PUSH-OVER ANALYSIS OF FRP-RETROFITTED EXISTING RC FRAME STRUCTURES

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1   INTRODUCTION

FRP–wrapping of columns is considered one of the most effective retrofitting techniques for RC structures in seismic regions. Plastic hinge confinement by FRP-wrapping enables the development of large displacement or chord rotation ductility factors, as many experimental studies confirmed (e.g. [1]). Moreover, in some cases, it may avoid to activation of brittle failure modes, such as soft-floor mechanisms [2].

Nonlinear dynamic analysis is the most complete method to describe structural response under seismic action. Nevertheless, such technique is a very time-consuming and complex process, inadequate for general design applications. As such, recent years have witnessed an increased focus on the development of design/assessment procedures based on nonlinear static analysis (or pushover analysis).

In the present study, nonlinear static and dynamic analyses of frame structures retrofitted by FRP are performed. Existing RC structures, not designed structures with seismic criteria are considered. Nonlinear analyses are performed by a fibre finite element model, considering appropriate cyclic constitutive laws for FRP confined-concrete, recently proposed in Ref. [3].

Different pushover procedures are adopted. For non-adaptive analyses, two different force distributions are considered, uniform and proportional to the first modal shape. For adaptive pushover procedures, Displacement-based (DAP) technique [4] is employed. In order to validate pushover procedures, Incremental Dynamic Analyses (IDA) [5] are carried out using a set of artificial time-histories derived to fit the Eurocode response spectra [6]. The limit state condition is defined as the attainment of ultimate strain in confined concrete or, alternatively, of a limit value of interstorey drift. Comparison of static against dynamic results, in terms of both capacity curves as well as interstorey drift profiles, leads to the conclusion that displacement-based adaptive pushover features the highest potential to better reproduce results of incremental dynamic analysis.

The effect of wrapping in increasing ductility against seismic actions is studied. It is shown that FRP wrapping strongly increases structural ductility. Moreover, by adopting FRP-wrapping, the effect of local deficiencies of strength in some columns of the frame is strongly reduced, so increasing overall reliability of the structure. This aspect in particularly significant for existing RC structures, where often concrete strength in some columns is lower than average due to incorrect casting processes.

2   PUSHOVER VERSUS DYNAMIC ANALYSES

Pushover methods consist on studying a frame structure subjected to gravitational loads and horizontal loads applied at each storey, where the latter are incremented up to failure. For conventional analyses, at least two different force distributions must be considered [6]: uniform and proportional to the first modal shape. Conventional pushover procedures, adopted by many codes and guidelines, consider an invariant load pattern during the analysis. This approximation is one of the most significant limitations of traditional methods, because real inertia force distribution changes during seismic event due to higher mode contributions and structural degradation, which modifies stiffness of individual structural elements.

For this reason, adaptive pushover methods have been most recently proposed. These methods are based on a pushover procedure where the applied horizontal load pattern is updated during the analysis. The first adaptive procedure can be attributed to Reinhorn [7], who proposed to update force

distribution as a function of base shear and floor shears calculated at previous load step.

The adaptive pushover procedure proposed by Elnashai [8] for simplified stick-models, and Antoniou et al. [9] for reinforced concrete frame structures, is conceptually similar to Reinhorn's method, with the main difference that the adaptive algorithm was implemented in a distributed plasticity fibre finite element code, so allowing for continuous rather than discrete updating of load patterns. In the present study, fibre-based finite element models are adopted for adaptive pushover procedures, following the incremental Displacement-based Adaptive Pushover (DAP) according to [4]. The method is able to take into account, for increasing values of applied external action, progressive structural stiffness degradation, change of modal characteristics and period elongation of a structure. Further, the influence of the frequency content of the input motion is also considered. In fact, a displacement response spectrum is employed to weight the contributions of each mode to the applied incremental horizontal load pattern, updated at each step. For this reason, DAP procedure seems to be capable of overcoming the limitations encountered in conventional analyses, thus capturing better the dynamic structural response of RC frame structures.

In order to evaluate the effectiveness of nonlinear static procedures in reproducing structural dynamic behaviour, Incremental Dynamic Analysis (IDA) has been adopted to obtain a reference solution. IDA is a parametric method [5], where the structure is subjected to a series of nonlinear time-history analyses of increasing intensity with the objective of attaining an accurate estimate of the "true" dynamic response of a structure subjected to earthquake action.

