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# The critical role of floor diaphragms in the seismic retrofit of existing buildings

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## EXTENDED ABSTRACT

Floor diaphragms are key components of the Lateral Force Resisting System (LFRS) of existing buildings, both in the as-built and retrofitted configurations. Nevertheless, their effectiveness is rarely verified in the seismic vulnerability assessments, nor in the conceptual design for the retrofit of existing buildings. Floor diaphragms are essential for responding to horizontal loads because their primary functions are: ensuring the integrity of the structure by connecting the vertical elements of the LFRS and enabling their activation; transferring the inertial loads of the floor to the vertical elements, providing load paths for lateral forces; accommodating transfer forces resulting from incompatible deformation patterns of the existing structure and the retrofit vertical system, or from discontinuities or irregularities in infill distribution; providing lateral support to the vertical elements against buckling and second-order effects; collecting the out-of-plane loads of the perimeter infills [1].

When assessing the vulnerability of existing post-World War II buildings, floor diaphragms do not usually appear to be the critical part of the structural system because other vulnerabilities can occur before their capacity is reached. However, as additional retrofit systems are added to the structure [2] and higher inertial loads or additional transfer forces occur on each floor, they could become the weak link in the LFRS. By triggering a tied-arch resisting mechanism [3], existing floors, even if conceived to withstand only gravity loads, can resist horizontal seismic loads. However, the introduction of discrete stiffer elements can lead to an increase in the span of the resisting arch, which varies from the span of a single bay to the spacing between the new lateral force resistant structural elements (Fig. 1).

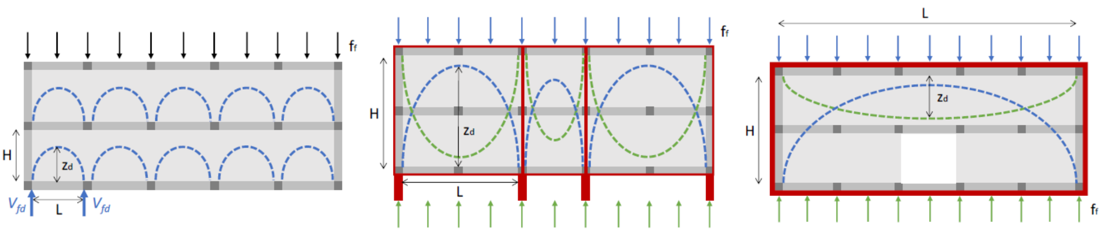


Fig. 1 Floor load path distribution for the building in as-is situation (a) and retrofitted with shear wall (b) or shell (c) configuration. In (c) the influence of a floor opening is also shown.

This work focuses on the role of floor diaphragms, starting from the evaluation of their in-plane capacity, and how they can influence the choice of various retrofit solutions, potentially compromising the feasibility of interventions completely carried out from the outside. Referring to beam-and-hollow clay blocks floor systems, particularly widespread over the Mediterranean countries, the main failure modes (Fig. 2) are discussed and formulations for the correct evaluation of the in-plane capacity are given [3].

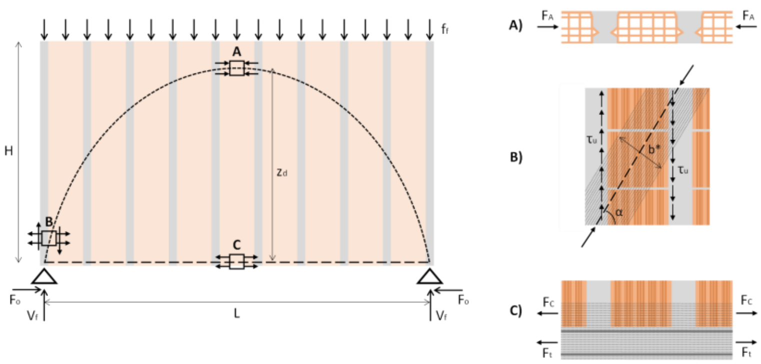


Fig. 2 Tied-arch mechanism activated within the floor depth and regions of possible failure of the tied-arch resisting system: A) the arch key section, B) the tied-arch supports where compression-shear failure may occur; C) the tied-arch bottom chord, with possible overcoming of its tensile strength.

