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Probability and structural reliability assessment of mortar joint thickness in load-bearing masonry walls

Nebojša Mojsilović [a,*], Mark G. Stewart [b]

[a] Institute of Structural Engineering, Department of Structural, Environmental and Geomatic Engineering, ETH Zurich, 8093 Zurich, Switzerland
[b] Centre for Infrastructure Performance and Reliability, School of Engineering, The University of Newcastle, Callaghan, NSW 2308, Australia

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ABSTRACT

Mortar joint thickness has a significant effect on capacity of structural masonry. Data on mortar joint thickness (bed and head joints) were collected from twelve typical storey-high walls at three different building sites and from four walls built in a research laboratory in Switzerland. The data obtained allowed an analysis of the spatial distribution of the joint thickness in each wall and the characterization of the probability distribution of joint thickness. The data has been statistically analysed and the results discussed: the central and dispersion measures were calculated and several probability distributions have been fitted to the sample data and subsequently tested using standard methods of statistical theory. Further, the results obtained from all four building sites have been compared, thus providing quantitative information about the quality of the work on different sites. The presented probabilistic information is then used to define reliability-based limit state specifications where the joint thickness acts as an important random variable. The reliability of the structural masonry subjected to a concentric normal force found that probabilistic modelling of bed joint thickness results in higher reliability indices.

1. Introduction

Structural masonry is typically subjected to: concentric or eccentric normal force, shear with concentric normal force and out-of-plane bending. Mortar joint thickness plays an important role in resisting these load situations since it is one of the key influencing parameters for determining masonry compressive strength. Moreover, head joints play an important role in properly transferring the lateral (shear) forces and thus influence the deformation capacity of structural masonry (storey drift). The influence of the bed joint thickness on masonry compressive strength can be easily seen from simple linear-elastic analysis, which takes into consideration the lateral deformation compatibility between the brick or block and the adjacent mortar joint, see Francis et al. [1]. For example, if a bed joint thickness is increased from 10 to 25 mm, the average compressive capacity of masonry is reduced by 25% and 55% for solid and perforated bricks, respectively [1]. The different influences on the mortar joint thickness such as workmanship, size tolerance of the bricks, etc., lends itself to probabilistic modelling, which would than allow structural masonry to be more accurately assessed.

One of the most important influences on mortar joint thickness is the workmanship at the building site. It is clear that variability in mortar joint thickness is unavoidable, especially keeping in mind that masonry walls are constructed not by a single mason but rather by a team of masons. The main question that arises here is how to measure the quality of the workmanship. One possible way is to use the coefficient of the variation (*COV*) of the joint thickness distribution as a criterion of the quality of workmanship. For example, when comparing the quality of work for different masonry walls the probability distribution of the *COV* for single walls will be inspected and the attributes (e.g., excellent, good, poor) will be determined from the distribution depending on the position of the single values within the distribution.

Further, it is important to consider two aspects of the topic under investigation: first issue is the deviation of the mortar joint thickness in the respect to the prescribed (design) values, which are usually given in the corresponding masonry code; and the second issue is the variation of the joint thickness, which can be assessed along one bed joint in the wall, within the single wall (all joints included), or even for the whole building site, etc. These two aspects will be investigated in the present paper.

Provisions for the mortar joint thickness, t_j, in masonry walls can be found in structural codes, see Table 1. Some codes, e.g., the Swiss Masonry Code SIA 266 [2] and the European Masonry Code EN 1996-1-1 [3], only give an allowable range for the joint

* Corresponding author. Tel.: +41 446333763; fax: +41 446331064.
E-mail address: mojsilovic@ibk.baug.ethz.ch (N. Mojsilović).

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Table 1
Code provisions for mortar joint thickness.

Country	t_j (mm)	Range (mm)	Tolerance (mm)	
			Bed joint	Head joint
Switzerland	–	8.0÷12.0	–	–
Europe	–	6.0÷15.0	–	–
USA	9.5	–	±3.2	−6.4/+9.5
Australia	⩽10.0[a]	–	±3.0	+10.0
Canada	10	–	±3.0	±3.0

[a] There is a lower limit for the head joint thickness of 5 mm.

thickness. However, the Building Code Requirements and Specifications for Masonry Structures ACI 530-08/ASCE 5-08/TMS 402-08 [4] and the Australian Structural Masonry Code [5] specify a standard value for joint thickness, and also specify allowable tolerances. Similar provisions can be found in the Canadian Structural Masonry Code A371-04 [6]. It should be noted here, that even though the Swiss Code SIA 266 gives the range of 8–12 mm for the joint thickness, it is considered that the standard thickness is 10 mm. These standard values are based more on practical and historical reasons, than on engineering considerations.