In the present work, six artificial time-histories compatible with Eurocode 8 [6] response spectrum are used. Comparison between results of incremental dynamic analyses and pushover analyses has been made in terms of base shear-top displacement relationship and interstorey drift profiles. Pushover analyses and IDA have been performed first with reference to a non retrofitted RC structure. The same structure is then retrofitted by wrapping with FRP all columns.

3   FIBRE MODEL FOR FRP-WRAPPED COLUMNS SUBJECT TO AXIAL AND FLEXURAL LOADINGS

In order to cover cases encountered in seismic applications, models for circular FRP-wrapped sections subjected to centred axial load must be extended to rectangular sections under combined axial and flexural loading, taking the cyclic behaviour also into account.

Two main differences can be outlined. First of all, for rectangular sections the confinement action of the composite is fully developed only in the central part of the cross-section. A commonly used criterion [10] to define the effectively confined area for centred compression is based on the parabolic arching action from section corners (see Figure 1). Accordingly, the fully confined area is defined as a function of cross-section shape and rounded corner radius: the cross-section is divided into an (internal) fully confined portion and an (external) unconfined portion. The problem is more complex if axial strain is variable over the cross-section due to the presence of a bending action (neutral axis may be even inside the cross-section) and then the confinement pressure is not uniform over the cross-section.

In Ref. [3], Spoelstra and Monti [11] iterative technique was extended to the case of (cyclic) axial and flexural loading by adopting a fibre model approach. The model is based on two main assumptions: a) the same division of the cross-section into unconfined and confined portions adopted for centred compression is retained; this assumption is motivated by the fact that concrete fibres close to neutral axis are subject to small strains and, then, difference between confined and unconfined behaviours is negligible; b) concrete fibres constituting the cross-section, subject to a given value of axial strain, are confined by the same lateral pressure of an equivalent FRP-wrapped circular cross-section under the same axial strain; confinement action is then variable over the cross-section and vanishes close to neutral axis. In the same paper, the model has been extended to cyclic loadings by defining hysteretic laws for confined concrete. Behavior of confined concrete subject to unloading is defined according to Mander model [12]. Cyclic behavior of concrete under tension is modelled starting from Reinhardt model [13]. For strains greater than ε_{ct} = 0.04 %, residual strength of concrete under traction vanishes. Loading curves from traction to compression are modified with respect to Reinhardt model, even though the general framework is maintained. In [3], numerical results have been compared with experimental results by Sheikh [14] and good agreement has been found in terms of both cyclic moment-curvature curves and specific damping ratios of hysteretic loops.

In the present work, the model has been implemented in a fibre finite element code [15] in order to investigate the behaviour of a frame structure with columns wrapped by FRP.
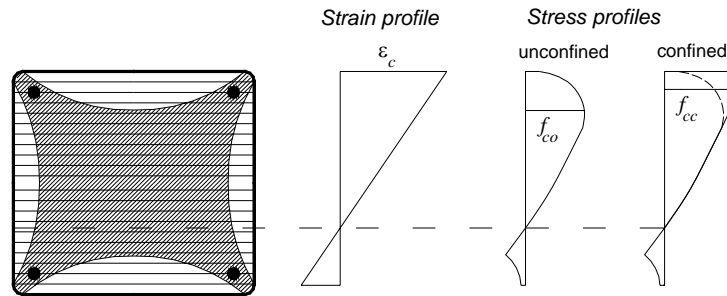

Fig. 1: Fibre model for FRP wrapped columns: linear strain profile over the cross-section and stress distributions for unconfined and confined concrete.

