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Influence of Workmanship on the Compressive Strength of Structural Masonry

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ABSTRACT: Structural masonry is a composite material that consists of brick/block units and mortar. Often, masonry is treated as a homogeneously material. The key mechanical characteristic of structural masonry is its compressive strength perpendicular to the bed joints. Estimating or even predicting this material property is thus an issue of central importance to assessing the reliability of masonry structures. As part of a course on structural masonry taught at ETH in Zurich, students are given an opportunity to do some practical work. During one lecture (one and half-hours) students are divided in smaller groups (five to six students) and each group is asked to build a standard masonry specimen (according to the European testing standard EN-1052-1) in the structural laboratory of the Institute of Structural Engineering. Simultaneously, two professional masons, which are instructing/helping students during the exercise, are asked to build one specimen. Such practical work has been performed every year since 2007, usually with clay block masonry, but also with calcium-silicate and AAC masonry. After the prescribed curing time all specimens are tested and the corresponding results (masonry compressive strength) are discussed with students. This paper presents the results and statistics of these test series. Special attention is paid to the influence of workmanship. Namely, strengths obtained from tests on specimens built by professional masons are, for all series, more or less near the mean values in spite of the fact that almost all students are without any skills as masons. The reasons for such distribution of the results are investigated and the findings are presented.

1. INTRODUCTION

Structural masonry is a construction material composed of units and mortar, two components representing materials with quite different mechanical properties. However, masonry is usually treated as a unique, more or less homogeneous material. The key masonry material characteristic is the compressive strength perpendicular to the bed joints, f_x. The first important issue to consider when establishing a probabilistic model for f_x is whether to base the modeling on test results from large masonry panels, or test results from the masonry components: units and mortar. Based on the experience of the authors, probabilistic models developed on the basis of tests on large masonry elements are generally more reliable, i.e. associated with less model uncertainty. However, the obvious drawback is that such tests are more expensive and labour intensive. The two approaches can, however, supplement each other such that the performance of masonry structures established on the basis of tests on the components individually can be updated based on a few large-scale tests on masonry using Bayesian updating, see Mojsilović and Faber (2009), and Nagel et al. (2015).

In general, uncertainties, which may be significant for masonry design, include lack of experimental evidence as well as simplifications and idealizations related to the probabilistic modeling and the formulation of limit state equations. One of the important sources of uncertainties, especially for structural masonry, is the quality of the execution. The workmanship can have a very strong influence on the safety factor for masonry properties; see also Fyfe et al. (2000). It is known that the excessive thickness of the mortar joints (both bed and head joints) and especially the variation of the joint thickness can have a large influence on the masonry compressive strength; see Mojsilović (2013), and Mojsilović and Stewart (2015). Further, the deviations in geometry of cross section, element dimensions and misalignment, and improper brick laying may have significant effects on masonry strength. In addition, an incorrect mortar mixture and improper judgement of the suction rate of blocks are also factors that could negatively influence masonry strength. However, most negative influences might be reduced through supervision and quality control procedures on site.

The main topic of the present investigation is the influence of the mason's skill. Here, we understand that skill influences the variation of the joint thickness, deviations form verticality and alignment, i.e. proper block laying. In order to tackle this issue several series of tests on the masonry specimens built by (unskilled) undergraduate students during the courses on masonry are analysed. 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.

The remainder of this paper is organized as follows. A short description of the wallette construction by students is firstly presented followed by a summary of the results obtained from testing the built specimens. These results are discussed and conclusion are drawn.

2. WALLETTE CONSTRUCTION

As a part of a course on structural masonry taught at ETH in Zurich, students are given an opportunity to do some practical work. During one lecture (one and half-hours) students are divided into smaller groups (of five to six students) and each group is asked to build a standard masonry specimen (wallette) in the structural laboratory. Simultaneously, two professional masons, who instruct/help students during the exercise, built one specimen. Such practical work has been performed every year since 2007 (with same instructors).

Figure 1: Working area in structural laboratory.

