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Determination of shear strength of historic masonries by moderately destructive testing of masonry cores

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HIGHLIGHTS

- Assessing the seismic vulnerability of historic masonry buildings is an urgent task.
- A novel method to determine masonry shear strength by using cores is here presented.
- Purposely constructed reference masonry panels were tested to shear–compression.
- Masonry cores were subjected to splitting test with various mortar layer rotations.
- Results found for reference masonry panels and cores exhibit very good agreement.

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ABSTRACT

To determine masonry shear strength, which is a fundamental parameter for evaluating the seismic vulnerability of existing masonry buildings, several experimental techniques can be adopted. A promising method is subjecting cores, easily core-drilled from masonry buildings, to splitting test with mortar layer rotation, so that in the centre of the mortar joint a mixed compression–shear stress state is present. To investigate the actual suitability of testing cores for determining masonry shear strength, in this study a systematic comparison between reference masonry panels, subjected to shear-compression test, and cores, subjected to splitting test with different mortar layer inclinations, was performed. Ten masonry panels were constructed using fired-clay solid bricks and a mixed lime-cement mortar with poor mechanical properties, with the aim of resembling materials used in historic buildings. After curing for 28 days, nine masonry panels were tested, compression stress being kept constant at a fixed value and shear stress being increased until failure. By plotting shear stress against compression stress and performing linear regression, the initial shear strength and the angle of internal friction of the masonry were obtained. The tenth masonry panel was core-drilled to obtain cylindrical cores (10 cm diameter, 25 cm length) with a central diametric mortar joint. The cores were then subjected to splitting test with mortar layer inclinations of 0°, 15°, 30°, 40°, 45° and 50° with respect to the horizontal. While cores tested at 15° and 30° exhibited a splitting failure mode, cores tested at higher mortar layer inclinations exhibited a sliding failure mode, which was considered as the most representative one for evaluating masonry shear resistance. By plotting the shear stress against the compression stress for cores tested at 40°, 45° and 50° and then performing a linear regression, the initial shear strength and the angle of internal friction were derived. As results found for reference masonry panels and for cylindrical cores exhibit very good agreement, the proposed methodology seems like a very promising technique, which has the advantage of requiring only moderately destructive samples that can be easily core-drilled from existing buildings.

1. Introduction

Recent earthquakes that in the last decades struck Southern Europe and Asia clearly showed the sensitivity of masonry buildings to this type of dynamic actions. In an effort to limit the damages from future earthquakes, the definition of the structural capabilities of this type of buildings has become a really actual and urgent task [1]. In this framework, evaluating the seismic

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vulnerability of historic masonry buildings, with the aim of predicting the damage level for a certain earthquake intensity, is a challenging task that structural engineers are often asked to deal with. For instance, recent studies have been aimed at evaluating the seismic vulnerability of masonry towers [2], masonry churches [3], masonry monumental palaces [4] and monumental building in general [5]. In particular, in Italy, after the Emilia earthquake of 2012, an increasing number of existing buildings has been subjected to seismic vulnerability analysis.

To assess the structural response of masonry buildings, masonry mechanical properties need to be first determined. Several methods have been reported in the literature for the assessment of the load bearing capacity of existing masonry constructions, including monumental buildings, towers, bridges, etc. [6–10]. As far as resistance to seismic actions is concerned, masonry shear strength is the most important parameter to be evaluated. According to Eurocode 6 [11], as well as Italian Code for constructions [12], the masonry characteristic shear strength (f_{vk}) for new constructions can be defined following the well-known Mohr–Coulomb failure criterion $f_{vk} = f_{vk0} + 0.4\ \sigma_n$, where f_{vk0} is the characteristic shear strength with zero compression stress and σ_n is the average compression stress owing to vertical loads.

A number of methods and techniques have been proposed so far to define the characteristic shear strength f_{vk0} and they will be discussed in the next section. Among them, masonry shear strength determination by testing of cylindrical cores seems like a promising technique, which has the advantage of causing limited damage to the building and allowing to obtain information on shear strength for different compression values. Nonetheless, the studies that have been carried out so far to evaluate the suitability of using masonry cores were based on either empirical formulas or experimental data obtained from samples coming from actual historical buildings [13–15]. In the latter case, test results exhibit significant dispersion, which can be attributed to the variability of both bricks and mortars used in historical buildings. To the authors' best knowledge, no experimental study for evaluating the suitability of testing cores, making use of purposely constructed and controlled masonry samples, has been carried out so far.