4   THE CASE STUDY

The 6-floor frame structure depicted in Figure 2 is considered in numerical applications. Geometry of the frame and mechanical properties of materials are reported in Figure 2 and Table 1, respectively. Distributed vertical loading on beams is equal to 20 kN/m. In order to analyse the structural behaviour against seismic excitation, a series of pushover analyses has been carried out adopting both conventional and adaptive techniques, as described in Section 2.
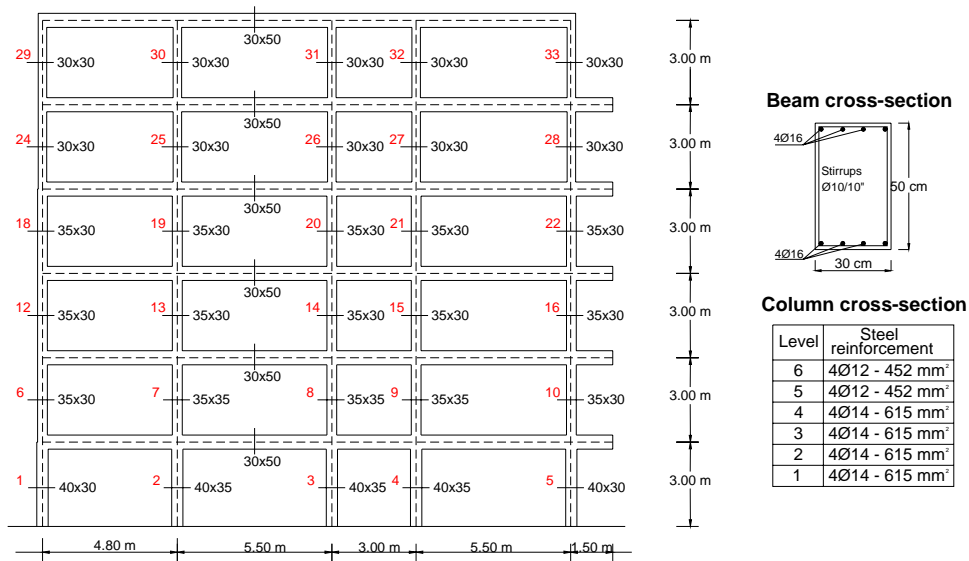

Fig. 2   6-floor frame structure: geometry and beam/column cross-sections.

Table 1   Mechanical properties of materials considered for the 6-floor frame.

Steel bars	f_y = 414 MPa	E_s = 210000 MPa	E_1/E_s = 0.009
Unconfined concrete	f'_{co} = 30 MPa	ε_{co} = 0.0022	ε_{cu} = 0.0035

4.1 Non Retrofitted Structure: Pushover analyses and IDA

In Figure 3, base shear-top displacement curves (called capacity curves) obtained using different pushover procedures are compared with IDA results, adopting six different artificial accelerograms (AR-1/AR-6). Black line represents the mean value of IDA. In the same figure, results of dynamic analyses corresponding to the attainment of ultimate strain of a fibre in concrete core are indicated with red marker. It is observed that the adaptive capacity curve is in-between the two conventional pushover curves, and that the latter seem to envelope results from dynamic analyses.

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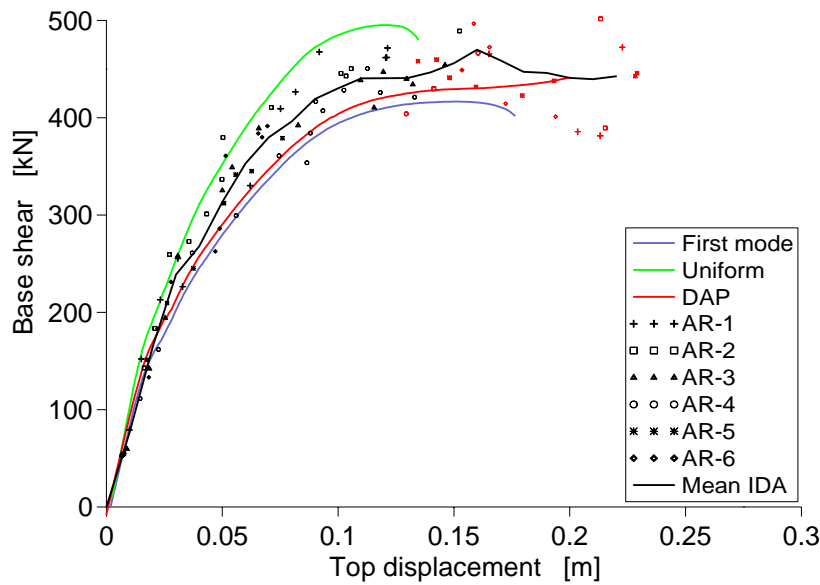
Fig. 3   Capacity curves from pushover analyses and results obtained by IDA.

