ASSESSMENT OF THE COLLAPSE CAPACITY OF P-DELTA SENSITIVE SYSTEMS THROUGH THE DDBA METHOD

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ABSTRACT

Current simplified methods for the assessment of the collapse capacity of p-delta sensitive systems rely on predictive equations calibrated from the results of nonlinear dynamic analysis performed for specific hysteresis rules, softening ratios or stability indices, and ground motion records. This phenomenological interpretation of the seismic response hinders the applicability of such methods to different hysteretic behaviors and to records of different spectral characteristics.

This study proposes an approach for the simplified seismic assessment of the incremental response and collapse capacity of p-delta sensitive systems. The approach is built upon the principles of the Direct Displacement-Based Assessment method; therefore, it is capable of accounting for arbitrary response spectrum shapes and for a number of hysteresis models. The effect of a negative stiffness branch on system response is explained and quantified through an analogy based on conservation of hysteretic energy. Application of the method is illustrated for a case study building of 4, 8, 12 and 20 storeys.

Keywords: P-delta effects; direct displacement-based assessment; collapse capacity; incremental seismic response

1. INTRODUCTION

Evaluation of the safety factor against collapse and of the probability of collapse are key aspects in performance-based design and assessment of building structures. Estimation of the collapse capacity often involves elaborated numerical models and lengthy analysis times. Nonetheless, during conceptual and basic design and retrofit design, a priori (or fast) estimations of the seismic response and collapse capacity are convenient to gauge the performance of different structural alternatives or to make timely adjustments to the design. The complexity of the numerical analyses are prohibitive during these stages, and simplified seismic response assessment methods are often considered.

Simplified methods for the seismic response assessment of p-delta sensitive structures have been proposed in Bernal (1987), Bernal (1992), Miranda and Akkar (2003), ATC (2005), Adam and Jäger (2012), and Belleri et al. (2016), among others. Out of these methods, only the Miranda and Akkar’s (2003) and Adam and Jäger’s (2012) are intended for the estimation of the collapse capacity, whilst the other methods are applicable only for intensity-based assessments. The Miranda and Akkar’s and Adam and Jäger’s methods are based on R-μ-T relationships that are calibrated from the results of nonlinear time-history analyses (NTHAs) run on SDOF systems, using specific ground motion (GM) record sets and hysteresis models.

Studies by Ibarra and Krawinkler (2005), and Adam and Jäger (2012) have pointed out the relevance of...
the hysteresis model, and in particular of its re-centering capabilities, in the collapse capacity of p-delta sensitive systems. In addition, studies by Baker and Cornell (2006) and Haselton et al. (2011) have demonstrated that seismic response and collapse capacity are dependent on the shape of the response spectrum (using the shape of the response spectrum as a proxy for the frequency content and intensity of a GM record set). These two factors indicate that the applicability of the simplified methods mentioned before, is restricted to hysteresis models and seismic conditions (GM records or spectrum shapes) that resemble the ones used in their respective calibration efforts. Desirable characteristics in a general simplified assessment method are then, precisely, the capability to account for arbitrary response spectrum shapes and for different hysteretic behaviors. These are recognized capabilities of the direct displacement-based assessment method (DDBA) (Priestley et al., 2007); nonetheless, this method has not evolved sufficiently as to account for system response and collapse capacity under p-delta actions.

The present study proposes a general approach for the assessment of the seismic response and collapse capacity of p-delta sensitive systems. To take advantage of the capabilities of the DDBA method, the approach is incorporated into its framework. The effect of response degradation, due to p-delta effects, is addressed through an analogy based on the equilibrium of an applied energy demand and absorbed hysteretic energy. The fundamentals of the p-delta phenomenon and of the DDBA method are introduced first, and then the constitutive analogy is formulated. Application of the approach for the estimation of the (incremental) seismic response and collapse capacity is illustrated for a case study RC building of 4, 8, 12 and 20 storeys.

2. FUNDAMENTALS

2.1 P-delta effects on the Monotonic and Cyclic Response of SDOF Systems

Modification of the monotonic and cyclic response due to p-delta actions is illustrated with reference to SDOF system shown in Figure 1a. Before application of the gravity loads, the system is regarded as a non-degrading system with characteristic monotonic and cyclic behavior shown in Figure 1b. The monotonic response is defined by the initial stiffness $K_p$, yield strength $F_p$, and post-yield hardening branch (also yield surface) with hardening ratio $r_0$. A Takeda hysteresis model is used to exemplify the cyclic behavior. Application of the vertical load $P$, causes a geometric transformation of the pushover curve which is observed as a reduction in stiffness ($K_o$), yield strength ($F_y$), rotation of the hardening branch (i.e., yield surface) and of the hysteresis loops, and a perceived reduction in lateral strength for deformations larger than the yield point (Figure 1c). This system is also regarded as a strength-degrading system.