The study also involves an evaluation of the seismic demands within the floors, which is related to the expected inertial forces at each level and is strongly influenced by the transfer forces [4] [5] [6], arising either from structural irregularities (e.g., distribution of infill panels), or from incompatible lateral deformation patterns of the LFRS of the existing and the retrofitting structures (dual systems). The former situation arises in buildings exhibiting soft storey behaviour, where there is an absence of infill panels at the ground floor level, or in buildings featuring ribbon windows at a specific height. The actions taken by the upper-floor infills experience a sudden redistribution through the diaphragms to the lateral load-resisting elements of the lower floors. This redistribution results in increased forces within the diaphragm compared to those induced solely by inertial loads at that particular storey (as illustrated in Figure 3a).

Similarly, if the RC frame is coupled with elements that have a different deformed shape, such as internal stairwell walls or additional shear walls, the loads need to be redistributed throughout the floors to align with the coupled behaviour of these elements. Therefore, supposing that a frame deforms like a 'shear building' and is linked with elements that deform either as cantilever beams or as hinged walls, the walls may be retained by the frame, especially at the upper floors (as depicted in Figure 3b). This arrangement generates floor loads oriented in the same direction of the seismic forces, instead of contributing to resist them as expected.

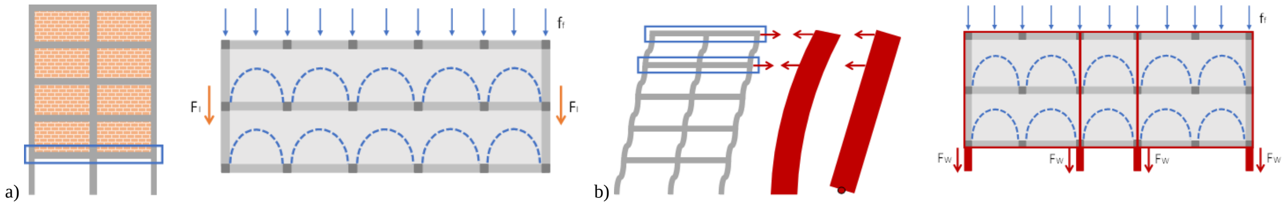


Fig. 3 a) Example of redistribution of the floor loads due to vertical geometric irregularities; b) Example of redistribution of the floor loads due to the coupling of a bare RC frame with additional shear walls with different deformed shape.

To study these seismic floor load patterns, pushover analyses were performed on a reference building by introducing various configurations of stiffening elements into the 3D numerical model. The results highlight the great magnitude of these types of internal forces, which need to be considered in the design process, especially when a rigid retrofit is carried out on an existing building [7]. As an example, in Fig. 4, it may be observed that, for this wall configuration (4 additional slender walls at the building ends), the exoskeleton is retained by the existing frame at the upper floor, causing additional forces in the floor in correspondence of the walls directed as the seismic loads.

