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Damage identification after seismic events through damage indexes

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Abstract

The seismic events that have affected the building heritage over the past years have highlighted the vulnerability and the huge direct and indirect losses associated with earthquakes. The research of methodologies able to evaluate the post-earthquake damage state is clearly decisive to allow a quick and safe estimation of the building state in the immediate hours following the event, reducing in this way the interruption of serviceability.

The aim of this article is to compare the suitability of different damage indexes developed in the literature over the years. The efficiency of each index, in terms of precision of damage evaluation for structural and non-structural elements, has been tested by applying them to synthetic outputs extracted from a bidimensional RC-frame modeled with OpenSees. In particular, the response of the RC-frame has been studied using a database made of 48 real seismic accelerations classified by soil site conditions, magnitude and distance from epicenter. It is worth noting that the implementation regard both indexes related to local damage both indicators that express global damage simply through a number. In the last section, the most capable indexes have been analyzed starting from the parameters involved in their mathematical formulation in order to outline which ones are compatible with a real-time evaluation registered by a minimal equipment installed on the building (i.e. accelerometers), making them fully operational in estimating post-earthquake damage.

Keywords: Structural Health Monitoring; Damage indexes; Seismic assesment; Seismic Vulnerability.

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1. Introduction

The severe grade of damage caused by seismic events worldwide highlighted the magnitude of the economic and social losses due to the vulnerabilities of the existing building stock (Calvi G.M., 2006). Such losses are composed both by direct and indirect costs, whose the latter are more difficult to estimate and often less considered, as for instance the temporary relocation of inhabitants and the economic losses related to the interruption of serviceability of the industrial and productive sector. Therefore, given the overall impact of seismic events, the interest of the scientific community in the identification of methodologies able to estimate the potential damage of a building is clearly understandable (Cornell, 2011, Günay and Mosalam, 2012).

After a seismic event, it should be noted that the current practice to ensure buildings usability involves the contribution of qualified technicians through the visual analysis carried out during inspections. The lack of information such as the maximum displacements occurred during the earthquake or the presence of residual deformation highlights the difficulty of an accurate assessment of the degree of damage, emphasizing the uncertainty of the decision in terms of structural safety. Such uncertainties encourage the deployment of sensors which, depending on the type, the number and the location on the building, can provide a significant support tool during the aftermath of a seismic event, allowing to derive parameters such as floor accelerations, inter-story drifts and the building base shear demand.

Nomenclature

DI_i	Damage Index (i) in the classic configuration
DI_{i-N}	Damage Index (i) in the normalized configuration
DI_e	Damage Index calculated at the yielding point of the element/floor
DI_u	Damage Index calculated at the incipient collapse point of the element/floor
k_0	Initial elastic stiffness of the element/floor
k_m	Secant stiffness at maximum rotation / inter-story drift
k_e	Elastic stiffness of the element / floor
k_u	Secant stiffness at incipient collapse
d_m	Maximum rotation reached by the element / Maximum inter-story drift reached by the floor
d_y	Yielding rotation of the element / Yielding displacement of the floor
d_u	Rotation of the element / Inter-story drift of the floor at incipient collapse
F_m	Maximum bending moment of the element / Maximum shear force reached in the floor
F_y	Yielding moment of the element / Yielding shear force of the floor
F_u	Bending moment of the element / Shear force of the floor at incipient collapse
E_h	Dissipated energy of the element/floor
k_i	Secant stiffness at maximum rotation / inter-story drift of the cycle (i)
d_I	Maximum rotation reached by the element / Maximum inter-story drift reached by the floor in the cycle (i)
n	Number of cycles
L	Height of the column
d	Height of the cross-section
ν	Normalized axial force
ρ_t	Percentage of longitudinal reinforcement bars
ρ_ϖ	Confinement ratio
μ_m	Maximum ductility reached by the element / floor
μ_u	Ductility of the element / floor at incipient collapse

2. Damage Indexes

The interest of the scientific community in the structural health monitoring has led to the definition of several damage indexes able to express the state of structural and non-structural damage in an element after a seismic event simply through a number, as reported by Datta and Ghosh (2008), Shiradhonkar and Sinha (2012), Azhdary and

Shabakhty (2012), among others. These indexes could be calculated starting from quantities such as ground accelerations, element rotations and bending moments, if a finite element (FE) model of the building has been defined, or floor accelerations and inter-story drifts recorded, or derived, by sensors installed on the structure. These indexes, calculated locally, play a fundamental role in estimating the global damage.