Table 2   Error of capacity curves from different nonlinear static analyses against results from IDA.

| Max Top Displacement [cm]	Uniform	First mode	DAP
12.4	16.0%	16.6%	10.0%
16.0	-	15.1%	9.1%
22.1	-	-	8.4%

With reference to capacity curves and interstorey drift profiles, respectively, relative errors of results from nonlinear static analysis with respect to those obtained from dynamic analyses will be evaluated as follows:

$$Error = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{V_i^S - V_i^D}{V_i^D}\right)^2} \qquad Error = \frac{1}{m}\sqrt{\sum_{j=1}^{m}\left(\frac{\Delta_j^S - \Delta_j^D}{\Delta_j^D}\right)^2} \qquad (1)$$

where superscripts S and D indicate results by static analyses and mean values of dynamic results, V and Δ are the base shear and the interstorey drift, respectively; n and m are the total numbers of dynamic analyses and frame floors, respectively.

In Table 2, relative error of different pushover methods in terms of capacity curves with respect to the interpolation curve obtained from IDA numerical results is reported. Errors are calculated for three different levels of maximum top displacement. It can be observed that DAP curve provides the closest fit to mean IDA values, so somehow confirming in the present case the superiority of displacement-based adaptive pushover algorithm, already noted in previous publications [4]. Nevertheless, in the present case, behaviours predicted by first-mode force distribution and DAP are quite similar.

In addition, in Figure 4 interstorey drift and horizontal displacement for different values of total drift are reported. The interstorey drift obtained from the six IDA and evaluated following the criterion suggested in Ref. [16] are reported in Figures 4(*a, c, e*). Mean values of IDA results is represented with black line. In Figures 4(*b, d, f*), results from pushover analyses are compared with mean IDA values. It can be observed that adopting IDA the limit state based on material deformation is attained with interstorey drift always smaller than 3%. The relative error of pushover results with different methods with respect to dynamic results has been evaluated according to Eq. (1b) and reported in Table 3. It is shown that DAP procedure gives better results also in terms of interstorey drift profile for both low and high values of total drift.

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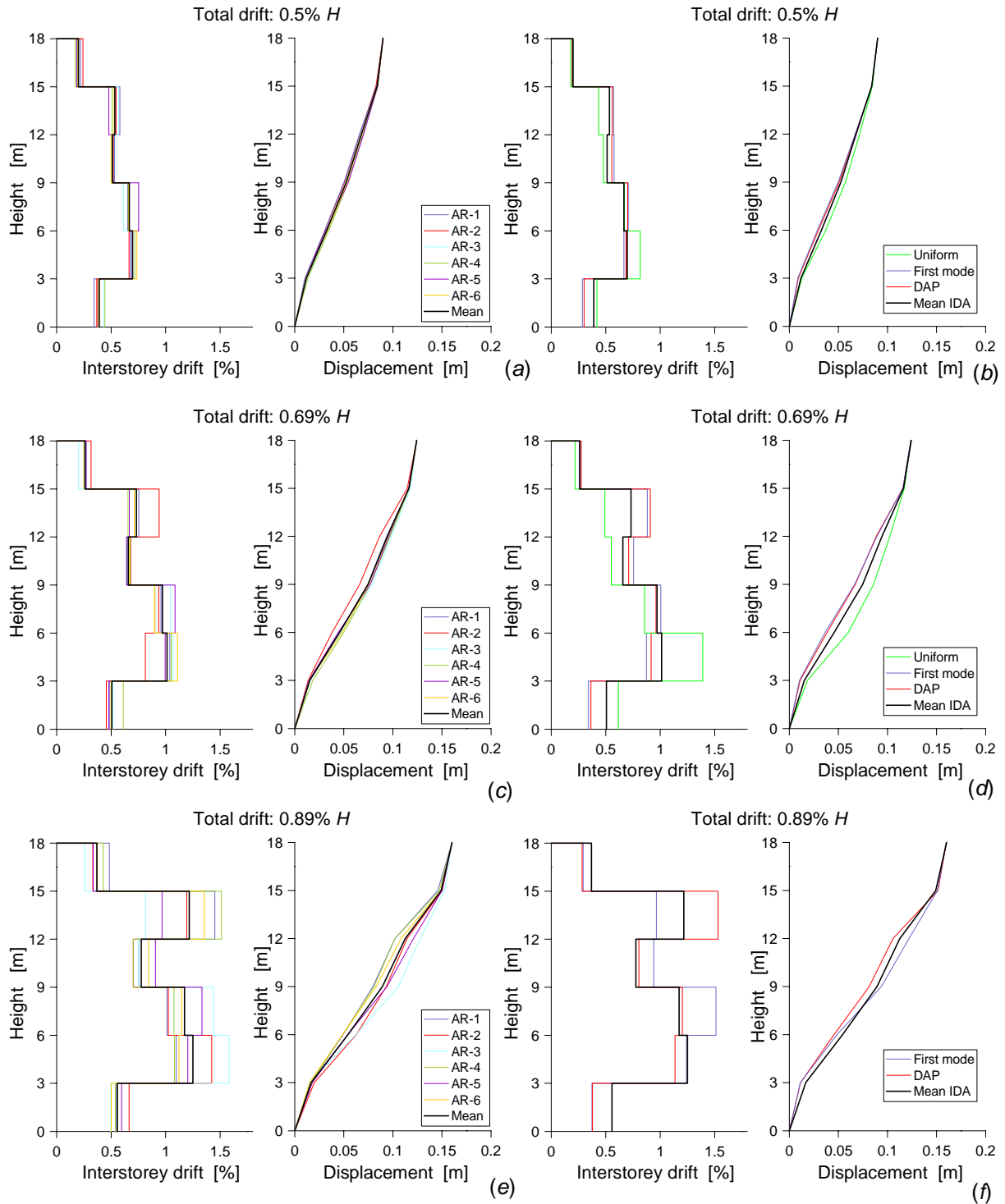
Fig. 4 Interstorey drift and horizontal displacement at different values of total drift obtained (*a,c,e*) from six different numerical simulations by IDA, together with their mean value (black line), and (*b,d,f*) by pushover analyses compared with mean IDA values.

