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Unbonded brickwork for the protection of infills from seismic damage

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ABSTRACT

Brittle masonry infills cannot cope with the interstory seismic displacements of ductile structural systems. They account for most of the economic impact of earthquakes, direct (for repair or replacement) or indirect (due to disruption of occupancy, as tenants are reluctant to use the building before all damage is repaired). Bricks not bound together by mortar at bed joints can slide freely along them and let the infill panel deform freely in its plane, following the seismic motion of the structural frame nearly unstressed and assuming its original shape when the shaking stops. Viscous fillers or factory-applied facings can control air-, vapor- and water transport via the dry joints, without compromising free movement along them. The frames of openings have articulated corners, which let them sway after a fuse breaks at each corner. Clearances between fixed glass panes and their frame are tailored to the seismic displacement demands. Rotating leaves of doors or windows slide vertically and in and out of special cavities in the frame. A rail-in-groove system at the horizontal faces of the bricks locks them together in the wall's out-of-plane direction and stabilizes the wall with the help of membrane forces due to confinement by the frame. Bricks alone can provide the insulation, via an optimal pattern of horizontal holes. Infill walls and their openings become engineered components, with their compliance to performance-based criteria explicitly checked in design calculations. A rudimentary application in a single bay, one-story steel frame infilled with off-the-shelve solid clay bricks was subjected to in-plane quasi-static cyclic loading and to out-of-plane shake table testing. Shallow longitudinal steel straps placed in slots cut along the top and bottom faces of bricks and facing each other, straddled the bed joints to prevent out-of-plane sliding between bricks. Damage after cyclic in-plane interstory drifts of 5.7% was limited to local distress of few bricks near the panel corners, due to hard contact with the columns. In the out-of-plane direction a panel with a slenderness ratio of 22.5 was stable under transverse response accelerations of 0.3 g; it collapsed when the deflection caused the weight of the infill to act outside the wall thickness at the bottom.

1. Introduction

Exterior or partition walls which are not part of the system resisting the loads and carrying them to the ground are considered as "non-structural"; as such, they escape the attention of structural design standards and structural designers. The only structural codes with rules for the mechanical integrity of "non-structural" walls are certain seismic design codes, and yet only to avoid casualties or injury in strong earthquakes ("falling hazards"). The reason is that, to date, seismic codes cater only for life safety and pay lip service to property protection under the full range of likely earthquakes. Indeed, the discipline of earthquake engineering has reached the level of maturity and knowledge that is necessary to meet its prime aim, i.e., to protect life. Strong earthquakes that hit in recent years areas where modern knowledge is effectively applied in practice (California, Japan, Italy, Taiwan, Chile, New Zealand, etc.) caused much fewer casualties than similar tremors in the past. Their main impact was economic due to damage inflicted to "non-structural" elements and the indirect cost of disruption of use for repair or replacement [4,7–10,15,21]. For example, the 2009 L'Aquila (IT) earthquake saw the collapse of most brick façades in which measures for energy efficiency had been implemented [25].

Seismic design codes consider individual "non-structural" walls as sacrificial components, as they are easy to replace if damaged in an earthquake. Indeed, even small or moderate earthquakes, which cause very little distress to the structural frame, most often inflict serious damage to these walls. Despite the very low direct cost of replacement or repair of individual wall panels, non-structural walls, with their high failure rate, contribute in total to economic loss much more than the structural framing [3,14,17]. For example, damage to exterior walls and interior partitions accounted for

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80–90% of the direct losses incurred due to damage to buildings after the 6.6 Magnitude San Fernando earthquake [14,17]. Even higher is the total indirect cost to individual owners and the affected community at large: occupancy and use are normally disrupted, not only during the repair and replacement works but also before, as tenants and users feel unsafe in a building with visible non-structural damage; notwithstanding the reassurances from competent engineers and the absence of damage in the structural framing [22].

An earthquake generates displacements of the building and deformation of its components, not forces. Components fail when they reach their deformation capacity. The structural framing is designed and constructed to have large deformation capacity: a commonly used conventional upper limit to the interstory displacement is 2% of the story height. A building with a State-of-the-Art seismic design does not collapse even at displacements much larger than this limit. By contrast, the wall panels filling the space between the members of the structural framing are inherently brittle and cannot cope with the large deformations of the frame: visible cracks form in masonry at interstory displacements as low as 0.15% of the story height, i.e., an order of magnitude less than the limit displacements for the design of the structural frame. Indeed, masonry panels are completely shattered if subjected to the design displacements of the framing. A possible way out of the problem in seismic regions would be to replace masonry with a non-brittle material, capable of coping with interstory displacement ratios of over 2%. The same level of deformation should also be accommodated by all strata adhered to the masonry: the plaster rendering, insulation layers, vapor barriers, etc. However, reasonably priced alternatives to brittle masonry are not yet on the horizon. Masonry is the oldest and still the most common construction material, thanks to its very low cost, local availability and simplicity of construction, as well as its very good qualities (strength, durability, dimensional stability, fire resistance, good sound and heat insulation properties, etc.) Unfortunately, the one quality it lacks, i.e., deformation capacity, is of the utmost importance in seismic regions.

