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Factors influencing the repair costs of soft-story RC frame buildings and implications for their seismic retrofit

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ABSTRACT

This paper examines the factors affecting the repair costs following major earthquakes, of reinforced concrete (RC) frame buildings with non-ductile detailing typical of construction practices in Italy and other parts of the world during the 1950s and 1960s. Two configurations of a RC frame structure, one with full infills and the other with partial infills, are numerically studied. Results of incremental dynamic analyses confirm that the partial infill RC structures, in which soft-story mechanisms form in the open story, are more likely to collapse. However, by undertaking a loss estimation study for different scenarios it is shown that the lower losses that are expected due to the reduced damage of non-structural components in upper levels could be an advantage of soft-story buildings provided that the collapse propensity is reduced at the first level. It is further shown that losses in soft-story buildings will be strongly affected by the repair value of the structural and non-structural components at the soft-story level relative to other levels and the magnitude of P-Delta effects. These observations indicate that an effective retrofit strategy, that would reduce both monetary losses and the probability of collapse, could be achieved by increasing the deformation capacity at the soft-story level without altering the isolating effect that the soft-story mechanism provides to the levels above and without any further intervention in the stories above. The changes in losses resulting from such a conceptual retrofit solution are presented in order to illustrate the merits of such an approach, that should therefore become the focus of future research.

1. Introduction

Although the potential benefits of the soft-story concept had been proposed by a number of researchers as early as the 1930s [1–5], the poor performance of such buildings in past earthquakes have ruled out this approach for seismic design [6]. For example, serious damage or collapse of first stories are reported in the 1971 San Fernando ($M_w = 6.6$) and 1978 Miyagi-ken Oki ($M_s = 7.7$) earthquakes. As a result of these earthquakes, soft-story structures were thoroughly studied and design procedures and recommendations were developed to prevent column side-sway mechanisms [7–10] as the benefits of designing using a weak-beam strong-column mechanism had already been recognized in New Zealand in the seventies [11]. Most previous studies emphasized that the column elements within a soft-story mechanism will reach their ultimate capacity at considerably lower levels of intensity than yielding beam and column elements within mechanisms that involve distributed deformation demands over most of the height of the buildings.

Current design practice aims to avoid the occurrence of soft-story mechanisms. However, there are a large number of older existing buildings that are expected to develop soft-stories under strong ground shaking. Engineers must therefore decide when retrofit is required for such structures and identify the best retrofit strategy for a given situation. This decision could significantly affect the distribution of damage over the height of the building in the event of intense earthquake shaking. This paper examines the effect of this distribution of damage on the total repair costs of structures with soft-story mechanisms. An initial case study structure with two types of infill distributions (partial infill and full infill) is taken as a benchmark building and incremental nonlinear time-history analyses are carried out. Secondly, the direct losses of the partial infill frame are compared to those obtained for the full infill frame, and factors affecting the likely losses, such as the distribution of non-structural components over the building height

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and P-Delta effects, are examined. In light of the results obtained, a potentially advantageous retrofit concept for soft-story structures is then proposed, and the influence of the proposed concept on loss estimation results is investigated.

2. Description of case study building and analysis approach

The six-story three-bay reinforced concrete frame structure shown in Fig. 1 was studied in this paper for two different distributions of masonry infills. In the first scenario, masonry infills were distributed over all stories uniformly, while in the second scenario, masonry infills were omitted at the ground story, which leads to a soft-story response during strong earthquake shaking. The first variant is labeled as the full infill (FI) variant, while the second variant is labeled as the soft-story (SS) variant in this paper. The frame configurations that were studied were taken from the work of Galli [12]. These frames are representative of typical buildings designed in Italy and in many other places throughout the world from the 1950s to the 1970s. In these buildings, structural elements were designed only for gravity loads without following any capacity design rules or ductile detailing requirements for seismic loading.

While full infill frame solutions can be found at end walls of apartment blocks, they are not expected to be as common as the open ground floor scenario. Nevertheless, the response of a full infill frame scenario can also be considered representative of a more traditional retrofit solution that aims to increase the strength and stiffness of the open ground floor of the SS scenario, without retrofitting the levels above. As such, a comparison of the FI and SS variants in this paper is considered relevant.

