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Alternative retrofitting strategies to prevent the failure of an under-designed reinforced concrete frame

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ABSTRACT

In Southern European countries several existing reinforced concrete (RC) buildings were designed before the introduction of modern seismic codes and thus they may be potentially vulnerable to horizontal loads. Recent seismic events have also shown that RC buildings designed without specific seismic provisions can be subjected to meaningful damages or even collapse during moderate-to-strong earthquakes. In this framework, straightforward methodologies for a preliminary and suitable seismic assessment and retrofitting of existing RC buildings are required, along with reliable and effective seismic rehabilitation techniques. In this study, a simplified displacement based procedure using non-linear static analyses is applied to obtain a preliminary estimation of the overall inadequacy of an under-designed four-storey RC frame and to propose suitable retrofitting interventions based on different rehabilitation strategies. To this aim, accurate numerical models are developed to simulate the seismic response of the RC frame in the original and retrofitted configurations. The effectiveness of three different retrofitting solutions countering the main structural deficiencies of the RC frame is evaluated through the displacement based approach. Then, non-linear dynamic analyses are carried out to assess and compare the seismic performance of the RC frame in the original and retrofitted configurations. A combined use of different approaches may represent a valuable tool to accurately address the retrofitting interventions and to assess their effectiveness in order to reduce the seismic vulnerability of poorly designed RC buildings.

1. Introduction

A huge amount of existing Reinforced Concrete (RC) buildings in European seismic prone areas were designed without any specific attention to horizontal loads, consistently with prescriptions given by old Codes of Practice. These structures are very likely to experience severe damage or even collapse during moderate-to-strong earthquakes, as shown by recent seismic events [1–10]. Therefore, simplified procedures to evaluate the seismic performance of existing and retrofitted buildings are needed, along with reliable and effective seismic upgrading techniques [11–14]. The present paper discusses the results obtained with advanced numerical techniques applied for the seismic assessment and retrofitting of a benchmark RC frame, designed mainly for gravity loads without specific earthquake-resistant provisions, that was pseudo-dynamically tested at the JRC ELSA laboratory in Italy. First, detailed non-linear dynamic analyses are performed to reproduce the seismic behavior of the RC frame without retrofitting (original configuration). A comparison with existing experimental data is provided. Then, a displacement based approach (pushover) is adopted to evaluate the seismic performance of the original frame and the most relevant results are critically reviewed. In a more

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general research framework, it is worth mentioning that the the effectiveness of a variety of different numerical approaches for the seismic assessment of other typologies of existing structures has been already presented by the authors in [15–18].

The displacement based procedure is also used for a preliminary design and evaluation of the most effective retrofitting strategies implementable. The aim is to provide a simplified procedure able to drive the process of retrofitting design by comparing the main structural deficiencies with the different rehabilitation strategies. In particular, three alternative retrofitting solutions for the RC frame are proposed and verified through a displacement based approach.

The first intervention scheme is defined basing on the results obtained on the bare frame, adopting two conceptually different strategies, namely strength-only and ductility only solutions [19–22]. Such selective interventions are applied to different members of the frame in order to improve its global and local seismic behavior. A strength-only intervention using RC jacketing is also introduced in the in the strong column at the third and fourth storeys of the frame to reduce the large difference in terms of flexural capacity. Moreover, a ductility-only intervention is implemented at the first three storeys of the frame, where a large inelastic deformation demand is present. Such strengthening needs the application of fiber reinforced polymer (FRP) strips, and results into an increase of the confinement of the RC columns.

The second retrofitting intervention is based on the implementation of steel bracing, which can be considered as a very effective method for global strengthening of structures [23–26]. In particular, the use of eccentric steel bracings in the rehabilitation of existing RC structures is efficient in limiting inter-storey drifts and can provide a stable energy dissipation capacity.

The third intervention is carried out by casting a concrete shear wall into the full width of the frame short bay [27]. This solution leads to significant increases in overall strength and stiffness of the retrofitted frame, when compared to those of the initial frame configuration. This intervention is efficient in controlling global lateral drift and thus reducing damage in structural members.

Then, the effectiveness of the three retrofitting solutions adopted for improving the seismic performance of the RC frame is estimated by performing non-linear dynamic analyses. The different seismic responses of the RC frame in the original and retrofitted configurations are critically compared and the most important results are discussed in detail.

2. Seismic upgrading with different retrofitting strategies

A displacement based procedure is used to evaluate the seismic performance of the existing and retrofitted RC frames. The procedure is based on a simplified approach using non-linear static pushover analyses and allows comparing alternative retrofitting strategies adopted to overcome existing structural deficiencies. The base shear-top displacement relationships obtained from pushover analyses were transformed into capacity curves in the acceleration-displacement (AD) format. Several target displacements and capacity curves were estimated assuming that different strategies could be used to retrofit the structure. In fact, different types of structural interventions on existing structures can be classified according to their effect on the behavior of the structure and can be represented by the capacity curves presented in Fig. 1. The first group (group 1) includes all those strengthening interventions aimed at improving the overall ductility of the structure; the second group (group 2) collects interventions resulting into an increase of strength and stiffness; finally, the intermediate group 3 comprises solutions increasing both ductility and strength. The range of available retrofitting solutions is bounded by assuming the two alternative structural intervention techniques corresponding to groups 1 and 2.

The bilinear red curve depicted in Fig. 1 shows the equivalent Single Degree of Freedom SDOF capacity of the bare frame. S_{ay} and S_{dy} are the spectral acceleration and the spectral displacement, respectively, at the yield point of the unretrofitted equivalent system. S_{dm} is the spectral displacement corresponding to the point at the end of the capacity spectrum before retrofitting and S_{dt} is the target spectral displacement after retrofitting according to the strategies of group 1. The extension of the horizontal (red) line represents the spectral displacement required to achieve the target spectral displacement. The green curve is the elastic demand spectrum and the

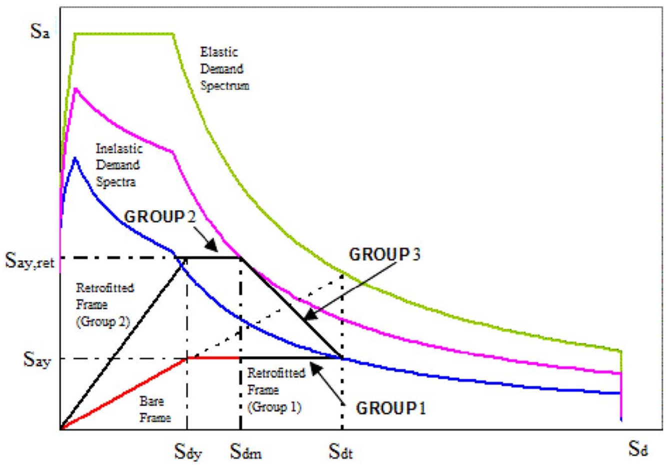

Fig. 1. Capacity curves, demand spectra and different retrofitting strategies in the acceleration-displacement (AD) format. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)