Of all codes in the world, the European Standard for seismic design, Eurocode 8, is the only one with rules for masonry-infilled buildings. Nonetheless, these rules are focused on protection of life. In its response to the EC Mandate to revise the Eurocodes, CEN singled out these rules for revision/improvement [6]:

> "**Infilled frames and claddings**: Framed buildings with masonry infills are very common in southern Europe. Eurocode 8 includes design provisions to account for the presence of infills, but they are mainly to avoid possible detrimental effects that the infills may cause to the main structure. The beneficial effects (namely being the source of overstrength and energy dissipation) are not yet accounted for. Improvement of the provisions of Eurocode 8 regarding infills could be sought, but the implications of fully exploiting masonry infills in the design of new buildings should be carefully evaluated, since it entails more complex design and stricter quality assurance requirements for the construction of the infills. Additionally the recent earthquakes, namely in l'Aquila (IT), have shown that in many recent buildings where the structure behaved properly, heavy damage in claddings and cladding panels occurred. This shows that the design provisions of Eurocode 8 for infilled frames should be extended to cover cladding elements and panels, together with other types of enclosures. This shall reduce the risk of out-of-plane collapse of these types of elements. Such collapse may be detrimental to the main structure, as it introduces irregularities in its seismic response. Also such collapses are life-threatening and may cause heavy economic losses".

2. Protection of masonry infills from seismic damage

A large volume of research and a series of lessons from past earthquakes, accumulated over several decades, show clearly that the overall effect of masonry infills on the seismic performance of buildings and on the safety of their users is in general beneficial, but can be detrimental in some cases [11–13]. To protect the structure from the potentially deleterious impact of non-structural infill walls, some experts and few design codes propose to separate the two vertical sides of each infill panel from the columns or walls of the structural system on either side, and the top of the panel from the soffit of the beam or the floor above [14,17,22]. The gap at each vertical side should exceed the horizontal seismic movement between two floors, which, if in the order of 2% of the story height, amounts to several centimeters. A gap of such a size is a major challenge for water- and air-tightness, fire resistance, acoustic and thermal insulation, etc. Technological answers to these problems are far from satisfactory, especially if the energy performance requirements on exterior walls are high. Another challenge is to prevent such a free-standing wall from toppling out-of-plane in an earthquake. For all these reasons, practice has not adopted separating gaps and is not likely to do so in the foreseeable future. Aliaari and Memari [1,2] proposed and studied an advanced version of this approach: they introduced between the free-standing infill wall and the structural frame another portal frame of light-gauge steel, for out-of-plane support at the top; the vertical gaps at the sides were filled with a deformable sound-proofing and fire-resistant material and housed replaceable fuses. However, owing to its high cost and complexity, this solution and similar ones did not go very far in practice.

The majority of experts and of seismic design codes accept nowadays that the advantages offered by masonry infills tightly placed within the frame outweigh any detrimental effects; after all, the structure can be designed against these effects. According to many experts, if one takes this standpoint in design, he or she should explicitly consider in the analysis model and in the verifications the interaction of the infills with the frame. Bertero and Brokken [5] expressed this viewpoint as follows:

> "...the second philosophy offers more conceptual and practical advantages, particularly if the basic structural system is moment resisting frame. This is because a main principle for seismic-resistant design is: Avoid unnecessary masses, and, if a mass is necessary, use it structurally to resist seismic effects."

The two old philosophies of separation and integration looked at the issue through the eyes of the structural designer who caters only for the structural framing and considers the infills as sacrificial components. The increased awareness of the impact of infills on the magnitude of losses and on the return of buildings to normal post-earthquake use raises the protection of infills almost on a par with the integrity of the structural framing. The new priorities require new technical solutions.

Conventional exterior walls have seamlessly continuous exterior and interior surfaces, for thermal and acoustic insulation and air- and water-tightness. In partition walls, continuity of the surface is common, yet not an absolute rule. Owing to its low deformation capacity, a continuous wall panel cracks when it is forced to follow the seismic movement of the structural frame. Cracks in the masonry accommodate the in-plane seismic deformation of the panel but constitute visible damage, often perceived as serious.

A new concept for the protection of masonry infill walls from seismic damage is to retain the tight fitting of the infill panel within the frame but to replace the continuity and rigidity of a conventional wall with complete or partial freedom to deform in its vertical plane like a mechanism. The idea was conceived sometime

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