The structure that is shown in Fig. 1 is part of a building that is formed by a series of parallel frames spaced at a distance of 4.5 m between the centerlines of the columns. The first floor height is 2.75 m, while other floors have a height of 3 m. The frame consists of two equal exterior bays of 4.5 m in length and one interior span with a length of 2 m. The frame is therefore symmetric about the vertical axis. Fig. 2 shows section configurations and reinforcement detailing of beams and columns in a typical bay of the frame.

The geometrical and material properties are as follows:

- Beam dimensions were assumed equal for all floors with a 500 mm depth and a 300 mm width. Column dimensions were obtained from axial compression force requirements only.
- All reinforcing bars were smooth round bars with hooked ends for anchorage.
- The steel reinforcement quantities for beams and columns were determined by Galli [12] based on the Italian code provisions and the design handbook in effect before 1970, and are shown in Fig. 2.
- Gravity design loads for beams were taken as 60 kN/m for the floors below the roof level and as 50 kN/m at the roof level.
- The characteristic yield strength of the bars and the concrete compressive strength were defined as 380 MPa and 20 MPa respectively.
- The horizontal and vertical compressive strengths of masonry were respectively 3.84 MPa and 2.7 MPa.

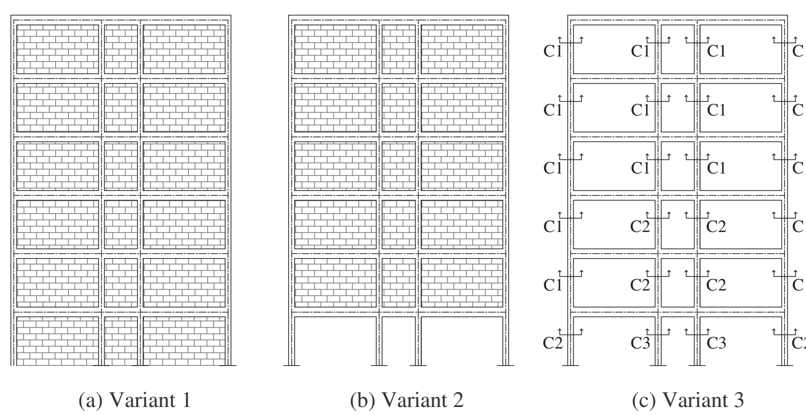

Fig. 1. Six-story concrete frame, (a) variant 1: full infill uniform distribution (FI), (b) variant 2: partial infill disconnected in the first floor (SS), (c) variant 3: bare frame (BF).

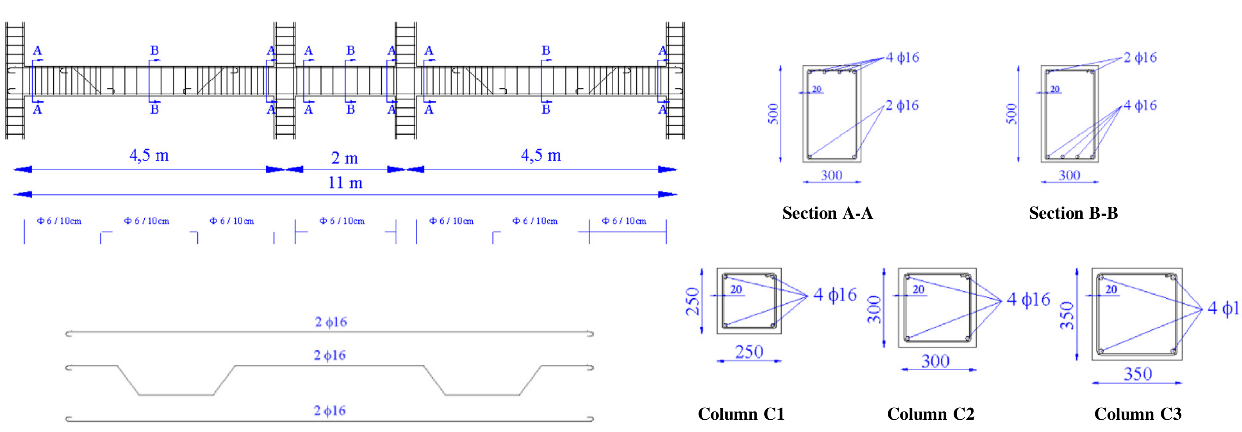

Fig. 2. Properties of beams and columns [12].