It is important to clarify that the comparison between the different type of indexes, each one characterized by its own mathematical formulation based on different parameters, is possible only by introducing a normalization which sets the range from 0 (no damage) to 1 (element collapsed) for each index. In this way, it is possible to define a clear and objective comparison between the indexes and assess the most efficient index in assessing the post-seismic conditions of the structure.

In the following, some of the most relevant damage indexes before (DI_i) and after normalization ($DI_{i\text{-}N}$) are described.

2.1. Lybas and Sozen (1977)

$$DI_1 = \frac{k_0}{k_m}; \quad DI_{1-N} = \frac{C}{DI_1} - C \tag{1}$$

Where:

$$C = \frac{k_e}{k_u - k_e} \tag{2}$$

2.2. FDR Banon (1981)

$$DI_2 = \frac{\frac{d_m}{F_m} - \frac{d_y}{F_y}}{\frac{d_u}{F_u} - \frac{d_y}{F_y}} \tag{3}$$

The index is already configured in the range 0-1.

2.3. Banon and Veneziano (1982)

$$DI_3 = \sqrt{\left(\frac{d_m}{d_y - 1}\right)^2 + \left[\left(\frac{2E_h}{F_y d_y}\right)^{0,38}\right]^2}; \quad DI_{3-N} = \frac{DI_3}{DI_u - DI_e} - \frac{DI_e}{DI_u - DI_e} \tag{4}$$

2.4. Hwang and Scribner (1984)

$$DI_4 = \sum_{i=1}^{n} \frac{k_i {d_i}^2}{k_e {d_y}^2}; \quad DI_{4-N} = \frac{DI_4}{DI_u - DI_e} - \frac{DI_e}{DI_u - DI_e} \tag{5}$$

2.5. Park and Ang (1985)

$$DI_5 = \frac{d_m}{d_u} + \frac{\beta}{F_y d_u} \int dE; \quad DI_{5-N} = \frac{DI_5}{DI_u - DI_e} - \frac{DI_e}{DI_u - DI_e} \tag{6}$$

Where:

$$\beta = \left(-0,447 + 0,073\frac{L}{d} + 0,24n + 0,314\rho_t\right) \cdot 0,7^{\rho_\varpi} \tag{7}$$

2.6. Wang and Shah (1987) – 1st formulation

$$DI_6 = 1 - \frac{F_y}{F_m}; \quad DI_{6-N} = \frac{DI_6}{DI_u - DI_e} - \frac{DI_e}{DI_u - DI_e} \tag{8}$$

2.7. Wang and Shah (1987) – 2nd formulation

$$DI_7 = \frac{e^{\eta\beta} - 1}{e^{\eta} - 1} \tag{9}$$

Where:

$$\beta = 0.15 \cdot \sum_{i=1}^{n} \frac{d_i}{d_u} \tag{10}$$

In particular, η ranges from -3 to -1 and the normalization is reached as in the previous index by normalizing the coefficient β.

2.8. Powell and Allahabadi (1988)

$$DI_8 = \frac{\mu_m - 1}{\mu_u - 1} \tag{11}$$

The index is already configured in the range 0-1.

2.9. Global damage assessment

These local damage indexes could be combined to achieve a global damage index of the whole building. This procedure is herein made considering a weighted average with the dissipated energy as weights:

$$D_{floor} = \frac{\sum_{i=1}^{n} D_i E_i}{\sum_{i=1}^{n} E_i}; \quad D_{structure} = \frac{\sum_{i=1}^{N} D_{floor,i} E_{floor,i}}{\sum_{i=1}^{N} E_{floor,i}} \tag{12}$$

3. Application to a reference case study

The efficiency of each index is assessed by applying its formulation to a specifically designed building representative of a typical Italian post-WWII RC building. The considered 4-story building has a rectangular plant (9.6m x 10m) and RC beam and block floors supported by 40cmx25cm beams (edge beams) and 70cmx25cm beam (spine beam). Regarding the vertical elements, the structure is composed by 12 columns disposed in a regular 4m x 3m grid. The structural elements are made of concrete C25/30 and steel Feb44k (f_y = 440MPa) rebars (Table 1). The analysis is herein conducted on a central frame of the building (Fig. 1).

Table 1. Dimensions of structural element and rebars.

