Construction and Building Materials 111 (2016) 199–208

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Geometric indices to quantify textures irregularity of stone masonry walls

Celeste Almeida [a,*], João Paulo Guedes [a], António Arêde [a], Aníbal Costa [b]

[a] CONSTRUCT-LESE, Faculty of Engineering (FEUP), University of Porto, Portugal
[b] Department of Civil Engineering, RISCO, University of Aveiro, Aveiro, Portugal

## HIGHLIGHTS

- Geometrical analysis using digital processing techniques applied to 2D images.
- Geometric irregularity definition of stone masonry by shape and alignments indices.
- Application to old stone masonry walls located in Porto (Portugal) historic centre.
- Three level irregularity classification based on indices ranges and visual surveys.

## ARTICLE INFO

*Article history:*
Received 15 April 2015
Received in revised form 10 December 2015
Accepted 16 February 2016

*Keywords:*
Stone masonry walls
Geometric characterization
Image analysis
Indices methodology

## ABSTRACT

This paper aims at developing a general methodology supported by quantifiable geometric indices to classify the irregularity of stone masonry walls by direct observation of the elevation texture. This classification is based on indicators proposed in procedures developed in Italy, complemented with new tools and criteria. In particular, the evaluation of the geometric irregularity is done through a set of partial indices that consider the stones' shape, size and their organization along horizontal and vertical alignments. The methodology was applied to twenty-four granitic stone masonry walls selected from old buildings located at Porto city centre, in Portugal, and a classification is proposed based on irregularity levels graded according to the ranges of the different indices found for these walls.



## 1. Introduction

The proper characterization of stone masonry should involve thorough analyses of constituents and construction techniques that were used. However, such characterization is a quite difficult task due to the variability of the geometrical and mechanical characteristics/properties of the materials (types of stones, mortar and infill, generally presenting large dispersions) and the dependence on the construction procedures/techniques, which differ from region to region, even within the same country. The existing wide-range studies on classifying stone masonry tend to converge to qualitative appraisals concerning the performance of stone masonry walls under certain loading conditions, while virtually no objective and quantitatively based proposals can be found in the literature for global characterization of masonry. Therefore, the identification and classification of masonry walls in terms of its geometry, material constitution, expected mechanical properties and behaviour, still remains a big challenge deserving the researchers' attention.

Giuffré [1] developed the first studies on the characterization of the behaviour of stone masonry walls based on their typology, supported by visual inspection and seeking to recognize the accomplishment of good construction practices. According to that proposal, first the facades and cross-section textures and the characteristics of the materials must be carefully analysed on the basis of various parameters, namely the presence of transversal connections, the arrangement type and size of stones, as well as the presence and amount of wedges. Afterwards, this data is inserted in abacus that allows classifying the walls into three categories, corresponding to different quality standards. Research developed in Italy by Penazzi et al. and Binda et al. [2–4] in earthquake damaged buildings allowed characterizing and classifying masonry walls based on the analysis of cross sections. Surveys carried out in different regions of Italy led to the organization of a database with the most frequent types of stone masonry. In Portugal, the work of Casella [5], which concerns the survey of construction types,

* Corresponding author.
*E-mail addresses:* celeste.almeida@fe.up.pt (C. Almeida), jguedes@fe.up.pt (J.P. Guedes), aarede@fe.up.pt (A. Arêde), acosta@civil.ua.pt (A. Costa).

http://dx.doi.org/10.1016/j.conbuildmat.2016.02.038
0950-0618/

*Notation*

| | |
|---|---|
| $F_{FP}$ | stone shape factor |
| $F_{DP}$ | stone size factor |
| $F_{AH}$ | horizontal alignment factor |
| $F_{AV}$ | vertical alignment factor |
| $I_{FP}$ | stone shape index |
| $I_{DP}$ | stone size index |
| $I_{AH}$ | horizontal alignment index |
| $I_{AV}$ | vertical alignment index |
| $I_{FG}$ | global index |

and the study involving the analysis of stone masonry walls of Tentúgal village [6] are two examples of this type of research applied to Portuguese masonry.