Figure 1 shows the working area in the laboratory together with the masonry materials and the necessary tools in 2017. In that year, students constructed 10 wallettes using typical Swiss clay blocks and standard cement mortar. The mortar was prepared in a factory and delivered to the laboratory before the start of the exercise. The two instructors constructed one additional wallette.

Figure 2: Students at work.

The vast majority of students participating in the exercise had no previous masonry experience. In eleven years (2007-2017) only a few times was there a student that had previously done some masonry work. Therefore, within the framework of the present investigation it can be assumed that all participating students had no masonry skills. Figure 2 shows a detail of students' work (placing mortar in bed joint). It was ensured that each student in the group contributed more or less equally to the wallette construction. Finally, Figure 3 shows the set of finished wallettes in 2017.

Figure 3: Finished wallettes.

2.1. Masonry materials

For the construction of the specimens, only Swiss materials were used. Wallettes for all test series were built according to the European testing standard EN-1052-1 (1998). In the majority of series, the typical clay block of nominal dimensions 290×190×150 mm and a void area of 49% was used with standard cement mortar to construct the wallettes, see also Figure 3. Only three series (2008, 2013 and 2016) were constructed using different materials. In 2008 and 2016 calcium-silicate blocks of nominal dimensions 250×145×140 mm and a void area of 24% with standard cement mortar have been used and in 2013 autoclaved aerated concrete (AAC) blocks of nominal dimensions 250×250×600 mm and with a standard thin-layer mortar were used for the construction. They were nominally 600 mm wide and 1000 mm high. Calcium-silicate masonry wallettes were nominally 510 mm wide and 900 mm high and those made of AAC had a nominal width of 1200 mm and a height of 1260 mm. All wallettes were built in running bond.

2.2. Test set-up and measurements

After the prescribed curing period of (at least) 28 days, except for AAC wallettes, which were constructed using a thin-layer mortar and could be tested earlier, wallettes were tested in the laboratory using a universal testing machine, see Figure 4 for the set-up as well as for applied measurements. Tests were performed according to the European Testing Standard EN 1025-1 (1998). Apart from the applied vertical load, measurements included deformations of the specimen, see Figure 4. Vertical deformations were measured by means of two potentiometers on each side of the specimen. Further, the horizontal deformation of the specimen was recorded by means of additional potentiometers on each side of the specimen.

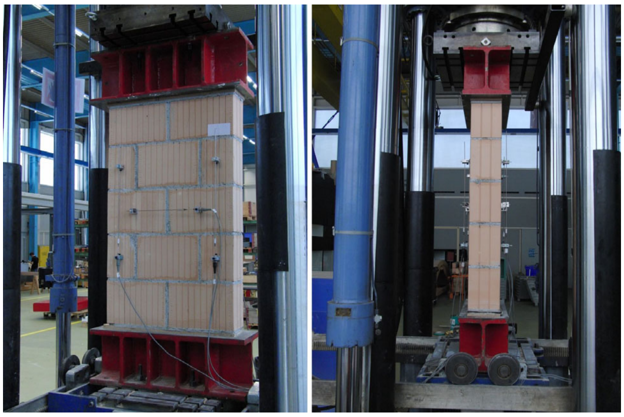

Figure 4: Test set-up and measurement devices.

3. TEST RESULTS

Table 1 shows the test results (masonry compressive strength) for all eleven series from 2007 to 2017. Note that the strength values obtained on the wallettes built by professional masons are highlighted. Note that in 2016 the masons built two specimens. In further analysis, the mean value of these two tests will be used as the representative strength (mason's wallette) for that year.

Table 1: Test results.

