a group of ground motion records. The calculated damage spectra show good correlation with the damage indices obtained directly from the nonlinear dynamic analysis of the 4-storey RC frame.

The damage spectra in this paper are also used to study the effect of a similar scenario as the one in 2009 in L'Aquila. Low-rise RC buildings show high vulnerability such an earthquake at close to mid-range distances. Structures with longer period of vibration show lower damage in a scenario similar to L'Aquila earthquake.

The developed damage spectra here can be also used in the seismic design of new RC buildings in Europe to determine the required ductility and yield strength for the credible earthquake in a region based on code requirements.

REFERENCES

Ambraseys, N., Smit, P., Sigbjornsson, R., Suhadolc, P. and Margaris, B. (2002). Internet-Site for European Strong-Motion Data. European Commission, Research-Directorate General, Environment and Climate Programme.

Bozorgnia, Y. and Bertero, V. V. (2003). Damage Spectra: Characteristics and Applications to Seismic Risk Reduction. *Jour. of Struct. Engrg.* **129**, 1330-1340.

Coburn, A. and Spence, R. (2002), Earthquake protection. Wiley, Chichester, U.K.

Ghobarah, A., Abou-Elfath, H. and Biddah, A. (1999). Response-based damage assessment of structures. *Earthquake Engng Struct Dynamics*, **28**,79–104.

Grünthal, G. (1998). European Macroseismic Scale, EMS-98, **Vol. 15**. Centre Européen de Géodynamique et de Séismologie, Luxembourg.

Kunnath, S. K., Reinhorn, A. M. and Lobo, R. F. (1992). IDARC Version 3.0: A program for the inelastic Damage Analysis of Reinforced Concrete Structures. *Technical Report NCEER-92-0022*, National Center for Earthquake Engineering Research, Buffalo.

Massumi, A. and Moshtagh, E. (2010). A new damage index for RC buildings based on variations of nonlinear fundamental period. *The Structural Design of Tall and Special Buildings*, doi: 10.1002/tal.656.

Park, Y. J. and Ang, A. (1985). Mechanistic seismic model for reinforced concrete. *Jour. of Struct. Eng*. **111,** 722–739.

Park, Y.J., Ang, A. H-S. and Wen, Y.K. (1987). Damage-limiting aseismic design of buildings, *Earthquake Spectra*, **3:1**,1-26.

Reinhorn, A. M., Kunnath, S. K. and Valles-Mattox, R. (2010). IDARC 2D Version 7.0: user manual. Department of Civil Engineering, State University of New York at Bufallo.

Takeda, T., Sozen, M. A. and Neilsen, N. N. (1970). Reinforced concrete response to simulated earthquakes. *ASCE J. Struct* , **96(12)**, 2557–2573.