Table 3 Error on estimate of interstorey drift according to different pushover methods against mean value obtained from Incremental Dynamic Analyses.

Total drift	Uniform	First mode	DAP
0.50%	19.0%	20.0%	17.6%
0.69%	32.0%	25.6%	23.8%
0.89%	-	28.6%	26.8%

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5   RETROFITTING INTERVENTION WITH FRP COLUMN WRAPPING

For the frame structure considered in the previous section, ultimate capacity is attained for column failure with limited structural ductility. This behaviour is typical of existing RC frame structures not designed for seismic criteria. In order to improve structural ductility, retrofitting with FRP-column wrapping is studied. All columns are wrapped with 2 CFRP layers. Sheet Young's modulus is 230000 MPa and thickness of each layer is 0.165 mm. This intervention aims at increasing sectional ductility of all columns, and consequently ductility increase of the entire structure.

5.1   Column Sectional Behaviour

In the constitutive model adopted for FRP-wrapped columns, confined concrete ultimate strain is reached because of FRP rupture. Experimental studies reported in Lam and Teng [17] show that FRP jacket rupture $\varepsilon_{FRP-rup}$ is attained when strain is about 60% of ultimate strain of composite material ($\varepsilon_{FRP-u} = 1.2\%$). Accordingly, ultimate longitudinal strain of confined concrete can be calculated following Ref. [10]. Concrete ultimate strain adopted in the present study to define the limit state for non retrofitted case and retrofitted columns with different cross-section are reported in Table 4.

As an example, moment-curvature diagrams of column n. 7 before and after retrofitting intervention are reported in Figure 5. Axial load is constant and corresponds to the presence of dead and live loads. It is possible to observe the increase of sectional ductility and the absence of significant strength degradation after the attainment of maximum moment. In Table 5, cross-sectional ductility for non-retrofitted and retrofitted case is reported for one column of each level, from ground to upper floor. It can be observed that yielding curvature χ_y does not significantly change after retrofitting intervention, while ultimate curvature χ_u considerably grows up. Therefore, FRP-wrapping technique is very effective in increasing sectional ductility as reported in the last column of Table 5.

Table 4   Concrete ultimate strain adopted as limit state.