Rotation of the hysteresis loops is characterized through the hysteresis curve centre (HCC) (MacRae, 1994); an imaginary line that connects the midpoint between the upper and lower yield surfaces. The slope of the HCC is computed from Equation (1) below.

![Figure 1](image-url)
where $\theta_{PA}$ is the stability index defined in Equation \(\theta_{PA} = \frac{P}{K_p H} \).

Identification of the HCC line and the yield surfaces is required in order to locate the unloading, reloading, and yielding points, in the positive and negative directions (Figure 1c). In addition, a negative slope of the HCC line is an indicator of unstable cyclic response, which is observed as the progressive accumulation of residual deformations towards a preferential direction, or ratcheting (Ibarra and Krawinkler, 2005), and a more rapid transition towards collapse.

### 2.2 Direct Displacement-Based Assessment (DDBA)

In DDBA, a seismic action, represented by an over-damped displacement response spectrum ($\eta S_d(T)$), imposes on an equivalent linear system a displacement demand, $\Delta$, estimated as per Equation (3). The equivalent linear system is defined as one with effective period, $T_e$, secant stiffness, $K_e$, and equivalent viscous damping (EVD), $\xi_{eq}$, at peak displacement response (Priestley et al., 2007).

$$\Delta = \eta \cdot S_d(T_e)$$  \hspace{1cm} (3)

In the equation above, $\eta$, is the displacement-modification factor (DMF) obtained from $\xi_{eq} - \mu$ relationships (Priestley et al., 2007), or alternatively, directly from $\eta - \mu$ relationships (Pennucci et al., 2011). It is relevant to point out that DMFs are sensitive to the shape of the response spectrum; more specifically, that higher DMFs (lower dissipation) are obtained for displacement response spectra that exhibits a displacement plateau or corner period (Pennucci et al., 2011). This is particularly important for tall buildings with fundamental or the effective periods larger than the corner period. An approach to account for spectral shape effects in $\eta - \mu$ relationships is developed in Perez (2018) and the reader is referred to that reference for further information.

In general, the DDBA method has been used in intensity-based seismic performance assessments; nonetheless, if the objective is to estimate the collapse capacity of the system, then an incremental dynamic analysis (IDA) format may be more convenient. In a conventional IDA (Vamvatsikos and Cornell, 2002), a GM record (or an ensemble of them), is scaled up monotonically by a scaling function $\lambda$. Nonlinear time-history analyses (NTHA) are performed on the system, and the system response is recorded for each GM record and scaling factor. Since scaling of the amplitudes of a GM record does not modify its frequency content (Vamvatsikos and Cornell, 2002), the scaling of its response spectrum is an equivalent representation of an incremental seismic demand. Extension of this concept to Equation (3) permits to express the basic DDBA equation in incremental form as:

$$\Delta_i = \lambda_i \left[ \eta_i \cdot S_d(T_e) \right]$$ \hspace{1cm} (4)

where the subindex $i$ refers to the $i$-th displacement increment. The scale factor that produces a given displacement demand is then estimated as:

$$\lambda_i = \frac{\Delta_i}{\eta_i \cdot S_d(T_e)}$$ \hspace{1cm} (5)

The format of Equation (5) is chosen intentionally so that IDA curves can be created in a displacement-
controlled fashion. This means that a vector of displacement demands (consistent with the pushover curve) is defined a priori from which a vector of $\lambda_i$ factors is obtained. Selecting as intensity measure (IM) the $\text{Sa}(T_i)$ value, the seismic capacity of the system can be defined as $R_{\mu} = \lambda \text{Sa}(T_i)$, or in expanded form as per Equation (6).

$$R_{\mu} = \frac{\Delta_i}{\eta \cdot \text{Sd}(T_{ei})} \cdot \text{Sa}(T_i)$$

(6)

