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SEISMIC STRENGTHENING OF AN EXISTING RC FRAME BUILDING DESIGNED FOR GRAVITY LOADS

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Abstract

In Italy, most of the residential buildings were constructed before 1981, when only 25% of the national territory was classified as seismic; the larger proportion of this building stock is Reinforced Concrete (RC) structures. These building designed only to resist to gravity load, shows several structural deficiencies under seismic action related both to the lack local details (e.g. absence of transverse reinforcement in beam-column joints) and poor structural material properties. The vulnerability of existing buildings designed without seismic arrangements was highlighted by recent earthquake that caused damage and several buildings collapse. Nowadays, the rehabilitation of existing structures, taking into account energetic and sustainability requirements, is a newsworthy and challenging task. In this work, the seismic performances of an existing, gravity load designed, RC frame residential building located in Mugnano di Napoli (NA, Italy) were investigated. First, the assessment of the existing structure's performance in a code-based approach was performed; then, a strengthening intervention by means of Orthogonal Steel Exoskeleton system was designed through a detailed step-by-step procedure. The efficiency of the proposed global strengthening intervention were assessed by means of a non-linear static analyses. Designed interventions allows to strongly increase the structural performance of the investigated case study.

Keywords: RC Buildings, Orthogonal Steel Exoskeleton, Low Impact, Structural Rehabilitation, Existing Structures.

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1 INTRODUCTION

Recently, there has been increased focus and extensive research on the seismic response of reinforced concrete (RC) buildings that were originally designed only for gravity loads and constructed before the implementation of proper seismic design codes [1-2]. This is due to the use of insufficient construction details and the lack of adoption of resistance hierarchy principles, which can lead to inadequate ductility both locally and globally, resulting in poor performance during seismic events, even of moderate intensity. Additionally, structures may become weakened over time due to environmental factors or changes in usage. It is therefore imperative to retrofit existing structures in order to enhance their seismic performance. In order to ensure that an existing building meets the required safety standards across all the investigated limit states, there are two main strategies that can be employed: (i) decreasing the seismic demand, or (ii) increasing the capacity of the existing structure. One of the most common intervention techniques is to increase the lateral stiffness lateral resistance of existing buildings by introducing new seismic-resistant systems that absorb the horizontal force generated by earthquakes (e.g. RC shear walls, infill walls, steel braces) [3-6]. However, the trend is moving towards retrofit interventions that are not only aimed at improving the structural performance of existing buildings but are also capable of promoting improvements in terms of energy efficiency, aesthetics, and functionality [7]. In this context, there is a growing interest in studying exoskeletons systems for structural strengthening. Such systems placed on the exterior of the structure to be reinforced, can be applied without any interruption to activities inside the building, by allowing for significant enhancement of the structural performance. Moreover, these external systems also offer valuable assistance for energy efficiency improvements and architectural makeovers. The aim of this study is to analyze the effectiveness of steel exoskeletons for retrofitting an existing reinforced concrete building, which was chosen as a case study. These systems are arranged perpendicular to the facade of the structure, in order to not obstruct the opening of doors or windows, and the passage of light. The present work is mainly divided in three part: in the first part, a general description of the case study is presented, describing the geometric characteristics and materials mechanical properties. Afterwards, the seismic performance of the structure is analyzed through nonlinear static analysis in the second section. Finally, the design of the strengthening intervention, and the verification of its effectiveness, are discussed.

2 CASE STUDY

2.1 General description

The case study selected is a three-story residential reinforced concrete building located in Mugnano di Napoli (NA). Built between 1970 and 1978, it has a rectangular floor plan with dimensions of 20 meters in the longitudinal direction and 10 meters in the transverse one. The building's total height (H) is 9.8 meters (see Figure 1).

Originally designed to sustain only gravity loads, the building's overall dimensions and cross-sectional properties of the elements were defined according to the original design report. Plain bars were used as reinforcement typology, and no transverse reinforcement was present in the beam-column joints, which was typical for pre-1980s RC buildings. In-situ destructive testing methods were conducted to accurately determine the mechanical properties of building materials. The quantity and quality of information gathered on the RC structure led to the selection of a Knowledge Level "KL2" in accordance with the regulations set by Italian and

European codes [8-10]. The parameters that characterize the seismic hazard of the site are summarised in Figure 1.

