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Laboratory validation of the hole-drilling technique on the most common load-bearing walls used in heritage constructions

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HIGHLIGHTS

- Hole-drilling technique applied in laboratory to several masonry walls.
- Satisfactory results achieved in sandstone ashlars and rammed-earth walls.
- Poorer results obtained in the case of rubble-stone masonries.
- Optical fiber strain gauges were used to perform one test. The results were adequate.
- Digital image correlation and tracking were also used. The results were inadequate.

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ABSTRACT

The article describes the application of hole-drilling in diverse constructive types, detailing the results achieved in calibration tests carried out on several laboratory-built walls. The theoretical stress levels were approximated very closely in the case of ashlar (0.96) and rammed earth (0.91), but less closely in the brick wall (0.61). The technique did not prove useful with rubble-stone walls, although the cause of the discordance was not related to the methodology employed. Additionally, a comparison was established among hole-drilling tests carried out with different deformation recording techniques.

1. Introduction

The diagnosis of ancient buildings supposes important challenges because of the complexity of their geometry, the variability of the properties of traditional materials, the different construction techniques that are commonly used, lack of knowledge about existing damage, and how certain actions affect the constructions throughout their life [1]. As a consequence, architectural heritage buildings are subject to a number of difficulties in diagnosis and restoration under field conditions. These difficulties limit the application of the standards and guidelines which currently apply in building construction so, understanding, analysis and repair of historic buildings remain among the most important challenges for modern technicians.

Knowledge of the stress levels in a masonry structural element is sometimes of crucial importance as it can dictate the intervention process. Since the start of the eighties the simple flat-jack technique [2–4] has been applied in different constructive types [5], which has enabled its progressive calibration.

Alternatively, and with much less impact in the international scientific community, Professor Sánchez-Beitia's team at the beginning of the 90 s worked on developing and optimizing the hole-drilling technique, as an adaptation of the one described in the norm ASTM E837-95 [6], for the in-situ quantification of the service stresses undergone by the masonry support elements in Architectural Heritage structures. Although they worked toward the laboratory calibration of the technique [7,8], their fundamental contribution was the introduction of an in-situ working methodology. It was applied for a little more than a decade in a significant number of ashlar buildings. Among the examples of religious architecture the following Spanish cathedrals can be highlighted: Barcelona, Palma de Mallorca [9], Santa María de Vitoria and Tarazona

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[10], the Santa María del Mar church in Barcelona [11], or Saint Jakob's church in Leuven (Belgium) [12]. As for the civil heritage the following can be remarked: the Altes Museum in Berlin [13], the Aqueduct of Sultan El Ghouri in El Cairo, the Walls of Hondarribia [14] and the Casa Botines in León.

This article shows the potential application of the hole-drilling technique in diverse construction types, not only in ashlar, but also in irregular masonry, brick and rammed earth. To do so, the results obtained in calibration tests carried out in the laboratory on several load-bearing walls built for the purpose will be used.

Despite the difficulties found in applying the technique, above all the laboriousness of its implementation and the unavailability of data for comparison in most of the constructive typologies, and its drawbacks compared to the simple flat-jack test, fundamentally the need to carry out complementary tests to establish the mechanical characteristics of the support material on which the test is done; it is clear that the hole-drilling technique provides several advantages that make its use attractive in specific circumstances: application in medium and small-sized supporting elements (pillars, small columns, etc.) and, given that it enables the deduction of the complete plane stress state, it is used to quantify stress levels under traction.

Based on the authors' experience, the cost of the basic equipment needed to carry out a hole-drilling test (an orbital polisher equipped with a sanding disc, a data logger, a laptop and a drill with bits) is about 4,500.00€ and the fungible cost (strain gauges, adhesive and malleable plastic adhesive for gauge protection) approaches 150.00€. On the other hand, the cost of the basic equipment to carry out a single flat jack test (a portable stone saw, a deformation meter, a manometer, a pump and the hydraulic system) is about 4000.00€ and the fungible cost (a flat jack, infill plates, control points and adhesive) 400.00€. Regarding the time necessary to perform the tests, depending on the masonry type, the hole-drilling duration might vary from $4^h00'$–$4^h45'$, and the flat jack one from $1^h30'$ to $2^h15'$, Table 1.