Therefore, in this study a systematic comparison between shear strength values obtained from reference masonry panels, subjected to shear-compression test according to EN 1052-3 [16], and values obtained from cores, core-drilled from analogous panels and subjected to splitting test with various mortar layer inclinations, was performed. For interpreting the results of the splitting tests on cores, a novel methodology was used, which is here presented and discussed.

2. Existing methods to define shear strength

When dealing with new masonry, Codes allow two possibilities to be followed for the definition of shear strength without axial force f_{vk0}: (a) direct experimental measurement by performing shear tests on masonry units with different axial load or (b) its indirect estimation by making use of tables or empirical expressions contained inside those same Codes [11,12], correlating f_{vk0} with brick and mortar compressive strength. Only the second method can be applied also to existing masonry but with a reduced reliability. For a more accurate estimation, *in situ* direct measurement of masonry shear strength, either with or without compression stress, has to be preferred. To this purpose, several techniques can be adopted, differing for their destructiveness, expensiveness, technical challenge and significance of results.

The most direct technique for *in situ* shear strength determination is performing a shear-compression test on a large masonry portion (about $90 \times 180\ \text{cm}^2$), disconnected from the rest of the masonry wall and loaded both horizontally and vertically by means of hydraulic jacks [6]. This method has the advantage of allowing to evaluate shear resistance for different compression levels. Moreover, the evaluation of test results is quite straightforward, as masonry shear resistance with or without vertical loads is directly measured. However, this method has the strong limitation of being highly destructive, so that its actual applicability is limited to a very few cases.

An alternative *in situ* testing procedure is subjecting a masonry portion (larger than $120 \times 120\ \text{cm}^2$, according to ASTM E519/519M-10 [17]) to a diagonal compression test [6,18]. This method, which is highly destructive as well, has also the limitation of not allowing compression stress to be applied independently from shear load. According to the standard interpretation, from *in situ* diagonal test the masonry shear strength with zero compression stress is obtained, since the centre of the panel is assumed to be subjected to pure shear [17,18]. However, further interpretations have been proposed so far, based on masonry panel modeling as an isotropic and homogeneous material. According to these interpretations, the centre of the panel is not subjected to pure shear, and different formulas for masonry shear strength calculation have been alternatively proposed [18].

A less invasive technique for estimating masonry shear strength is subjecting triplets (made of three brick courses and two mortar joints in-between) to a shear test, as described in EN 1052-3:2007 [19]. This method requires relatively small test specimens, and has also the advantage that triplets can be tested by either applying or not axial force to bricks, so that masonry shear strength with or without compression loads can be estimated. However, while in the case of new masonries testing triplets is a simple and straightforward method, in the case of existing masonries its applicability is rather limited [18,20].

A semi-destructive method that can be successfully performed *in situ* is measuring masonry mortar joint shear strength, according to ASTM C 1531-09 [21]. The idea is determining the horizontal force required to produce the relative slip of a brick with respect to the rest of the panel. This is possible since adjacent bricks along the same course have to be removed. This *in situ* testing technique has the advantage of being less destructive, less time-consuming and more economical than direct shear-compression or diagonal compression tests on masonry portions. However, its suitability is limited to those cases where masonry wall shear strength is governed by shear strength of the mortar joints rather than shear capacity of the bricks [21]. As pointed out in the cited standard, the proposed method for measuring *mortar joint* shear strength tends to overestimate the actual *masonry wall* shear strength, which can be derived from the former by making use of an empirical relationship [21].

An alternative technique, requiring only moderately destructive samples that can be easily core-drilled from existing masonries [6,8,10], consists of subjecting to splitting test masonry cores with a rotated mortar joint [13,22,23]. The method is based on the idea that in a core (made of two bricks and a central diametrical mortar joint) subjected to a splitting test, with the mortar layer rotated by 45° with respect to horizontal, the stress state in the centre of the mortar joint will be a mixed compression–shear stress state, which resembles that of a masonry panel subjected to a diagonal compression test [13,22]. Then, by projecting the failure pressure (obtained by dividing the failure load by the mortar layer area) in the two directions orthogonal and parallel to the mortar layer, the respective stress states can be derived.

The first experimental studies, aimed at evaluating the suitability of using splitting test on cores with a rotated mortar layer for evaluating masonry shear strength, pointed out that the nominal shear strength of cores was about 1.5–1.9 times the nominal shear