In the present paper, data on mortar joint thickness (bed and head joints) were collected from twelve typical single storey-high walls (see Fig. 1) at three different building sites, and from four walls built in the research laboratory of the Institute of Structural Engineering (ETH Zurich) for an unrelated masonry research project. The data obtained allows an analysis of the spatial distribution of the joint thickness in each wall and the characterisation of the probability distribution of joint thickness.

The sample data has been statistically analysed and the results discussed: the central and dispersion measures were calculated and several probability distributions have been fitted to the sample data and subsequently tested using standard methods of statistical theory. Further, the results obtained from all four sites have been compared, thus providing information about the quality of the work, i.e., the workmanship on different sites.

A limit state function is established to describe the performance of masonry structures subjected to a concentric normal force (i.e., compression loading). With known limit state function and probabilistic models for the basic random variables the probability of failure can be calculated by FORM, SORM or Monte Carlo simulations, see e.g., [7]. Appropriate probabilistic models for the basic random variables as well as model uncertainty will be introduced. Special attention will be paid, based on the performed statistical analysis on the acquired data, to the modelling of the bed joint thickness as a random variable.

Fig. 1. Typical clay block load-bearing masonry wall.

2. Previous research

Previous research related to the statistical assessment of mortar joint thickness in structural masonry walls is sparse. To the authors' knowledge there are only a few reports on the topic [8,9]. Grimm [8] reported the statistical analysis of field data on the joint thickness measured on 24 buildings of different age. He also investigated the deviation in the vertical alignment of head joints. Fyfe et al. [9] investigated numerically the influence of the bed joint thickness on the partial safety factor considering the misalignment of the walls, excessive thickness of joints, and excessive variations in mortar joint thickness. It was concluded that the variation in the joint thickness had the highest influence on the partial safety factor. Recently, preliminary results of the statistical analysis and spatial distribution of the mortar joint thickness in structural masonry walls has been reported by Mojsilović [10].

Probabilistic modelling and structural reliability analysis of structural masonry have been investigated by many researchers [11–24]. The previous work concentrated on probabilistic modelling and assessment of the masonry characteristics in general, see Ellingwood [11], Ellingwood and Tallin [12], Schueremans [13], Stewart and Lawrence [14], Glowienka [15], Heffler et al. [16], Mojsilović and Faber [17], Lawrence and Stewart [18] and Mojsilović [19,20]; on defining and evaluating different limit state functions (corresponding to specific load situations) see for example Stewart and Lawrence [21], Mojsilović and Faber [22], Lawrence and Stewart [18] and Zhai and Stewart [23]. In addition, reliability based code calibration of structural masonry was investigated by Hart et al. [24] and Stewart and Lawrence [14]. Much of this work implicitly allows for the variations in mortar joint thickness when deriving statistics of model error from laboratory wall tests.

The present paper significantly contributes to filling this void in engineering knowledge by explicitly allowing for the influence of mortar joint thickness on structural reliability. This is achieved by expanding the available data on the statistical distribution of mortar joint thickness. Moreover, the results will have impact on the practical design of masonry structures as specific recommendations for the probabilistic distribution of the mortar joint thickness and reliability analysis of the structural masonry subjected to compression are given.

3. Joint thickness survey data

3.1. Building site and wall selection

In order to get a realistic picture of the mortar joint thickness distribution, three different building sites in the Swiss city of Zurich were selected (sites S1, S2 and S3). Residential buildings were built at these three sites by three different construction companies. At two of the sites six-storey apartment buildings were built whilst at the third site a smaller, two-storey family house was built. To enable a further comparison, a fourth site (S4), the research laboratory of the Institute of Structural Engineering of ETH Zurich was chosen, where four masonry walls have been built for an unrelated masonry research project. All the selected walls were built by experienced masons or mason crews. As previously mentioned, it is expected that the thickness of the bed joint on the sites is 10 mm. In addition, the mason in the research laboratory was instructed to take special care that both bed and head (cement mortar) joint thicknesses were equal to the design specification of 10 mm. It should be noted here that the Swiss structural