Year	*Masonry compressive strength [MPa]*										
2007	*4.13*	*4.25*	*4.60*	*5.26*							
2008	*5.91*	*6.13*	*6.51*	*6.80*	*7.38*	*7.50*					
2009	*5.53*	*6.67*	*7.17*	*7.80*	*7.92*	*7.98*	*8.86*	*9.41*			
2010	*5.32*	*5.91*	*6.12*	*6.44*	*6.67*	*6.70*	*8.30*				
2011	*2.80*	*3.71*	*4.22*	*4.29*	*4.32*	*4.95*	*5.23*	*6.06*	*6.28*		
2012	*5.87*	*6.99*	*7.53*	*7.71*	*7.82*	*7.87*	*8.00*	*8.10*	*8.14*	*9.13*	
2013	*1.39*	*1.45*	*1.50*	*1.52*	*1.54*	*1.70*	*1.72*	*1.73*	*1.81*		
2014	*5.69*	*5.82*	*5.94*	*5.96*	*6.12*	*6.34*	*6.53*	*7.01*	*7.14*		
2015	*4.54*	*5.29*	*5.46*	*5.82*	*5.88*	*5.90*	*6.10*	*6.12*	*6.38*	*6.55*	*7.02*	*7.19*
2016	*4.79*	*4.81*	*5.04*	*5.11*	*5.18*	*5.25*	*5.56*	*5.68*	*5.84*	*6.31*	*6.34*	*6.36*
2017	*4.61*	*5.08*	*5.64*	*5.67*	*5.73*	*5.85*	*5.92*	*5.96*	*6.05*	*6.29*	*6.84*	

Table 2 shows the statistics for the sample data grouped in the year of construction, i.e. of the exercise. Using descriptive statistics, central and dispersion measures of measurement data were calculated and are presented in Table 2. The central measure is represented by the sample mean, x, and dispersion measures by the sample standard deviation, s, and the sample coefficient of variation, v. The total number of wallettes tested, n, together with the previously mentioned parameters, is given.

Table 2: Test results statistics.

Year	*n*	*x[MPa]*	*s[MPa]*	*v[%]*
2007	*4*	*4.56*	*0.51*	*11.13*
2008	*6*	*6.71*	*0.65*	*9.66*
2009	*8*	*7.67*	*1.22*	*15.93*
2010	*7*	*6.49*	*0.93*	*14.33*
2011	*9*	*4.65*	*1.11*	*23.80*
2012	*10*	*7.72*	*0.84*	*10.94*
2013	*9*	*1.60*	*0.15*	*9.19*
2014	*9*	*6.28*	*0.52*	*8.24*
2015	*12*	*6.02*	*0.73*	*12.18*
2016	*12*	*5.52*	*0.58*	*10.57*
2017	*11*	*5.79*	*0.58*	*10.10*

Table 3 shows the probability distribution parameters for normal (μ and σ) and lognormal (λ and ζ) distributions. These parameters were estimated applying the maximum likelihood method. The two above-mentioned probability distributions, using parameters from Table 3, have been fitted to the sample data. Figure 5 shows, typically, histograms and log-normal fits for the strength (year 2015). It should be noted that the sample size is rather small to perform fully robust statistics but is sufficient to identify trends.

Table 3: Maximum likelihood estimators.

Year	*μ[MPa]*	*σ[MPa]*	*λ[MPa]*	*ζ[MPa]*
2007	*4.56*	*0,44*	*1,51*	*0,09*
2008	*6.71*	*0,59*	*1,90*	*0,09*
2009	*7.67*	*1,14*	*2,03*	*0,16*
2010	*6.49*	*0,86*	*1,86*	*0,13*
2011	*4.65*	*1,04*	*1,51*	*0,24*
2012	*7.72*	*0,80*	*2,04*	*0,11*
2013	*1.60*	*0,14*	*0,46*	*0,09*
2014	*6.28*	*0,49*	*1,83*	*0,08*
2015	*6.02*	*0,70*	*1,79*	*0,12*
2016	*5.52*	*0,56*	*1,70*	*0,10*
2017	*5.79*	*0,56*	*1,75*	*0,10*

Figure 6 shows the ratio between the strength obtained on the wallette built by the mason and the mean value of corresponding students' results for the same year. As can be seen from the figure, the ratio (deviation of the masons value from the mean value) lies between -11% and +12%. In only three years was the ratio below one – indicating that the students (in mean) outperformed the masons in those years. However, the mean value of the ratio is 1.01 and the corresponding coefficient of variation is 5.91%.

