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Seismic retrofit options for non-structural building partition walls: Impact on loss estimation and cost-benefit analysis

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ABSTRACT

The importance of non-structural components in building performance under seismic action is well recognized in the scientific community. Damage to residential buildings registered in past earthquakes has demonstrated that the damage to non-structural components represents a substantial percentage to the resulting economic losses. In the context of performance-based earthquake engineering (PBEE), the probabilistic estimation of building-specific losses has highlighted the importance of non-structural walls, in particular, due to their direct influence on building response and contribution to the overall damage. However, limited research has been produced on the subject of seismic retrofit of non-structural components and their economic advantages. In this manuscript, focus is given to non-structural partition walls, with the aim of determining the potential economic benefit of implementing non-structural retrofit solutions, in terms of the corresponding reduction in average annual earthquake losses. Building on an extensive literature review on the state-of-the-art of non-structural retrofit solutions, representative retrofit options are investigated for six combinations of building class and seismic hazard at the building location (in Italy), by means of probabilistic seismic loss estimation and corresponding cost-benefit analysis. The results show that the seismic retrofit of non-structural partition walls only (as opposed to retrofitting both structural and non-structural components) can be sufficient to achieve a reduction of seismic losses that guarantees the return of the retrofit investment during the building's life cycle, specifically when dealing with highly vulnerable buildings located in regions of high seismicity.

1. Introduction

The importance of non-structural components in seismic design and building performance is now well recognized by researchers and practicing engineers. This subject received special attention after the San Fernando earthquake in 1971, when it became clear that non-structural damage can not only result in major economic losses, but also pose real threat to life safety [1]. More recently, the importance of non-structural damage has been identified after events in Turkey (e.g. 2011 Van earthquake – Sucuoglu [2] and Italy (e.g. 2012 Emilia Romagna earthquake sequence – Penna et al. [3].

Research efforts have evidently moved towards the investigation of the seismic behaviour of non-structural components. After the development of performance-based earthquake engineering (PBEE) methodologies, it is now obvious that non-structural components are one of the most critical elements of the PBEE framework [4]. According to [5], non-structural components account for approximately 82%, 87% and 92% of the total monetary investment in office, hotel and hospital buildings, respectively, in the United States, whereas [6] point to an equal proportion between the cost of structural and non-structural components. Moreover, unlike structural components, most of the non-structural components are not seismically designed and therefore vulnerable to relatively low levels of earthquake action. As a result, economic losses due to non-structural components generally exceed that of structural elements (e.g. [7,8]).

Non-structural components of a building are those that are not part of the structural load-bearing system but are in any case subjected to the building dynamic response [1]. A large variety of building parts – non-structural walls, ceilings, power/gas lines, water and sewage systems – fall into this category and their impact on building loss estimation has been investigated in recent studies [9–11]. Amongst them, interior and exterior non-structural walls are particularly relevant in the context of this study, due to their direct interaction with the structural system and inherent drift-imposed damage. In this study, particular attention is given to two widely used solutions worldwide: plasterboard partitions (herein denoted as drywalls) and unreinforced infill masonry walls (both interior and exterior).

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1.1. Masonry infill walls and drywall partitions: main properties and code requirements

Masonry infill walls and drywall partitions can be qualitatively described as respectively heavy and light partitions. This distinction stems from the different issues that may arise due to damage to each of those non-structural components. The failure of heavy masonry infills may threaten life safety of people and may affect structural response due to their high strength and stiffness, whereas light drywall partitions are associated with economic loss issues rather than life safety concerns.

Drywall partitions with light steel or timber framing are usually weak enough not to modify the lateral load capacity of the structure [12]. For this reason, they can be catalogued as non-interacting partitions in the framework of the non-structural components defined in Eurocode 8 [13].

The interaction of masonry infill walls with the adjacent structural system is accounted for in the same code. However, engineers are encouraged not to take advantage of their properties to reduce the effects of the design seismic action. The reasons for this approach are various but can ultimately be linked to the difficulty in reaching consensus on whether the local effects of masonry infill walls increase or decrease the global vulnerability of buildings. Various researchers have suggested that infill walls have detrimentally affected the structural response of reinforced concrete buildings in past earthquake events [14], leading to building collapse in extreme situations [15]. However, beneficial effects are also suggested in the literature (e.g. [16,17]). The reason for this apparent contradiction may reside in the observations made by Negro & Colombo [18] and Hashemi & Mosalam [19], who highlight both positive and negative effects.