	No Retrofitted	**Retrofitted**
Cross-section	ε_{cu}	ε_{cu}
30x30	0.35%	1.56%
35x35 / 40x35	0.35%	1.48%
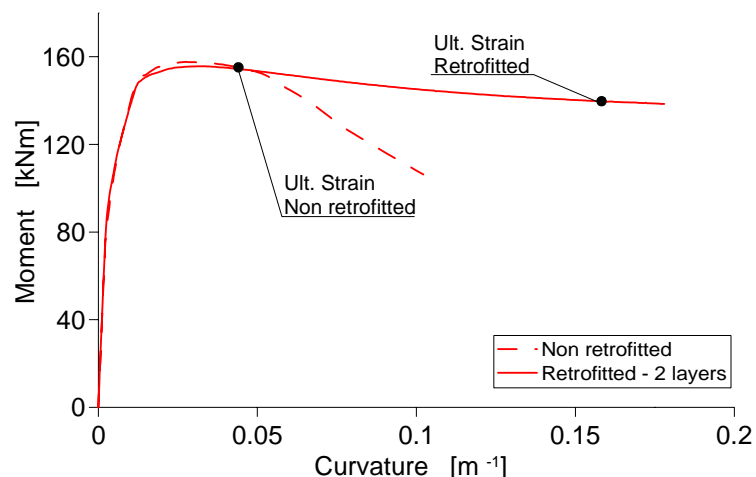
Fig. 5   Moment-curvature diagrams for retrofitted and non retrofitted column n. 7 (see Figure 2) on the ground floor, with constant axial load given by dead and live loads.

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Table 5   Cross-sectional ductility of original and retrofitted columns.

Column	Section	P [kN]	Non retrofitted			Retrofitted			Δμ/ μ$_o$
			χ_y	χ_u	μ$_o$	χ_y	χ_u	μ	
2	40x35	1020	0.01019	0.03633	3.57	0.01008	0.12447	12.35	**246.3%**
7	35x35	850	0.01159	0.04488	3.87	0.01150	0.15822	13.76	**255.2%**
13	35x30	680	0.01124	0.04899	4.36	0.01150	0.19103	16.62	**281.3%**
19	35x30	510	0.01030	0.07396	7.18	0.01053	0.24864	23.62	**228.9%**
25	30x30	340	0.01157	0.12757	11.03	0.01162	0.37433	32.21	**192.1%**
30	30x30	170	0.01048	0.15432	14.73	0.01076	0.75694	70.33	**377.6%**

5.2 Comparison of Results obtained by Different Pushover Analyses vs IDA

In Figure 6, capacity curves for retrofitted structure obtained using different pushover procedures have been compared with IDA results in order to establish which static procedure gives results closer to nonlinear seismic behaviour of the structure. Black line represents the mean value of results obtained by IDA. Dynamic analysis results obtained employing six artificial records are more scattered than for the original structure, however most of them are in-between the two conventional curves. As in the case of non retrofitted structure, capacity curve from adaptive pushover analysis is in-between the two conventional pushover curves.

In the same figure, results of dynamic analyses are indicated as red marker, when ultimate strain of a fibre in concrete core is attained. Often, 3% of interstorey drift is considered as a limit state for the structure, because of the degradation of infill walls. Hence, for IDA, failure points corresponding to the achievement of 3% interstorey drift limit state are reported as blue points. The limit state based on concrete ultimate strain (red points) is always reached when the value of maximum interstorey drift at the fifth floor is greater than 3%.
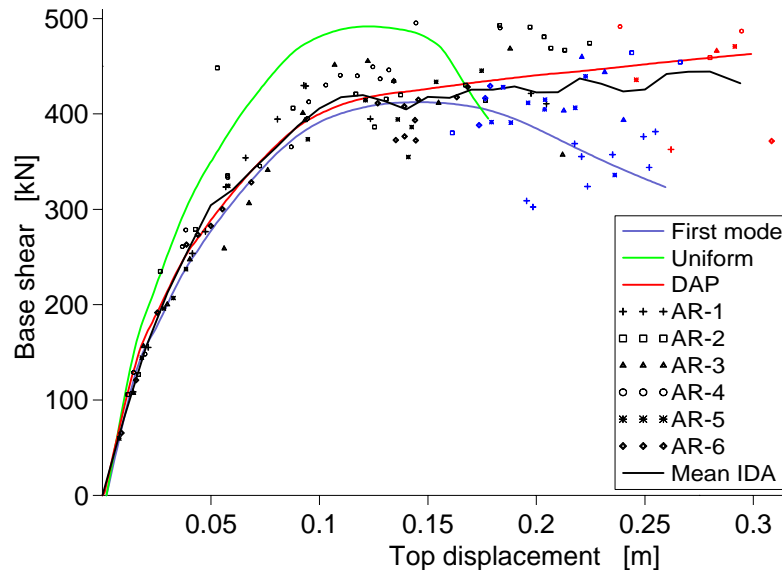