3. FORMULATION OF THE APPROACH

3.1 The Constitutive Analogy

The effect of strength degradation in the seismic response of a system is interpreted as the reduction in the energy absorption capacity caused by the progressive reduction in lateral strength and the instability of the hysteresis loops (i.e., ratcheting). Quantification of the reduction in the energy absorption capacity is carried out through comparison of the displacement response of a non-degrading system and an elastic-softening one, when subjected to the same seismic action. In order to offer a simple, yet concise, representation of the phenomenon, seismic demand and system response are represented through an analogy. Fixed energy demands applied in the positive and negative directions represent the seismic actions ($E_d$). Under the assumption that inertial and damping effects are negligible, the absorbed hysteretic energy ($E_a$) constitutes the only resisting component; hence, system response is obtained as the displacement at which the applied and absorbed hysteretic energies are equal ($E_d = E_a$).

The approach is illustrated for a Takeda thin hysteresis model in Figure 2. First, the non-degrading system is subjected to the energy input $E_{d1}$ that produces a displacement demand, $\Delta_{11}$, in the first direction of loading. The same energy input is applied to the elastic-softening system, what results in a displacement response, $\Delta_{11} > \Delta_{11}$. Second, a symmetric response is enforced in the non-degrading system by applying an energy input, $E_{d2}$, in the unloading direction (first unloading). Application of the energy input $E_{d2}$ to the elastic-softening system produces a displacement response $\Delta_{12} > \Delta_{11}$. Finally, to complete one full hysteretic cycle, the non-degrading system is subject to the energy input, $E_{d3}$, that pushes the system back to the displacement $\Delta_{11}$ (first reloading). Once more, the energy input $E_{d3}$ is applied to the elastic-softening system, that produces a displacement demand $\Delta_{12} > \Delta_{11} > \Delta_{11}$. Application of the procedure to obtain the second hysteresis cycle is also shown in Figure 2. It is noted that at completion of the second cycle the hysteresis loops replicate, to some extent, the ratcheting effect that characterizes the seismic response of p-delta sensitive systems. Consequently, the displacement response at the end of the cycle is, $\Delta_{13} > \Delta_{12}$. Although the increase in displacement after each cycle serves as an indicator of the degradation in system response, a more convenient proxy is defined in Section 3.2.

One important aspect of the proposed approach is its dependency on the applied number of hysteretic cycles. In theory, definition of the number of cycles might respond to criteria such as duration and frequency content of the ground motion. Nonetheless, for practicality of the intended approach it is necessary to define an arbitrary number of cycles. As will be shown in the next section, the responses obtained for three or more cycles tend to saturate; therefore, for simplicity, two full hysteretic cycles are adopted for the further development of the proposed approach.
3.2 Proxy for the Degradation in Response

Quantification of the degradation in response, due to p-delta effects, is performed through direct comparison of the incremental response of the non-degrading and strength-degrading systems. To this end, the procedure described above is applied under incremental energy demands to obtain incremental response curves (IRC) that relate the scaled energy input, $\lambda E_d$, with the displacement response, $\Delta$, in a format similar to that of an IDA curve. In an IRC, the energy input corresponds to the cumulative energy applied at the end of the second hysteretic cycle (i.e., $E_d = E_d1 + E_d2 + \ldots + E_d5$). For convenience the energy input is normalized by the strain energy at yielding, $E_y$, and the displacement response is normalized by the yield displacement, $\Delta_y$. Sample IRCs of a non-degrading and an elastic-softening system are shown in Figure 3. The degradation in response, $\delta_s$, is defined as the ratio between the slopes of the IRCs of the elastic-softening system, $S_i,D$, and the non-degrading system, $S_i$, measured at the displacement demand $\Delta_i/\Delta_y$. The concept is defined in Equation (7), and illustrated in Figure 3.

$$\delta_s = \frac{S_i,D}{S_i}$$  (7)
Because the $\delta s$ ratio varies along the softening branch, the degradation in response is better represented through a continuous function, or response-degradation function (RDF). The RDFs are more conveniently expressed in terms of the strength ratio, $F_i/F_y$, instead of the displacement ratio $\Delta_i/\Delta_y$. For an elastic-softening system, the strength ratio is computed from Equation (8), below. Only for the scope of this study, a polynomial function has been fitted to the RDF of the second hysteresis cycle; the function is presented as Equation (9). A sample of the IRCs and corresponding RDFs obtained for the first four hysteretic cycles of an elastic-softening system with $r_p=-0.10$, and with a Takeda thin hysteresis model, is shown in Figure 4. Note that, as anticipated in section 3.1, system response tends to saturate after the second hysteretic cycle.