Element	Dimension	Rebars
Column	30cmx30cm	4 ϕ14 / 4 ϕ14
Spine beam	70cmx25cm	4 ϕ14+4 ϕ18 / 4 ϕ14+3 ϕ18
Edge beam	40cmx25cm	4 ϕ14 / 4 ϕ14

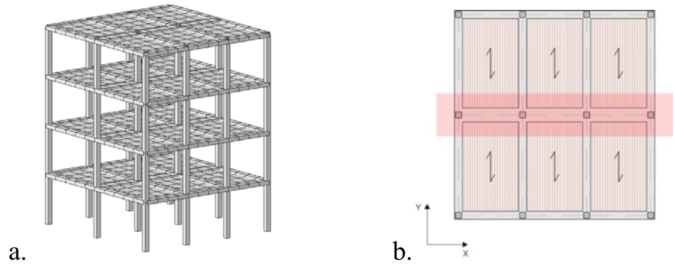


Fig. 1. (a) RC Structure; (b) Chosen RC Frame.

The FE model of the selected RC frame is developed through *Opensees* (Mckenna and Fenves, 2013) with "elasticBeamColumn" type elements for beams and columns. The non-linearities are introduced through "zeroLength" elements at the end of each element. The "uniaxialMaterial Hysteretic" model was considered and defined according to the details in Table 1 and the actual axial load in the elements. Furthermore, it is important to define the hypothesis made about the infill: the chosen configuration is 12cm (brick) +6cm+ 12cm (brick) and the specific characteristics have been derived from Hak et al. (2013). The infills are modelled using compression only bi-diagonal truss through "twoNodeLink" elements associated with a "uniaxialMaterial Concrete01" hysteresis. The definition of the backbone curve is based on the Decanini (1993) and Sassun (2016) model. Two sets of nonlinear time history analyses were conducted on the reference RC frame with and without the infills. 48 ground motions taken from the Italian database ITACA (Table 2) were considered with increasing magnitude and epicentral distance. The selected earthquakes were applied to each of the principal directions of the building one at the time, H1 and H2.

Table 2. Chosen earthquake ground motions.

Earthquake	M_w	Soil category	Event date	Epicentral distance		
				A (km)	B (km)	C (km)
Gubbio	3	B	08/01/2014	7.2	34.4	82.3
Fiordimonte (MC)	4	D	27/11/2016	5.8	29.9	61.1
Norcia	4	A	31/10/2016	5.2	31.6	81.4
Ponte San Pellegrino (MO)	5	C	20/05/2009	7.4	31.5	80.4
Norcia	5	E	18/01/2017	17.7	34.1	76.4
L'Aquila	5	B	18/01/2017	9.7	20.2	74.3
L'Aquila	6	B	06/04/2009	4.9	30.8	80.1
Capo del Colle (PG)	6	A	30/10/2016	11	26	91.1

In the first set of analyses the infills are considered only in term of mass. The damage indexes are calculated either using bending moment and rotation values or using the floor shear forces and the inter-story drifts. In this regard, the reference values for each story have been calculated through nonlinear static analyses (Table 3).

Table 3. RC Frame characteristics in term of story shear and inter-story drift without infills.

Floor	F_y (kN)	d_y (mm)	F_u (kN)	d_u (mm)
1	263	10.5	286	46.0
2	226	8.9	252	63.0
3	187	7.6	210	91.0
4	143	6.0	165	126.0

The results of the analyses show that only 9 earthquakes led to the nonlinear behavior of the plastic hinges, while only 4 of them overcome the yielding shear force in, at least, one floor (Fig. 2).