1.2. Drywall partitions: earthquake performance

Drywalls are currently the most common partition wall solution in use around the world. They are especially popular in Europe and other developed regions such as New Zealand and the United States. Due to of their light weight compared to heavier options (i.e. clay bricks and concrete blocks), they are usually not considered to be part of the structural system. Although there are standardized regulations, there is a general lack of quality control that can mainly be attributed to the misleading definition of non-structural components, which seems not to trigger requirements for adequate check by structural engineers [12]. As a result, the amount of research does not seem to match the relevance of this topic, as highlighted by their significant vulnerability to seismic action.

McMullin & Merrick [20] and Filiautrault et al. [21] conducted respectively 11 and 36 tests using full-scale drywalls with timber and steel framing. According to [20], two main failure modes were reported: joint failure and racking of the gypsum linings, and the conjoint rotation of the gypsum linings. On the other hand, Filiautrault et al. [21] highlighted the concentration of damage at the vertical joints between drywalls in orthogonal directions. In a more recent endeavour, Tasligedik [12] highlighted that after the 22nd February 2011 Christchurch earthquake, the most common damage to drywall partitions consisted of the cracking at interfaces between adjacent linings, as well as the cracking at lining corners caused by inappropriate finishing (e.g. around the corners of windows or doors).

1.3. Unreinforced masonry infill walls: earthquake performance

Unreinforced brick masonry walls are still one of the most common non-structural partition types in Europe and South America. These walls are usually assumed as non-structural and therefore typically neglected in the analysis phase of structural design, despite being stiff enough to interact with the structural system during the dynamic response. The result of this interaction is generally a significant damage to the infill wall itself or the surrounding structural system [22]. Because of the brittle nature of clay bricks and the mortar joints, the interaction is inevitably brittle, which may change the ductile response of a reinforced concrete frame and induce, to some extent, global brittle behaviour.

In the last decades, this issue was widely recognized by the earthquake engineering community. The observation of damage to reinforced concrete (RC) buildings with infill panels after severe earthquakes (e.g. [23]), triggered the first efforts towards full-scale experimental tests [24], as well as the development of code prescriptions featuring the consideration of infill partitions in seismic design (e.g. [13]). Several efforts have been made since the early 1990s in order to investigate the seismic behaviour of RC frames with infills. In spite of the valuable information retrieved from the aforementioned studies, several questions remain regarding the influence of several parameters; e.g. material strength, reinforcement details, and ground motion input. The detailed description of each experimental study is not the objective herein therefore readers are referred to the works of Polyakov [25], Fiorato et al. [26], Klingner & Bertero [27], Bertero & Brokken [28], Mander et al. [29], Fardis et al. [30], El-Dakhakhni et al. [31], Dolce et al. [32], Hashemi & Mosalam [19], Blackard et al. [33], Pujol & Fick [34], Stavridis et al. [35], and Manfredi et al. [36].

1.4. Objectives and organization

Building upon the state-of-the-art of performance analysis of non-structural partition walls, the objectives of this manuscript are: (a) to provide a comprehensive review and comparison of available solutions for the retrofit and performance enhancement of partition components, focusing on drywall and masonry infill components; and (b) perform a cost-benefit analysis of available solutions based on probabilistic seismic loss estimation of three real building configurations located in sites of low, medium and high seismicity (in Italy).

Section 2 presents a literature review of existing seismic retrofit techniques for non-structural building walls, organized based on their common characteristics and effects on the performance under seismic action. In Section 2.3, different options are compared in terms of relevant attributes in the context of performance analysis and seismic loss estimation. As a result, two representative solutions are selected for further assessment of "as-built" versus retrofitted buildings.

Section 3 refers to the description of the case-study buildings and structural configurations, together with the assumptions regarding the numerical analysis of the "as-built" structures and corresponding retrofit options. Section 4 addresses the implemented probabilistic seismic loss estimation framework. The proposed methodology builds on recent developments on the treatment on uncertainty in the analysis of earthquake performance and vulnerability [37,38], specifically with respect to: (a) seismic hazard conditions and simulation of earthquake action through natural ground motion records; and (b) issues related with building collapse fragility. Moreover, the assessment of monetary loss through the inventory of damageable components, their cost estimates, and component fragility curves are addressed.

Section 5 deals with the probabilistic seismic risk assessment of each studied building, as the input to a loss (and time)-based cost-benefit analysis of the selected non-structural retrofit solutions. These results are further presented and critically reviewed in Section 6 in order to evaluate the possible benefits of implementing non-structural retrofitting techniques.

2. Retrofit solutions for non-structural walls

This section presents a summary of relevant solutions available for the retrofit of existing drywall partitions and masonry infill walls.

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