\[
F_i / F_y = 1 - r_p \left( \frac{\Delta_i}{\Delta_y} - 1 \right) 
\]  
(8)

\[
\delta s_i = -9.54 \left( \frac{F_i}{F_y} \right) ^5 + 20.73 \left( \frac{F_i}{F_y} \right) ^4 - 14.25 \left( \frac{F_i}{F_y} \right) ^3 + 4.26 \left( \frac{F_i}{F_y} \right) ^2 - 0.23 \left( \frac{F_i}{F_y} \right) + 0.013 
\]  
(9)

![Figure 4. Sample (a) incremental energy curves and (b) response-degradation functions for the first four hysteretic cycles of an elastic-softening system with Takeda thin hysteresis model.](image)

### 3.3 Incorporating Response-Degradation Functions into the DDBA Method

Incorporation of the RDFs into the DDBA method is also addressed through an analogy between IRC and IDA curves. For this purpose, Equation (7) is first rewritten in a discrete form as shown in Equation (10).

\[
\delta s_i = \left( \frac{E_{d_i,D} - E_{d_{i-1},D}}{\Delta_i - \Delta_{i-1}} \right) / \left( \frac{E_{d_i} - E_{d_{i-1}}}{\Delta_i - \Delta_{i-1}} \right) 
\]  
(10)

The IRC of the elastic-softening system is then expressed as a function of the IRC of the non-degrading system and the RDF, as shown in Equation (11).

\[
E_{d_i,D} = E_{d_{i-1},D} + \delta s_i \times \left( \frac{E_{d_i} - E_{d_{i-1}}}{\Delta_i - \Delta_{i-1}} \right) \times (\Delta_i - \Delta_{i-1}) 
\]  
(11)

Given that IRCs and IDAs are analogous representations of demand and capacity, it is hypothesized that the incremental seismic response of a p-delta sensitive system can also be obtained from the IDA curve of a non-degrading system, and a RDF that accounts for degradation in system response. Therefore, from analogy with Equation (11), the IDA curve of a p-delta sensitive system can be written as:
\[ R_{\mu,D} = R_{\mu-1,D} + \delta \eta \times \left( \frac{R_{\mu} - R_{\mu-1}}{\Delta_{\mu} - \Delta_{\mu-1}} \right) \times (\Delta_{\mu} - \Delta_{\mu-1}) \]  

(12)

where \( R_{\mu,D} \) and \( R_{\mu-1,D} \) are the seismic capacities of the non-degrading and the strength-degrading systems, respectively. Substituting Equation (6) into Equation (12), the seismic capacity of the p-delta sensitive system can be defined as per Equation (13). In addition, assuming that in the interval, \( \Delta_{i-1} \) to \( \Delta_{i} \), the DMFs are approximately constant, i.e., \( \eta_{i-1} \approx \eta_{i} \), Equation (13) can be simplified into Equation (14):

\[ R_{\mu,D} = R_{\mu-1,D} + \delta \eta \times \left( \frac{\Delta_{i}}{\eta_{i} \cdot \text{Sa}(T_{d})} - \frac{\Delta_{i-1}}{\eta_{i-1} \cdot \text{Sa}(T_{d-1})} \right) \times \text{Sa}(T_{i}) \]  

(13)

\[ R_{\mu,D} = R_{\mu-1,D} + \left( \frac{\delta \eta}{\eta_{i}} \right) \times \left( \frac{\Delta_{i}}{\text{Sa}(T_{d})} - \frac{\Delta_{i-1}}{\text{Sa}(T_{d-1})} \right) \times \text{Sa}(T_{i}) \]  

(14)

The term \( (\eta/\delta \eta)^{-1} \), in Equation (14), represents the DMF of a p-delta sensitive system.

### 3.4 Limitations of the Proposed Approach

The approach presented in this study addresses only the strength degradation due to p-delta effects. Nonetheless, in the most general condition, strength degradation can also result from material softening (in-cycle strength degradation) and low-cycle fatigue (cycle-to-cycle degradation). An approach to account for the combined effect of p-delta actions and material softening is proposed in Perez (2018). Other limitations correspond to those of the DDBA method; namely, the buildings have to be regular in plan and elevation. Additionally, though the method is originally intended for first-mode-dominated systems, higher mode effects can be addressed, for instance, through the Effective Modal Superposition (EMS) method (Priestley et al., 2007). However, the application of such method is not considered in the present study.