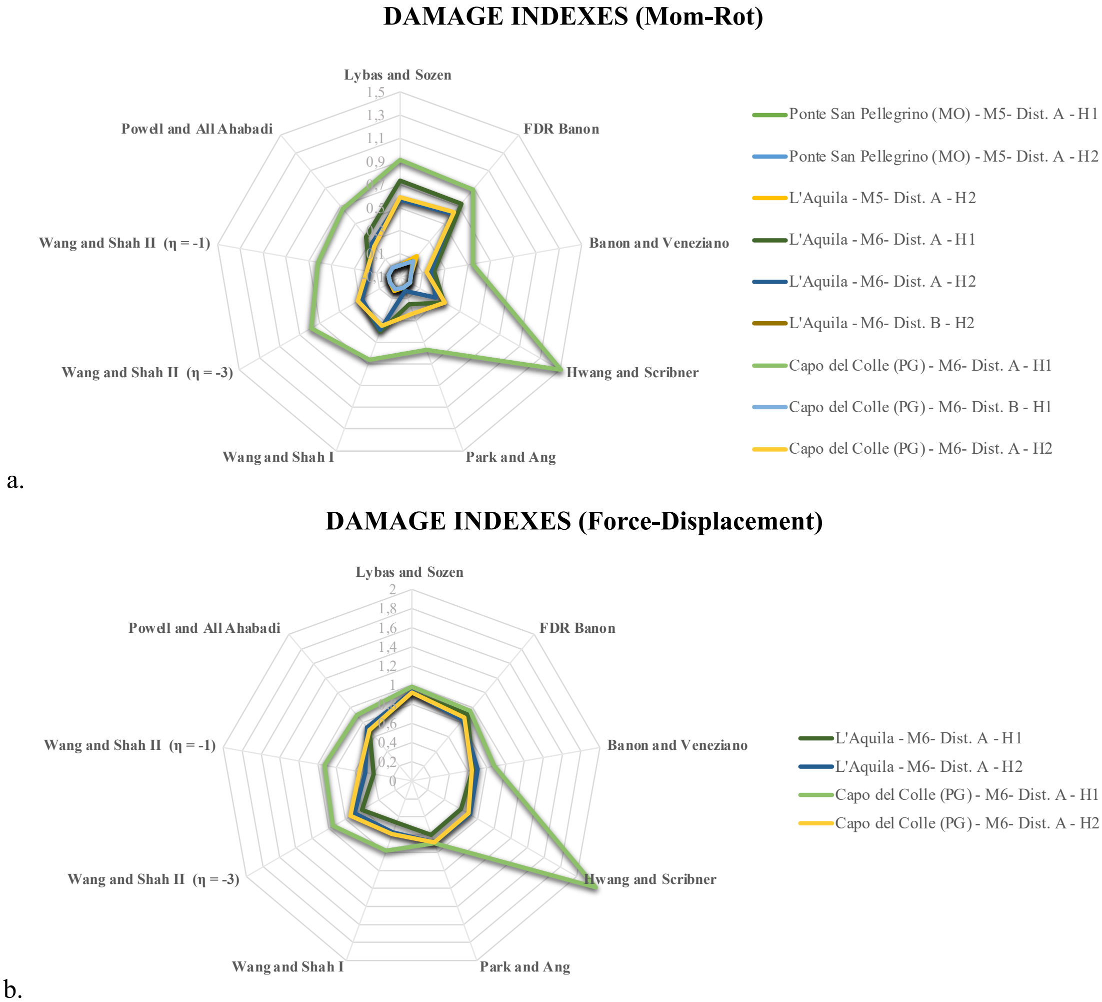


Fig. 2. (a) Damage indexes based on bending moment and rotation; (b) Damage indexes based on shear and inter-story drift.

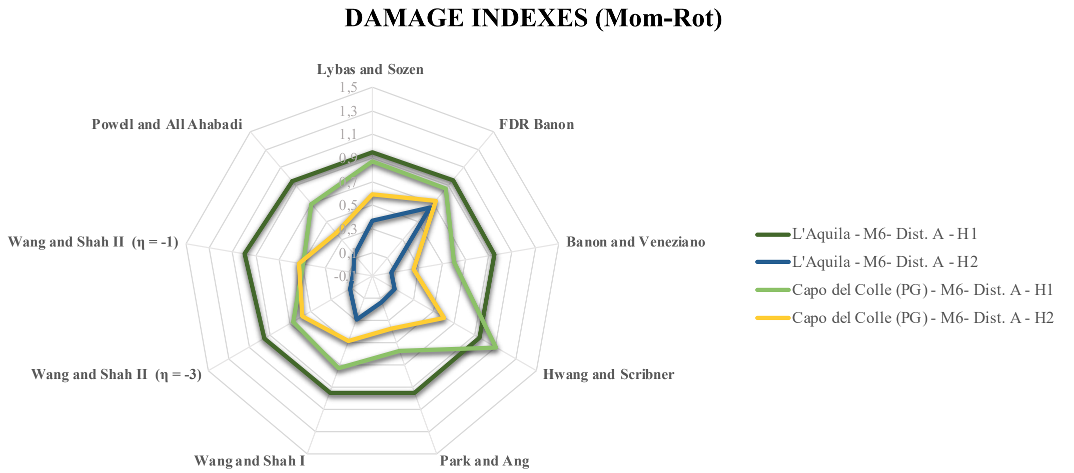
Starting from the damage indexes calculated from the bending moment and rotation values, it is clearly observable that all the formulations are able to detect the most relevant earthquakes in terms of damage. Nevertheless, Lybas and Sozen and FDR Banon indexes are not efficient in expressing the different rates of damage, overestimating the global damage for less damaging earthquakes. This fact highlights the tendency of these damage indexes to give more attention in the maximum inelastic deformation achieved by each element rather than in terms of dissipated energy. Banon and Veneziano and Park and Ang damage indexes show the opposite result with a slight underestimation on the value associated with the dissipated energy. The best results in terms of ability to express the damage are achieved by Wang and Shah (I formulation) and Powell and Allahabadi damage indexes. The mathematical formulation of Hwang and Scribner and Wang and Shah (II formulation) damage indexes prevents the comparison with other indexes since a value greater than one could be obtained.