Fig. 6   FRP-Retrofitted frame structure - Capacity curves obtained by pushover analyses and IDA.

Table 6   Error on capacity curves obtained from nonlinear static analyses against results from IDA.

Total Drift [cm]	Uniform	First mode	DAP
17.2	19.4%	8.5%	6.8%
25.1	-	10.8%	6.0%
29.4	-	-	7.2%

Comparing ultimate top displacements from IDA for original and FRP-retrofitted structures (Figures 3 and 6), considerable increase of structural ductility (about 1.6 times) is observed by using composite material for strengthening.

In Table 6, relative error of different pushover methods in terms of capacity curves with respect to interpolation curve obtained from IDA numerical results is reported. Errors are calculated according to Eq. (1a) at different levels of maximum top displacement. It is observed that also in the present case the DAP curve provides the closest fit to the mean IDA values. As shown in Figure 6, the DAP
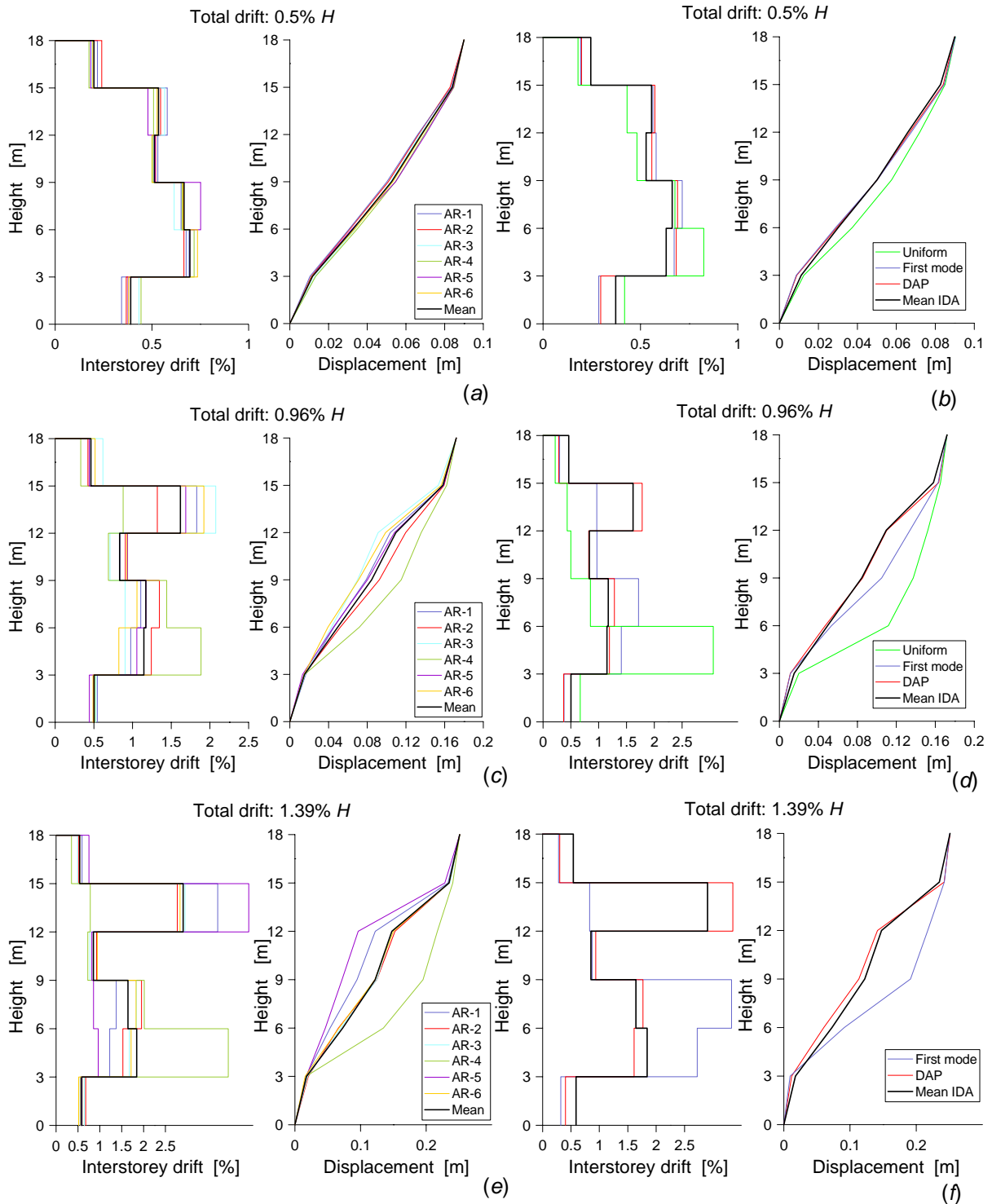
Fig. 7 FRP-Retrofitted case - Interstorey drift and horizontal displacement at different values of total drift obtained (*a,c,e*) from six different numerical simulations by IDA, together with their mean value (black line), and (*b,d,f*) by pushover analyses compared with mean IDA values.