### 4. APPLICATION EXAMPLE

The proposed approach is applied in the assessment of the incremental seismic response and collapse capacity of four reinforced concrete (RC) cantilever wall buildings of 4, 8, 12 and 20 storeys. The building has plan dimensions of 18m x 24m, and typical storey heights of 4.0m. The RC walls constitute the lateral-force resisting system and are located at the perimeter of the building. An interior moment frame provides support for gravity loads, but its lateral capacity is ignored for design and analysis purposes. The seismic weight per storey is 410 tones and the weight per unit area is 10kN/m². The building is assumed to be located in California; therefore, the ASCE7-10 (ASCE, 2010) code spectrum is used to estimate the design seismic actions. The spectrum is defined by spectral accelerations \( S_s = 1.5g \) and \( S_1 = 0.9g \), and with site coefficients \( F_a = 1.0 \) and \( F_v = 1.5 \). The basic design performance limits are: maximum storey drift of 2%, maximum re-bar tension strain of 0.05, and maximum concrete compressive strain of 0.02 (Sullivan et al., 2012). The adopted design method is the DDBD. More detailed design inputs and outputs are provided in Perez (2018).

Because the buildings are designed under strict performance limits, p-delta effects are negligible; this is evidenced in the first-mode pushover curve of the ‘as-designed’ system in Figure 5a. The p-delta condition is enforced by increasing the magnitude of the gravity loads until a negative stiffness branch with softening ratio, \( r_{p} = 0.10 \) is reached in the first-mode pushover curve (Figure 5a). Furthermore, in order to achieve a pure p-delta condition, the ductility capacity of the original system is increased from \( \mu = 4.5 \) to \( \mu = 11 \). The hysteretic behavior of the RC walls is defined through a Takeda thin hysteresis model, with unloading and reloading parameters, \( \alpha = 0.5 \), and \( \beta = 0.0 \), respectively. The system is subjected to IDAs using the FEMA P695, far-field record set (FEMA, 2009), which is compatible with
design spectrum. Sample percentile representations of the displacement spectra are shown in Figure 5b. The selected IM is the Sa(T₁) value, and the EDPs are the maximum displacement at the effective height, Δ₀, and the maximum drift, θₘ. The proposed approach is applied to estimate 16, 50 and 84 percentile IDA curves and collapse capacities.

Figure 5. (a) First-mode pushover curves of the as-designed system and the system with an enforced p-delta condition. (b) Sample FEMA P695, displacement response spectra.

4.1 Procedure for the Estimation of IDA Curves and Collapse Capacities

The following steps address the creation of IDA curves in terms of Rμ and Δₜₐ:

(a) Identify the controlling collapse mechanism of the system, and obtain a pushover curve representation of it. Although, adaptive pushover schemes are recommended for this purpose (Vanvatsikos and Cornell, 2005; Priestley et al., 2007), it can be proven that, for the buildings and degradation mode under consideration, a first-mode pushover curve suffices.

(b) Express the pushover curve in terms of the first-mode base shear and the displacement at the equivalent height. The displacement at the equivalent height is computed from the displacement profile at a given load increment, in the pushover procedure, as per Equation (15) below.

\[
\Delta_{di} = \sum_{k=1}^{n} \left( m_k \Delta_{ki} \right) / \sum_{k=1}^{n} \left( m_k \Delta_{ki} \right)
\]

(15)

where mₖ and Δₖᵢ are the seismic mass and lateral displacement at the storey k, n is the total number of storeys, and the subindex i indicates the load increment (or scale factor) in the pushover procedure.

(c) Discretize the pushover curve into m displacement demands, Δ₉ₖ. For each Δ₉ₖ value, compute the strength ratio, Fᵢ/Fₚ, the ductility demand, μᵢ, the effective period, Tₑᵢ, the EVD ratio, ξₑᵢ, and the DMF, ηᵢ. For an elastic-softening system, estimate the effective period as:

\[
T_{ei} = T_n \sqrt{\mu_i}
\]

(16)

(d) Adjust the ηᵢ values for spectral shape effects as proposed in Perez (2018).

(e) Using Equation (9), estimate the response degradation factor, δₛᵢ, for each Fᵢ/Fₚ ratio.
(f) Using Equation (14) and the median displacement response spectrum, estimate the median IDA curve of the system.