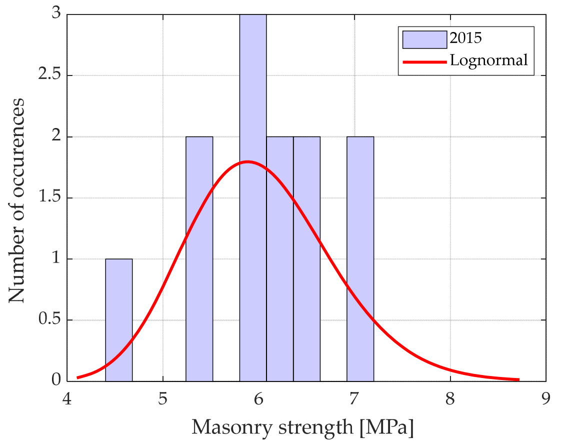

Figure 5: Histogram and lognormal fit for masonry strength for 2015.

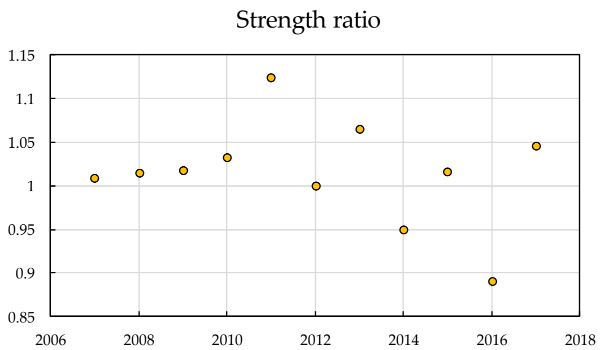

Figure 6: Strength ratio: mason divided by sample mean.

In total, 97 wallettes were tested. Since different masonry materials were used the strength values are normalized using the mean value for the corresponding year, e.g. the strength values shown in the row for the year 2014 (Table 1) will be normalized by dividing each value by the mean of 6.28 MPa obtained form Table 2. The dispersion measure of this aggregate sample, i.e. standard deviation was 0.12, leading to a sample coefficient of variation of 12.31%. Probability distribution parameters for lognormal distribution were estimated applying the maximum likelihood method and equalled -0.0078 and 0.126. Using these parameters the distribution has been fitted to the sample data. This fit is shown, together with corresponding histogram, in Figure 7.

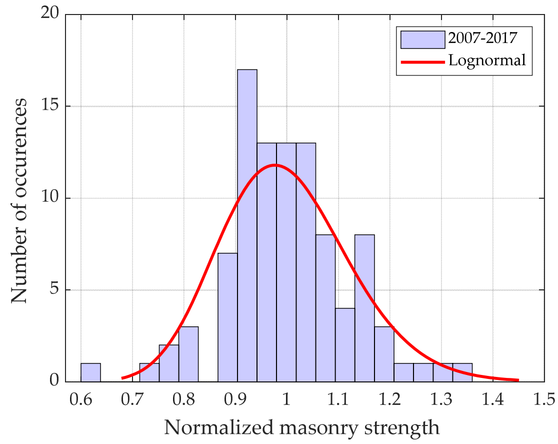

Figure 7: Histogram and lognormal fit for normalized masonry strength (all wallettes).

4. DISCUSSION

For each year, all participants in the exercise used the same materials: i.e. same batches of blocks and mortar. After construction, all wallettes were cured in the same way and after the prescribed curing time of (at least) 28 days they were tested on the same day by the same laboratory staff. Thus, the difference in strength obtained was mainly caused by the unequal skills of students and professional masons. As mentioned earlier, this is reflected in the joint thickness and the misalignment of blocks in the wallette. Generally, one would expect that the wallettes constructed by the masons would perform (far) better than those built by unskilled students. This however was not the case: the strength of wallettes built by the masons was for all series within the values obtained for wallettes constructed by students, cf. Table 1.