The same considerations apply also to the formulations related to story shear and inter-story drifts with the exception of Park and Ang damage index that in this case overestimates the damage and Banon and Veneziano damage index that fits perfectly. It is worth noting that the efficiency of each index could not correspond to the easiness of calculation of the parameters involved in the formulations: the indexes related to rotation and displacement of a structural element after an earthquake are easier to be manage than, for example, Powell and Allahabadi indicator, which is based on the ductility achieved by an element.

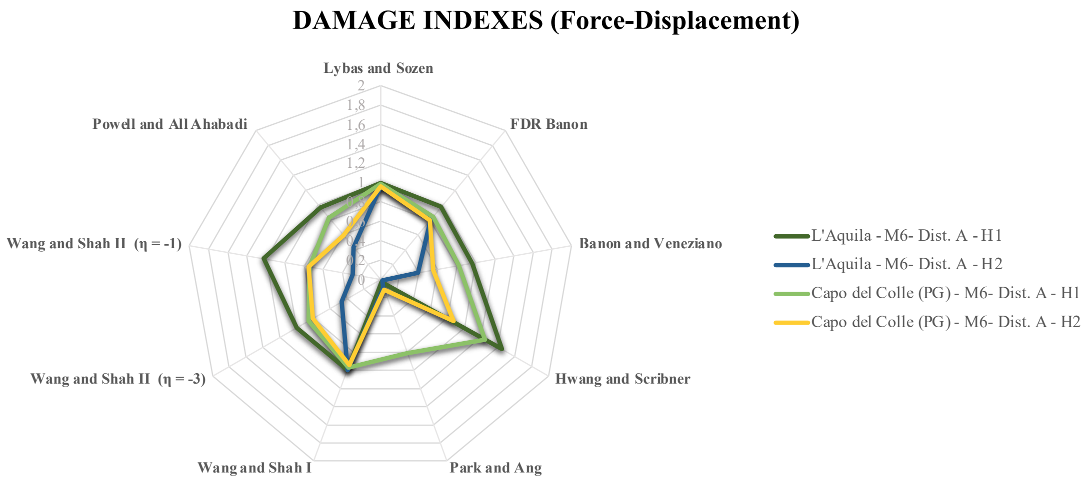
The second set of analyses considered the infills as diagonal strut elements. The reference values in terms of story shear and inter-story drift have been calculated through nonlinear static analyses (Table 4). The results of the analyses show that only 4 earthquakes led to the nonlinear behavior of the plastic hinges and to overcome the yielding shear force in, at least, one floor (Fig. 3).

Table 4. RC Frame characteristics in term of story shear and inter-story drift with infills

Floor	F_y [kN]	d_y [mm]	F_u [kN]	d_u [mm]
1	703	10.9	454	45.5
2	644	11.3	213	64.8
3	625	11.0	173	92.7
4	589	10.9	141	125.9



a.



b.

Fig. 3. (a) Damage indexes based on bending moment and rotation; (b) Damage indexes based on shear and inter-story drift.

The same comments related to the RC frame without infills substantially apply in the case with infills except for the shear-drift calculation where the Park and Ang damage index is not able to detect the most damaging earthquake and Wang and Shah (I formulation) overestimates the value. The RC frame with infills highlights that the combination of the stiffening effect of the infills and the spectral shape of the ground motion makes the earthquake *L'Aquila - M6-Dist. A - H1* the most damaging one, probably due to a displacement demand concentration after failure of the infills of one story.

4. Conclusion

The study conducted on the damage indexes demonstrates their potentiality in the definition of the structural safety of an existing building after an earthquake. The damage indexes based on the values of the bending moment and the rotation are suitable in the case of a structure that has a minimum equipment of sensors and an associated finite element (FE) model has been defined: the accelerometers at the ground record the ground accelerations; the recorded data are transferred to the cloud where a time history analysis is conducted on the FE model to determine the bending moments and the rotations in the plastic hinges of each element allowing for the calculation of the damage indexes. Taking into account the damage indexes that involve the story shear and the inter-story drift, these ones may be associated with a wider distribution of sensors on the structure. In this case, at least two accelerometers per floor (one for each of the principal directions) are recommended to obtain the floor acceleration and, through a double integration process or other algorithms, the inter-story drift. The advantage of this approach lies in the direct calculation of the damage indexes without the requirement of a FE Model of the building.

Both approaches have been applied to a selected case study by means of nonlinear time history analyses after the normalization of the damage indexes. The results allowed to highlight the most suitable damage indexes in identifying the seismic damage.

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