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Damage assessment of squat, thin and lightly-reinforced concrete walls by the Park & Ang damage index

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ABSTRACT

Damage progression indexes are widely used to evaluate the performance of structural elements in buildings and bridges subjected to seismic actions. Although the Park & Ang damage index is currently implemented in several computational tools, the index has not been calibrated for squat and thin reinforced concrete (RC) elements controlled by shear deformations. It has been observed that the equations originally proposed for the Park & Ang damage index are unsuited for these types of structural elements, which are characterized by a failure mode dominated by shear instead of flexural deformations. The index was evaluated in this study for squat, thin and lightly-reinforced concrete walls using experimental data from a program comprising monotonic and reversed-cyclic load testing of 25 RC squat cantilever walls. The experimental program included walls, with and without openings, having height-to-length ratios equal to 0.5, 1.0 and 2.0. Full-scale wall thickness and clear height were 100 mm and 2.4 m, respectively. The specimens were built using three different types of concrete (normal-weight, light-weight and self-consolidating) with nominal compressive strength of 15 MPa. A novel formulation for the parameter β included in the Park & Ang damage index was proposed in this study using key variables of the wall specimens such as web reinforcement ratio and cumulative ductility. Comparison between the computed damage index and crack pattern evolution observed in wall specimens at different damage states demonstrated the ability of the model to numerically assess the damage of the wall specimens. Hence, this new formulation proposed for parameter β leads to a better estimation of damage for this particular type of elements when applying the broadly used Park & Ang damage index.

1. Introduction

Several structural response parameters can be associated with damage, such as drift, permanent deformations and energy dissipated by hysteresis. The challenge for the structural analysts is to detect and characterize the severity of damage and to determine the remaining capacity of the structure before reaching the failure condition. To achieve this in an effective way, it is deemed necessary to define threshold for the maximum or cumulative values of these parameters, and provide mechanical conditions that guarantee an optimal structural performance within these predefined limits. Damage index (*DI*) is a concept introduced for assessing damage in a quantitative manner. It consists on mathematical functions based on several structural parameters that quantify the structural damage in a scale varying between 0 and 1; zero for the no damage condition and one for the structural failure state [1]. In the case of reinforced concrete (RC), parameters such as non-recoverable deformations, displacement ductility and energy dissipated by hysteresis are generally considered as suitable damage parameters to introduce in these damage index functions [2].

Damage indexes have been used for more than 40 years [1–8]. One of the most widely used *DI* is the formulation proposed by Park & Ang [3, 4]. The index was conceived to quantify the structural damage for slender elements (beams or columns) that generally fail by flexural deformations. There is, however, a large inventory of buildings conformed by squat structural elements (walls), which failure mode is dominated by shear deformations and parameters for the Park & Ang *DI* (DI_{PA}) have not been calibrated. In particular, due to economic reasons, a large percentage of recent low- and medium-rise (up to four-story height) residential buildings in some countries in Latin America consists of RC walls with thickness smaller than 150 mm and only one center layer of

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Table 1
The Park & Ang damage index for different states of damage.

DI_{PA}	Observed damage
0.00–0.10	No damage - Localized minor cracking
0.10–0.25	Light damage - Minor cracking throughout.
0.25–0.40	Moderate damage - Severe cracking and localized spalling.
0.40–0.80	Severe damage - Crushing of concrete and exposure of reinforcing bars.
>0.80	Failure - Total failure of the structure.

web reinforcement.

Previous studies have investigated the capability of the DI_{PA} in assessing damage on squat elements (walls) showing that current parameters are not well suited to make accurate estimations for this type of structures [7,8]. Previous experimental programs have provided information about the seismic behavior of low aspect ratio reinforced concrete thin walls [9–14], and there are some studies aimed at evaluating its seismic performance in terms of damage. For instance, Carrillo and Alcocer [14] utilized a damage index based on the relation between the damaged area (area of cracks) and the area of the façade of the RC wall. Carrillo [6] proposed a damage index based on the stiffness degradation of walls. Such index depends on the story-drift ratio and the number of cycles experienced by the wall during a particular seismic event. Carrillo et al. [5] proposed a damage index to estimate the damage level and the residual performance based on the fractal dimension of the cracking recorded after an earthquake. Although damage index formulated by Park & Ang [3,4] is currently implemented in several computational tools, the index has not been calibrated for squat and thin elements controlled by shear deformations. Thereby, to improve the estimation of damage for squat, thin and lightly-reinforced concrete walls when applying the broadly used Park & Ang damage index, a novel formulation for the parameter β included in the Park & Ang damage index is proposed in this study. This novel equation is based on the experimental results obtained from quasi-static monotonic and reversed-cyclic test performed on 25 reinforced concrete walls. Damage of walls was initially assessed using the original formulation of Park & Ang [3,4]. Regression analyses were then performed for parameter β considering some of the variables originally considered by Park & Ang. Finally, the computed damage index was compared with the crack pattern evolution observed in typical walls at three different damage states.