One could try, using numerical simulation, to estimate the probability that the strength of the wallette built by the masons lies within the range of values obtained on the wallettes constructed by the students. For this purpose, let us assume that the wallette strength is a lognormal random variable depending on the intrinsic variability of the wallette strength, i.e. $R(x)=KR_0\exp(\zeta_i x)$. R_0 is the median value and the intrinsic variability is defined by the parameter ζ_i, which can be determined from previous experimental experience/evidence. Further, $K(x)=\exp[(\lambda+\zeta)x]$

is the lognormal random variable used to describe the variability of masonry strength scatter as well as to distinguish between the qualities of workmanship between students and mason. The variability of scatter for students and mason is described by the parameters ζ_s and ζ_m. The median of K is equal to one for students, i.e. λ equals zero, and is larger than one for the masons meaning that the mason's quality of workmanship is (for a certain percentage) higher than that of the students. Finally, choosing randomly the (normal distributed) masonry strength values for a given sample size and applying Monte Carlo simulations the above-mentioned probability could be estimated.

In order to verify this procedure a set of parameters based on the available data (cf. Table 1) and prior experience were chosen. The intrinsic variability parameter is set to ζ_i=0.15 and the variability of scatter for students and mason is defined by ζ_s=0.12 and ζ_m=0.06, respectively. Setting the median for mason to 1.01 parameter λ can be readily calculated. Finally, setting the sample size of wallettes to 9 (average value per year for period under investigation) and running 10^5 Monte Carlo simulations one obtains the probability of 0.83, which is not far from reality, i.e. in the present case all strengths of wallettes built by the masons were within the strengths obtained for the wallettes built by the students. This suggests that there is no significant difference between student and mason performance.

Applying the same procedure, but choosing the parameters without knowing the test results one gets a different picture. Based on experience one would choose ζ_s=0.20 and a median of 1.25 for the mason, meaning that the mason's quality of workmanship is 25% higher than that of the students. Other parameters take the same values as previously described. Calculated in this way, the probability falls to 0.72.

5. CONCLUSIONS

In the course of eleven years, professional masons could not over-perform unskilled students. Moreover, the strength of wallettes built by the masons was almost equal to the average value of those built by the students. One possible explanation for such an outcome could be that the professional masons are more consistent in their work and thus their values are always in the middle.

On the other hand, from a broader point of view a question that arises is if the skill is (so) important, it seems that the only advantage of professional masons is their construction speed. Other advantages such as high quality and low variability of workmanship seem to be overcome by uncertainty.

There may also be less incentives for masons to produce consistent high quality work as masonry in compression rarely fails in building structures, so their task may not be viewed as safety critical. Speed of construction is likely to be a higher priority. Motivation is a key driver to good performance, and it might be that students are more motivated in their task than the masons in this case.

It might also be that the masons provided enough advice and training to the students during the laboratory exercise that student performance was enhanced. In other words, the students may not necessarily be "unskilled", but semi-skilled. If possible, it would be useful to conduct a control experiment where some students receive no training from masons to see if their performance is lower than their trained peers from previous years.

Future generations of students will be given the same opportunity for practical work and thus provide more data to reassess the presented views and maybe to implement new approaches to the laboratory classes to help isolate the effect of mason quality on compressive strength.

6. ACKNOWLEDGMENTS

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7. REFERENCES

EN 1052-1 (1998). Methods of test for masonry, Part 1: Determination of compressive strength, European Committee for Standardization (CEN), Brussels.

Fyfe, A.G., Middleton, J., and Pande, G.N., (2000). "Numerical evaluation of the influence of some workmanship defects on partial factor of safety for masonry" *Masonry International*, 13(2), 48-53.

Mojsilović, N., (2013). "Statistical analysis and spatial distribution of mortar joint thickness for clay block masonry walls", Proceedings, 11th International Conference on Structural Safety and Reliability, New York, 475-481.

Mojsilović, N., and Faber, M. H. (2009). "Probabilistic assessment of masonry compressive strength", Proceedings, 10th International Conference on Structural Safety and Reliability, Osaka, Japan.

Mojsilović, N., and Stewart, M. G. (2015). "Probability and structural reliability assessment of mortar joint thickness in load-bearing masonry walls" *Structural Safety*, 52, 209-218.

Nagel, J., Mojsilović, N., and Sudret, B. (2015). "Bayesian assessment of the compressive strength of structural masonry", Proceedings, 12th International Conference on Applications of Statistics and Probability in Civil Engineering, Vancouver, Canada.