algorithm gives a capacity curve not exhibiting a softening behaviour. On the contrary, adopting conventional procedures, after the attainment of the peak value of base shear, structural strength degradation is evident. According to results reported in Figure 6, simulation results from IDA seems to confirm results from DAP algorithm.

In Figures 7, interstorey drift and horizontal displacement for different values of total drift are reported. In Figure 7 (*a, c, e*), the interstorey drift from the six IDA evaluated following Ref. [16] are reported and mean IDA values are represented with black line. In Figure 7(*b, d, f*), results of pushover analyses are compared with mean IDA values. It is worth noting that, as shown in Figure 7*d* (total drift equal to 0.96% of structure height), uniform loading distribution predicts a soft-floor mechanism (significant increase of interstorey drift) at the second floor. This behaviour is not confirmed by IDA results. Analogously, for total drift equal to 1.39% of *H*, first mode distribution exhibits very high interstorey drift at the second and third floor (Figure 7*f*) not confirmed by non linear dynamic results.

For all values of total drift, DAP procedure reproduces well interstorey drift profile when compared with mean results from IDA simulations. By analysing relative error of pushover procedures against dynamics reported in Table 7 for lower and higher values of total drift, it can be stated that DAP is able to predict more accurately the failure mode of the structure.

Table 7 Error on estimate of interstorey drift according to different pushover methods against mean value obtained from Incremental Dynamic Analyses.

Total drift	Uniform	First mode	DAP
0.5%	27.3%	21.0%	19.7%
0.96%	89.7%	41.1%	29.5%
1.39%	-	70.4%	37.4%

6   CONCLUSIONS

In the present paper, the behaviour of existing RC frame structures under seismic action has been investigated using nonlinear static and dynamic analyses. For nonlinear static analyses, different pushover procedures have been adopted. Conventional (first-mode and uniform distribution) and Displacement-based Adaptive Pushover analyses (DAP) have been performed to predict structural behaviour of frame structure under horizontal forces. In order to verify the effectiveness of pushover procedures to predict the structural behaviour under seismic action, a series of incremental dynamic analyses have been performed. Comparisons of static against dynamic results, in terms of both capacity curves as well as inter-storey drift profiles, leads to the conclusion that displacement-based adaptive pushover features the highest potential to better reproduce results of incremental dynamic analysis.

In order to improve structural performance, retrofitting intervention by FRP-column wrapping has been studied. Nonlinear analyses have been performed by a fibre finite element model, considering appropriate cyclic constitutive laws for FRP confined-concrete. Retrofitted structure behaviour has been investigated by nonlinear static analyses and Incremental Dynamic Analyses. The effectiveness of such method of structural upgrading in terms of sectional and structural ductility has been once again confirmed, and so was the superiority of DAP in predicting the response of the retrofitted structure.

ACKNOWLEDGEMENTS

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