2. The Park & Ang index

The original formulation proposed by Park & Ang [3,4] consists of a linear combination of the damage caused by excessive post-elastic deformations and the energy dissipated by the hysteresis or repeated cyclic loading effect of the element, as shown in Eq. (1).

$$\boldsymbol{DI_{PA}} = \frac{\boldsymbol{u_{max}}}{\boldsymbol{u_{mon}}} + \boldsymbol{\beta}\frac{\boldsymbol{E_H}}{\boldsymbol{F_y} \cdot \boldsymbol{u_{mon}}} \tag{1}$$

where $u_{\max}$ is the ultimate deformation recorded on the element due to reversed-cyclic loading, u_{mon} is the ultimate deformation recorded on the element for monotonic loading, E_H is the total energy dissipated by hysteresis cycles, F_y is the yield strength of the element, and β is a non-negative parameter. Based on experimental data, the mentioned authors defined that the non-negative parameter β for slender elements is a function of the confinement ratio (ρ_w), the shear span ratio (l/d), the longitudinal reinforcement ratio (ρ_t) and the normalized axial force (n_0), as presented in Eq. (2).

$$\boldsymbol{\beta} = 0.7^{\boldsymbol{\rho_w}}\left(-0.447 + 0.073\frac{\ell}{d} + 0.24\boldsymbol{n}_0 + 0.314\boldsymbol{\rho_t}\right) \tag{2}$$

The variables are limited to the following values: ρ_w varying between 0.2% and 2.0%, l/d between 1.0 and 6.6, n_0 between 0 and 0.52, ρ_w between 0.04% and 0.45%, and f'_c between 16 and 41 MPa. In addition, the variables must be considered as $l/d = 1.7$ when $l/d < 1.7$, $n_0 = 0.2$ when $n_0 < 0.2$ and $\rho_t = 0.75\%$ when $\rho_t < 0.75\%$. Table 1 shows the values of DI_{PA} reported by further investigations [15,16]. As shown in the table, these values are associated to different damage states.

Stephens and Yao [17] proposed a modified version for DI_{PA} to incorporate the effect of cumulative plastic deformations. These authors used this modified approach to assess the structural damage in a numerical model of a reinforced concrete frame structure tested under seismic actions. In this way, the DI_{PA} obtained from this numerical analysis was compared with the damage observed during seismic testing. The damage estimation obtained by the numerical model was consistent with the localized damage observed in the columns located at

Table 2
Main characteristics of wall specimens.

No.	Wall specimen	h_w mm	t_w mm	l_w mm	h_w/l_w	Type of concrete, f_c' MPa	Type of web reinf., f_y, MPa	Web reinf. % (ρ_w)	Boundary reinf. % (ρ_l)	Type of testing
3	MCN100 M	2417	101	2402	1.01	N, 18.8	D, 447	0.28	0.98	M
5	MCL50 M	2427	102	2397	1.01	L, 16.3	D, 447	0.14	0.68	M
6	MCL100 M	2425	101	2398	1.01	L, 16.3	D, 447	0.28	0.98	M
8	MCS100 M	2424	102	2397	1.01	S, 19.4	D, 447	0.28	0.97	M
10	MCN100C	2432	101	2397	1.01	N, 17.5	D, 447	0.28	0.98	C
12	MCS100C	2426	103	2401	1.01	S, 22.0	D, 447	0.28	0.96	C
17	MRN100C	2433	100	5400	0.45	N, 16.2	D, 447	0.28	0.22	C
18	MEN100C	2435	100	1240	1.96	N, 16.2	D, 447	0.28	1.50	C
19	MRN50C	2425	100	5400	0.45	N, 16.2	D, 447	0.14	0.22	C
20	MEN50C	2421	100	1240	1.95	N, 16.2	D, 447	0.14	1.04	C
21	MRL100C	2423	101	5413	0.45	L, 5.2	D, 447	0.28	0.32	C
22	MRN50mC	2401	103	5396	0.44	N, 20.0	W, 605	0.12	0.22	C
23	MCN50mC	2396	103	2398	1.00	N, 20.0	W, 605	0.12	0.72	C
24	MEN50mC	2399	101	1239	1.94	N, 20.0	W, 605	0.12	0.96	C
25	MRL50mC	2419	106	5415	0.45	L, 5.2	W, 605	0.12	0.21	C
26	MCL50mC	2423	100	2403	1.01	L, 26.0	W, 605	0.12	0.74	C
27	MEL50mC	2435	100	1221	1.99	L, 26.0	W, 605	0.12	0.82	C
28	MVN100C	2397	110	3826	N/A	N, 16.0	D, 447	0.26	0.82	C
29	MVN50mC	2397	110	3826	N/A	N, 16.0	W, 605	0.11	0.74	C
30	MCN50C-2	2400	100	2398	1.00	N, 20.0	D, 447	0.14	0.71	C
31	MCS50C-2	2404	104	2402	1.00	S, 27.1	D, 447	0.14	0.71	C
32	MCL50C-2	2426	100	2441	0.99	L, 26.0	D, 447	0.14	0.73	C
33	MCL100C-2	2432	98	2407	1.01	L, 5.2	D, 447	0.29	1.01	C
34	MCN50mC-2	2404	102	2401	1.00	N, 8.9	W, 605	0.12	0.73	C
35	MRN50mC-2	2401	100	5400	0.44	N, 8.9	W, 605	0.13	0.22	C