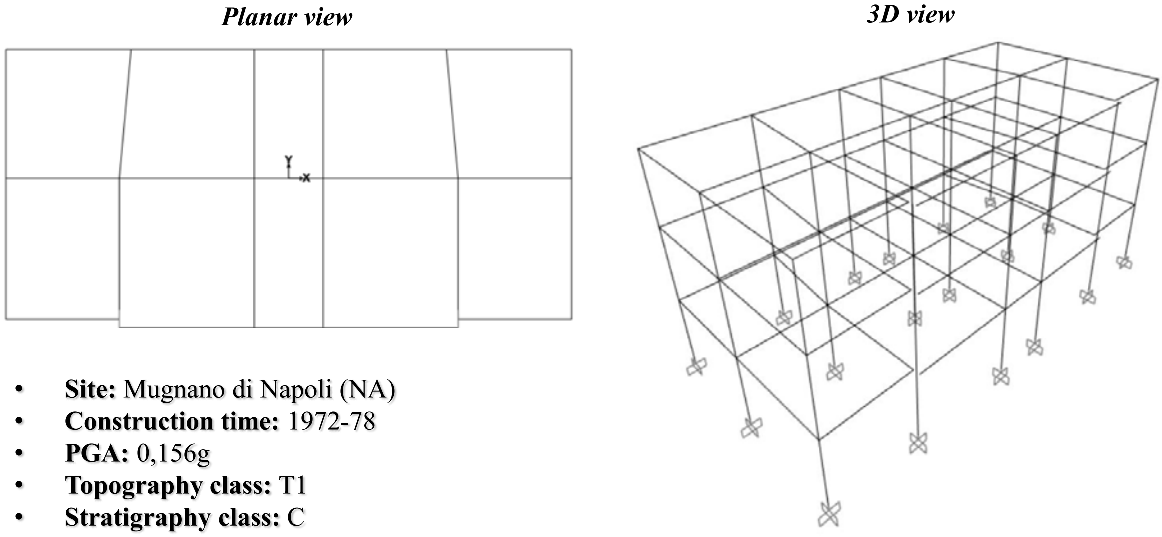

Figure 1. Case study: general description

3 SEISMIC PERFORMANCE OF THE INVESTIGATED STRUCTURE

3.1 Modelling assumption

The structure was analyzed using a three-dimensional finite element model (FEM). The FEM was utilized to perform static non-linear analyses using SAP2000 software [11]. The structural system was analyzed by modeling the beams and columns as frame elements, taking into account their geometric axes. To account for the presence of the 22 cm thick floors, with 4 cm of RC slab thickness, a diaphragm constraint was included in the model. While the foundations were not directly modeled, the column-foundation connections were modeled as fixed based on the information provided in the original drawings. The inelastic behavior of a structure was simulated by using a lumped plasticity model, in which zero-length elements (plastic hinges) were added at the end of beams and columns. The inelastic flexural behaviour was represented by a trilinear moment-rotation backbone curve, which main points were computed in line with Italian code prescriptions [9-10].

3.2 Pushover-based safety assessment

Static non-linear pushover analyses were performed to assess the structural safety against seismic loads, employing two different lateral loads' patterns as prescribed by [8-10]. Then, according to the N2 method the capacity curves of equivalent single-degree-of-freedom systems were idealized as an elastic-perfectly plastic curves [12]. The seismic performances of the investigated case study were checked with respect to the Damage Limitation (DL) and Significant Damage (SD) limit states as prescribed by the code for residential buildings. For the sake of brevity, in Figure 2 only the ADRS check for the uniform load pattern was depicted. The result in terms of capacity over demand ratio for the DL and SD limit state were reported in Table 1.