(g) Repeat step (f) using the 16 and 84 percentile representations of the displacement response spectra to obtain the 84 and 16 percentile IDA curves, respectively.

(g) Obtain the 16, 50 and 84 percentile collapse capacities as the maximum ordinate, $R_{\mu}$, in the corresponding percentile IDA curves.

IDA curves in terms of $R_{\mu}$ and $\theta_m$, are obtained from $R_{\mu}$-$\Delta_d$ curves, by replacing the maximum drift, $\theta_m$, in correspondence to the $\Delta_d$ value obtained from the pushover procedure.

4.2 Results and Discussion

Simulated and predicted IDA curves are presented in Figure 6 for the four building heights. IDA curves of the two selected EDPs, displacement and drift, are presented side-by-side. A qualitative comparison indicates that the predicted IDA curves reproduce closely the features and the ordinates of the simulated ones, especially for the 4- and 8- storey cases (Figure 6a and Figure 6b). For the 12- and 20- storey cases, the predicted IDA curves fail to capture some local features of the simulated ones, and also, the differences between simulated and predicted capacities of the 50% and 84% IDA curves appear to be larger. These increased differences for the 12- and 20- storey cases are attributed to a larger contribution of higher mode effects. The trends described are common to both EDPs.

A more quantitative comparison is performed in terms of collapse capacities. Simulated ($R_{\mu\text{ NTHA}}$) and predicted ($R_{\mu\text{ DDBA}}$) collapse capacities are summarized in Table 1, for the 16th, 50th and 84th percentiles. Prediction errors are estimated as per Equation (17).

$$\text{error} = \frac{R_{\mu\text{ NTHA}} - R_{\mu\text{ DDBA}}}{R_{\mu\text{ NTHA}}} \quad (17)$$

As observed in Table 1, errors in predicted collapse capacities range between -22% and +17%. These range of values is deemed satisfactory given that, for non-degrading systems, the DDBA method offers estimates of system response within an error range of ±25% (Perez, 2018). Prediction errors of the 50th percentile appear to increase as the building height increases; however, such trend is not present in the 16th and 84th percentiles.

<table>
<thead>
<tr>
<th>Storeys</th>
<th>16th Percentile</th>
<th>50th Percentile</th>
<th>84th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{\mu\text{ NTHA}}$</td>
<td>$R_{\mu\text{ DDBA}}$</td>
<td>error</td>
</tr>
<tr>
<td>4</td>
<td>0.44</td>
<td>0.51</td>
<td>-15.2</td>
</tr>
<tr>
<td>8</td>
<td>0.35</td>
<td>0.29</td>
<td>17.2</td>
</tr>
<tr>
<td>12</td>
<td>0.32</td>
<td>0.30</td>
<td>6.0</td>
</tr>
<tr>
<td>20</td>
<td>0.41</td>
<td>0.39</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 1. Simulated and predicted Collapse Capacities and prediction errors.
Figure 6. Simulated and predicted IDA curves for the EDPs displacement at the equivalent height (left) and maximum drift (right). Building cases: (a) 4 storeys, (b) 8 storeys, (c) 12 storeys and (d) 20 storeys.
5. CONCLUSIONS

In this study an analogy has been proposed for explaining and quantifying the effect of p-delta actions on the seismic response and collapse capacity of SDOF systems. By comparing the displacement response of elasto-plastic (non-degrading) and elastic-softening (strength degrading) systems, response-degradation functions (RDF) have been developed as a means of quantifying the degradation in system response. By interpreting the RDFs as functions that reduce the energy absorption capacity of the system, they can be set to operate directly on the displacement modification factors, $\eta$, used in the DDBD/DDBA methods, to obtain estimates of displacement response of p-delta sensitive systems.

The proposed approach is applied in the prediction of the incremental response and collapse capacity of a RC cantilever wall building of 4, 8, 12 and 20 storeys. It was shown that the approach is capable of reproducing the major features of simulated IDA curves both, in terms of displacement at the effective height and of maximum drifts. Nonetheless, differences were observed in the 50th and 84th IDA curves as higher mode effects become more relevant to the response. For the building case and GM set considered the proposed approach offered satisfactory predictions of median collapse capacities, as well as, of 16th and 84th collapse capacities. Maximum observed prediction errors ranged between -17% and 22%, which is deemed satisfactory.

6. REFERENCES