2. Description of the methodology employed

The hole-drilling method is set in the field of the Non-Minor Destructive Tests, N-MDT. It is an experimental adaptation of the recommendations of ASTM E837-95 [6] for its use in Architectural Heritage. The general test procedure, with some slight adaptations depending on the substrate type, is described next.

First, the test zone is prepared by superficial polishing, except in the case of the rammed-earth wall in which the surface was sufficiently polished. For this, a variable speed orbital polisher equipped with a sanding disc was used, Fig. 1(a). The polishing speed was slower in the case of the sandstone than in the limestone or brickwork, because the former material is softer than the latter ones. Although three strain gauges are sufficient to derive the plane stress state, in order to eliminate or modulate experimental errors, eight strain gauges are adhered to the surface of the masonry wall [15], one every 45° around a circumference of 8 cm diameter, using cyanoacrylate adhesive, except in the case of the rammed-earth substrate in which an adhesive made with thermoplastic polyurethane was used [16]. In all cases, the strain gauges were 6-mm long, Tokyo Sokki Kenkyujo FLA-6-11. However, as the resistive part is integrated on a slightly longer plastic substrate, the real length of the gauges is 8 mm. Next, the gauges are protected using a malleable plastic adhesive (Tokyo Sokki 5B Tape) and by a final covering of adhesive tape. Additionally, in a zone at a distance from the analyzed one, or on a portion of the same material, an extra strain band is placed and connected, which will serve as a temperature compensation band, Fig. 1(b).

The eight strain gauges and the temperature compensation one were connected to a data logger to record the strains. In this way, after zeroing the measurements, the test was begun. This test consists of recording the strains before and after the execution of a perforation of 36 mm in diameter and 36 mm in depth in a concentric way with the circumference of position of the strain gauges. In all tests, to ensure this coincidence, the center of the circumference is marked using a center punch to guide the successive bits of variable and increasing diameters, until the tracer bit can be inserted into the perforation in the center of the empty diamond crown, Fig. 1(c). The drilling speed was slower in the case of the rammed-earth wall than in the other.

The execution of the perforation affects the gauges through heating and stress redistribution. Therefore, it is necessary to discern which part of the deformation registered corresponds to the purely mechanical effect. To do so, the deformations are registered until they stabilize, which occurs when the heat in the test zone dissipates along with the deformations due to thermic phenomena caused by drilling, Fig. 2. The value of deformation chosen is the mean of the last 30 min of the test when in this time the eight gauges register average fluctuations less than ±5 μm/m. This value is a product of experience and can be considered acceptable.

Furthermore, the strains registered in the eight strain gauges enable the deduction of eight combinations to derive the initial stress state; later, the principal stresses and their directions can be obtained. Thus, for every combination of strain gauges, Table 2, which fulfils the geometric disposition shown in Fig. 3, the principal stresses (σ_{max} and σ_{min}) can be obtained from the three associated deformations (ε_1, ε_2 and ε_3), according to Eqs. (1) and (2), respectively. The angle β between σ_{max} and the direction of ε_1, measured anticlockwise, is obtained using Eq. (3). The criterion for adopting sign is as follows: negative values indicate compression.

$$\sigma_{max} = \frac{\varepsilon_1 + \varepsilon_3}{A} - \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{B} \quad (1)$$

$$\sigma_{min} = \frac{\varepsilon_1 + \varepsilon_3}{A} + \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{B} \quad (2)$$

$$\beta = \frac{1}{2} \arctan\left(\frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{\varepsilon_3 - \varepsilon_1}\right) \quad (3)$$

where:

- ε_1, ε_2, ε_3: are the deformations registered at 0°, 225° and 90° to a reference direction.
- σ_{max}, σ_{min}: are the maximum and minimum principal stresses, respectively.

Table 1
Test duration. Comparison between hole-drilling and single flat jack.

Test	Construction type			
	Sandstone ashlar	Rubble-limestone masonry	Brickwork	Rammed-earth wall
Hole-Drilling	$4^h00'$	$4^h30'$	$4^h45'$	$4^h15'$
Single flat jack	$1^h30'$	$2^h15'$	$1^h45'$	$1^h45'$