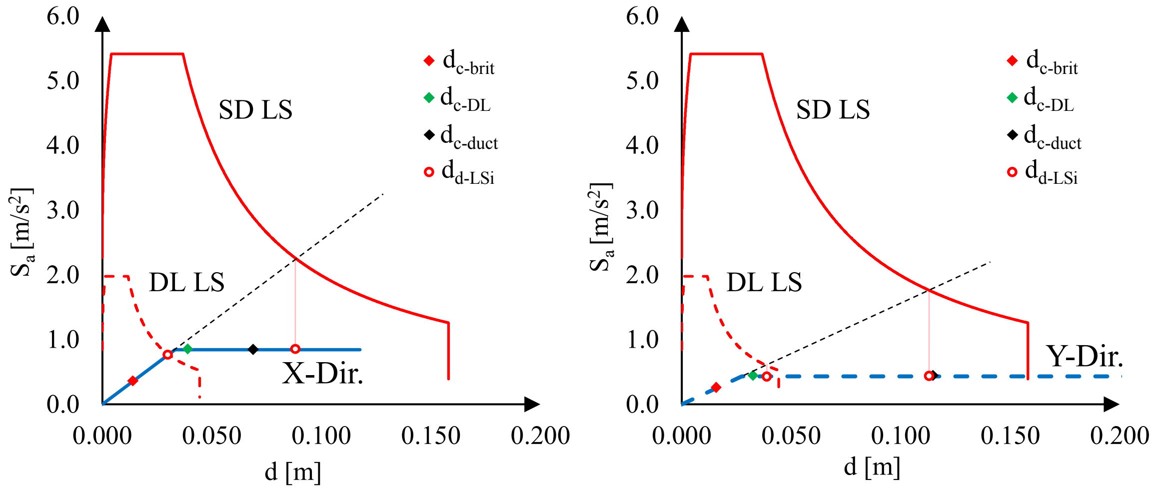

Figure 2. ADRS global verification check

Table 1. As-built building safety verification

Load Pattern	Damage Limitation			Significant Damage			
	$d_{d\text{-DL}}$ [m]	$d_{c\text{-DL}}$ [m]	C/D ratio	$d_{d\text{-SD}}$ [m]	$d_{c\text{-brit}}$ [m]	$d_{c\text{-duct}}$ [m]	C/D ratio
1° Mode X	0.026	0.031	1.19	0.107	0.011	0.107	0.11
1° Mode Y	0.031	0.020	0.65	0.128	0.012	0.127	0.09
Uniform X	0.022	0.026	1.18	0.088	0.014	0.069	0.16
Uniform Y	0.027	0.022	0.81	0.111	0.014	0.114	0.13

4 EXTERNAL STRENGHTENING INTERVENTION

4.1 Main feature of the orthogonal exoskeleton system

In order to improve the seismic performance of existing RC building in terms of lateral stiffness and resistance global interventions involving the addition of new seismic-resistant systems that can be applied both internally and externally to an existing building [13-15]. Exoskeletons systems placed outside the structure they protect, could be installed avoiding any interruptions or disruptions to the existing building. In this context, the study of strengthening systems through steel exoskeletons orthogonal to the facade of the building to be protected is of great interest [16]. In fact, the use of steel as a construction material allows for sustainable, high-performance, and fast application interventions [17-24]. The high structural performance of steel systems is widely reported in numerous works in literature [25-38]. Therefore, starting from the result of the pushover analyses performed on the existing structure, the dimensioning of the orthogonal steel exoskeleton strengthening intervention was carried out following a step-by-step procedure properly introduced by the Authors in a previous publication [39]. Figure 3 depicts the plan distribution of the exoskeleton system, the aim of the strengthening intervention was to avoid any local shear failure of the RC beam-to-column joint at the SD limit state and to avoid excessive deformability at the DL limit state.

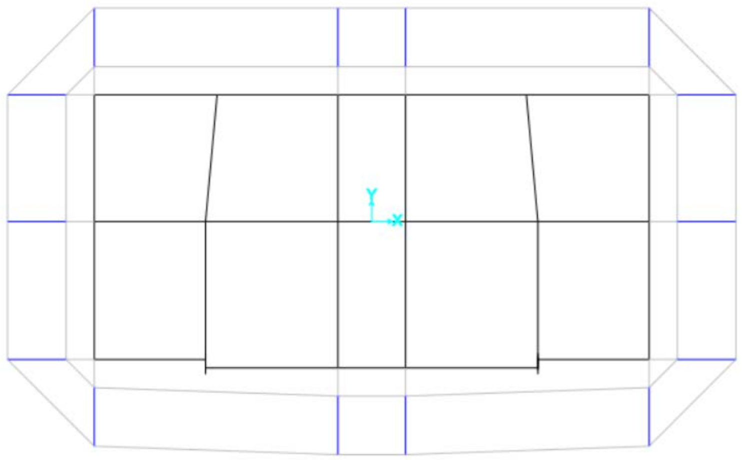

Figure 3. Plan distribution of orthogonal steel exoskeletons

4.2 Safety assessment of the strengthened structure

A re-assessment of the retrofitted structure was investigated performing non-linear static analyses based on the assumptions explained in the previous section. The non-linear behaviour of the exoskeleton elements was taken into account by the introduction of lumped plastic hinges, that were modelled according to the final version of next generation of Eurocode 8 [38-39].

The results of the pushover analyses are summarized in Table 2.

Table 2. Retrofitted building safety verification

Load Pattern	Damage Limitation			Significant Damage			
	$d_{d\text{-}DL}$ [m]	$d_{c\text{-}DL}$ [m]	C/D ratio	$d_{d\text{-}SD}$ [m]	$d_{c\text{-}brit}$ [m]	$d_{c\text{-}duct}$ [m]	C/D ratio
1° Mode X	0.004	0.032	8.0	0.010	0.011	0.074	1.1
1° Mode Y	0.003	0.025	8.3	0.009	0.012	0.077	1.3
Uniform X	0.003	0.029	9.7	0.009	0.013	0.06	1.4
Uniform Y	0.002	0.024	12	0.007	0.013	0.058	1.9

5 COCNLUSION

The global behaviour of existing RC frame building designed for gravity loads were investigated by means of static non-linear analysis. The retrofit solution was designed to increase the global structural performance in terms of lateral resistance and stiffness in order tp avoid any failure at the significant damage limit state. From the analyses results, the following consideration can be pointed out:

- The existing residential building selected as case study has shown poor seismic performances, typical of the existing RC structure erected before the 1980s;
- The introduction of the exoskeleton on the external perimeter of the industrial building allows to increase both the lateral stiffness and strength;
- The results of the pushover analyses performed on the retrofitted configurations show the effectiveness of the exoskeletons systems to achieve the desired performance level at the DL and SD limit state.

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