More comprehensive studies have established survey forms of the geometric and material characteristics of masonry walls meant to assess their quality, mostly to quantify the seismic vulnerability of buildings and to define procedures for post-earthquake interventions [7,8]. For instance, within the RELUIS project, methods were defined for evaluating the quality of masonry by identifying factors that characterize good construction practices. Examples of that are the method for assessing a Quality Index for Masonry (IQM) [9,10], distinguishing quality according to the three type of actions masonry may be subject to, namely vertical and in-plane and out-of-plane horizontal loads, and the method of Minimum Trace Line (LMT) [11] that is devised to "measure" the stones' interlocking by analysing the elevation and cross section textures of a masonry wall.

Considering this, and the lack of research on this topic, the paper presents a methodology for characterizing and classifying masonry using an irregularity index defined by quantitative geometric parameters based on indicators proposed in procedures previously developed in Italy, complemented with new tools and criteria. In particular, the methodology focuses on the analysis of the elevation texture of masonry walls using photography and image processing tools. Although general, the indices depend on the walls typologies and, therefore, the methodology was applied to a series of granitic stone walls selected from old buildings located at Porto, Portugal, ranging from dressed stones assembled in regular geometric patterns, to poor quality typologies, with undressed stones defining irregular wall textures.

## 2. Geometric indices methodology

### *2.1. Methodology*

The methodology that is presented aims at evaluating stone masonry walls based on the quantification of their geometric characteristics through the analysis of the elevation textures using digital processing techniques applied to two-dimensional photographic pictures. Similarly to other studies in Italy, in this work the quality of stone masonry is associated to geometric regularity, which is strongly related to the accomplishment of the good construction practices established for masonry, a key to ensure the good performance and behaviour of stone masonry under static and, in particular, dynamic loads.

In agreement to studies of Borri [9,10], the present methodology selects the shape, size and organization of stones along horizontal and vertical alignments, as the characteristics which define the geometric irregularity of masonry, and quantifies factors and indices for the four of them. Although being recognized as important, at this stage the methodology doesn't consider the influence of the mechanical characteristics of the masonry constituents (stone and mortar) and of the presence of transversal connections. Finally, and according to the values obtained for the parameters, three classifications are assigned to masonry according to its geometric irregularity.

The criteria that justify the selection of those characteristics are the following:

- *Stones' shape*: stones having flat seating surfaces allow proper stresses distribution and ensure good mobilization of friction forces.
- *Stones' size*: larger stones tend to provide more regular textures.
- *Horizontal joints*: well-defined horizontal layers of stones provide uniform contact surfaces between stones and a better distribution of vertical loads along the wall.
- *Vertical joints*: the misalignment of vertical joints improves stones interlocking and increases the path of friction forces.

According to the described criteria, stone masonry made of more regular stones, with larger dimensions, settled in more uniform horizontal layers and with more clear vertical joints discontinuities tends to present better global behaviour to applied loads. The next section describes the factors and indices adopted to quantify each of the referred characteristics, noting that they are defined based on a panel sample with no pre-fixed dimensions which, however, should be large enough to represent the main characteristics of the masonry texture, i.e. larger stones will involve larger samples. In general, for a panel to be representative of the wall characteristics, the lateral dimensions should be about or greater than four times the average diagonal size of stones.

### *2.2. Quantification of geometric indices*

The present methodology involves the definition of four partial factors associated to the four geometric parameters previously identified, i.e. stones' shape and size and horizontal and vertical joints' alignments, referred to $F_{FP}$, $F_{DP}$, $F_{AH}$ and $F_{AV}$, respectively. Afterwards, four dimensionless indices, $I_{FP}$, $I_{DP}$, $I_{AH}$ and $I_{AV}$, are established by normalizing the corresponding factors ($F_{FP}$, $F_{DP}$, $F_{AH}$, $F_{AV}$) by quantifying extreme values for each factor. Finally, a global index ($I_{FG}$) is obtained by combining the four normalized partial indices. Note that the measurements are all done using just the walls elevation surface. The adopted procedures are further detailed below.

#### *2.2.1. Shape factor*

The shape factor, $F_{FP}$, measures the deviation of each stone from the ideal regular shape, i.e. a rectangle. Thus, the method first associates to each stone a reference rectangle ($R_{Ref}$, with horizontal and vertical sides, i.e. zero angle rotation) so that afterwards can establish how close the stone contour and the associated rectangle are. The method considers three different possibilities for defining the reference rectangle as illustrated in Fig. 1a, namely: (i) an envelope rectangle ($R_{env}$) containing the stone shape, (ii) an equivalent homothetic rectangle ($R_{eq,hom}$) obtained by homothetic scaling (i)