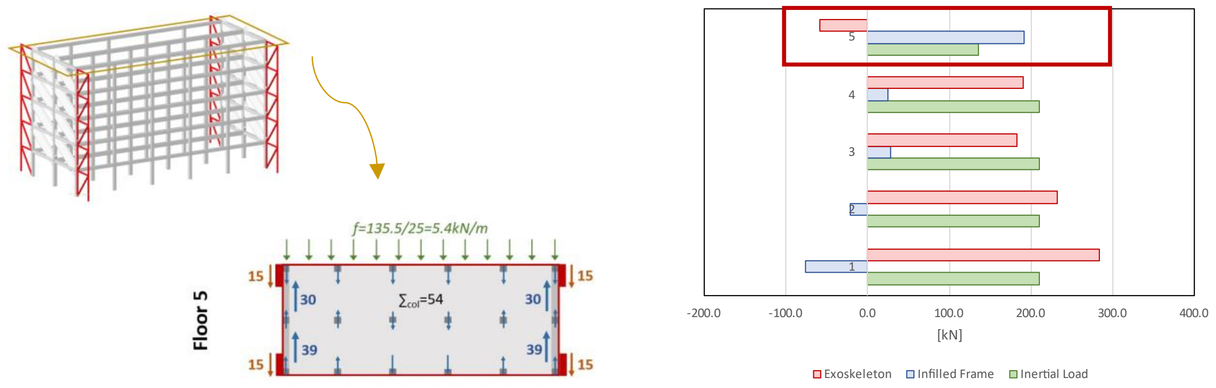


Fig. 4 Retrofit intervention with shear walls fixed at the base: distribution of the inertial load between the infilled frame and the exoskeleton (right), in-plane forces at the upper floor (left). The graph shows the results of the pushover analysis for an elastic configuration of the building at 0.3% drift, subjected to a distribution of forces proportional to the masses (which was the worst one).

Furthermore, in order to identify the main parameters affecting the magnitude of the transfer forces and their paths, a sensitivity analysis was performed on a 2D frame coupled with additional walls. In particular, 4 different walls with the same equivalent stiffness (Fig. 5) were considered to evaluate the effects of different lateral deformation patterns on the development of the transfer forces within the floor diaphragms. The results show that evolving from retrofit with similar (RET 1) to incompatible (RET 4) lateral deformation patterns, the transfer forces in the floors increase.

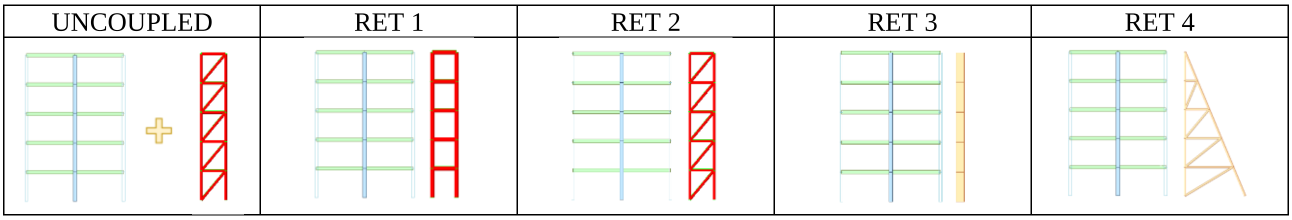


Fig. 5 Different configuration of iso-performance retrofit intervention applied to a reference frame. The aim is to highlight the role of different compatible/incompatible lateral deformation patterns caused by the coupling of the existing frame and the retrofit structure, in generating the development of transfer forces within the floor diaphragms.

Other studied parameters include: the presence of infill panels to simulate the soft storey mechanism behaviour of the building; different constraints at the base to evaluate the impact of the soil-structure interaction on these forces; the number of storeys to evaluate the influence of height; different steps of pushover analysis to evaluate the evolution of the transfer forces from the elastic to the non-linear behaviour of the structure.

The aim of this work is to highlight the critical role of floor diaphragms in seismic retrofit of existing buildings. Floors are usually neglected in the design phase, and they are typically not even included in finite element models. In order to draw attention to the need to assess their vulnerability, especially when rigid retrofit intervention is added to the building, the first part of this study examines the in-plane ultimate capacity of beam and hollow clay block floor systems, considering a rigid behaviour and brittle collapse. In the second part, the seismic demand is investigated, and the contribution of the transfer forces is evaluated. This type of forces results from the irregularities of infilled RC buildings or from the incompatible lateral deformation patterns of the existing building and the retrofit intervention. The choice of the retrofit intervention may thus affect the magnitude of forces within the floor diaphragms; so, if minimisation of transfer forces is required, a retrofit structure whose lateral deformation pattern is similar to that of the existing building is recommended.

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