Assessment of masonry strength in a heritage building

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Abstract

Heritage buildings in the Czech Republic are made of different types of masonry. Decisions concerning upgrades of these buildings should be preferably based on a reliability assessment, taking into account actual material properties. Due to inherent variability of historical masonry, information on its actual mechanical properties has to be obtained from tests. Estimation of masonry strength from measurements may then be one of the key issues in the assessment of historical structures. In the submitted study, the standard technique provided in the Eurocode EN 1996-1-1 is applied in the assessment of a masonry structure built in the 19th century. Characteristic and design values of the masonry strength, derived using principles of the Eurocode, are compared with corresponding fractiles of a developed probabilistic model. It appears that the characteristic value based on the probabilistic model is lower than that obtained by the standard technique. To the contrary, the partial factor for masonry recommended in EN 1996-1-1 seems to be rather conservative.
Keywords: masonry, characteristic strength, statistical methods.

1 Introduction

At present, heritage structures, particularly those located in urban areas, are often affected by numerous environmental influences that may yield deterioration and gradual loss of their durability and reliability. Hence protection and conservation of heritage structures, including design of adequate construction interventions, is an important issue for various experts, such as art historians, architects and civil engineers, in most European countries. Construction interventions may also become necessary due to the change of use of heritage structures. The rehabilitation of heritage structures is also a matter of great economic

WIT Transactions on The Built Environment, Vol 109, © 2009 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/STR090171

significance, as more than 50% of all construction activities apply to existing structures, including heritage structures. Decisions about various interventions should always be a part of the complex assessment of a heritage structure that should be based on relevant input data, including information on actual material properties.

In the Czech Republic numerous heritage structures are made of different types of masonry. Due to the inherent variability of historical masonry, information on its actual mechanical properties has to be obtained from tests. Estimation of masonry strength from measurements may then be one of key issues of the assessment of heritage structures.

The submitted study is focused on the assessment of masonry strength of a historical structure built in the 19th century. Masonry strength is estimated from a limited number of destructive tests and a series of non-destructive tests. The standard method provided in the Eurocode EN 1996-1-1 [1] is supplemented by use of classical statistical techniques, including the method of moments and test of outliers. The characteristics and design values of masonry strength derived using the principles of the Eurocodes are compared with the corresponding fractiles of a proposed probabilistic model.

2 Evaluation of tests

The historical residential house, located in the downtown area of Prague, was built in about 1890. The six-storey masonry building is shown in Figure 1. The structural analysis consists of models for several structural parts. In the submitted paper the key issue of estimation of unreinforced masonry strength is described in detail.

The mechanical properties of historical masonry are strongly dependent on properties of its constituents. Commonly, there is a large variability of mechanical properties within a structure due to workmanship and inherent variability of materials as indicated by Lourenco [2] and Stewart and Lawrence [3]. In the present case, information about material properties needs to be obtained from tests. A series of non-destructive tests was supplemented by a few destructive tests. In addition, previous experience on accuracy of applied testing procedures is taken into account in the evaluation of test results. The masonry of a wall and foundations is indicated in Figure 2.

2.1 Strength of masonry units

Non-destructive tests of the strength of masonry units by Schmidt hammer were made in 33 selected locations all over the structure. A histogram of the obtained measurements is indicated in Figure 3. It appears that the sample includes an extreme measurement (maximum) that may result from an error within the measurement procedure. Therefore, the test proposed by Grubbs [4] is used to indicate whether the hypothesis that there is no outlier in the sample can be rejected or not. For the significance level 0.05 the test indicates that the hypothesis can be rejected and the measurement is deleted from the sample.

Figure 1: View of the assessed building.

Figure 2: Masonry of a wall and foundations.

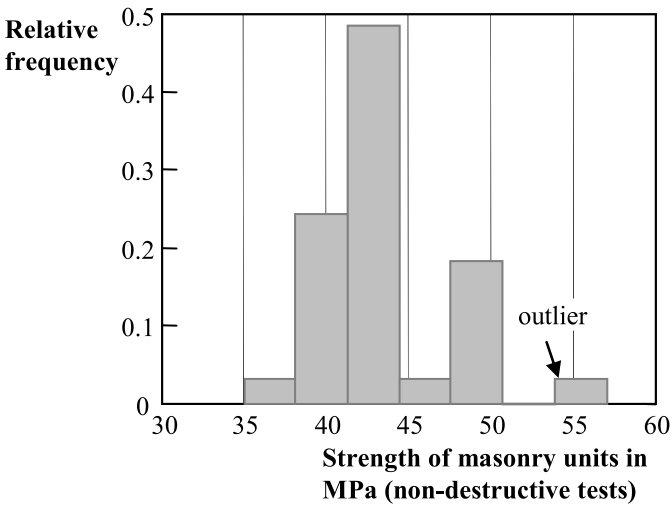

Figure 3: Histogram of the masonry unit strength obtained by non-destructive tests.

Table 1: Statistical characteristics of variables influencing the masonry strength.

Variable	Symbol	Mean	Coefficient of variation	Skewness
Strength of masonry units (non-destructive tests)	f_b'	43.1 MPa	0.08	0.15
Conversion factor - masonry units	η_b	0.45	0.2	unknown
Strength of mortar (non-destructive tests)	f_m'	1.26 MPa	0.41	-0.06
Conversion factor - mortar	η_m	1	0.2	unknown
Model variable	K	0.66	0.2	unknown

Point estimates of the sample characteristics – mean, coefficient of variation and skewness – are then estimated by the classical method of moments described by Ang and Tang [5], for which prior information on the type of an underlying distribution is not needed. The sample characteristics are indicated in Table 1.

It appears that the sample coefficient of variation and skewness of the masonry unit strength estimated by the non-destructive tests are low. These characteristics may provide valuable information for choice of an appropriate statistical distribution to fit the sample data. However, it is emphasized that the sample size may be too small to estimate convincingly the sample skewness.

The sample characteristics in Table 1 indicate that the strength of masonry units estimated by the non-destructive tests might be described by a two-parameter lognormal distribution having the lower bound at the origin (LN0) or

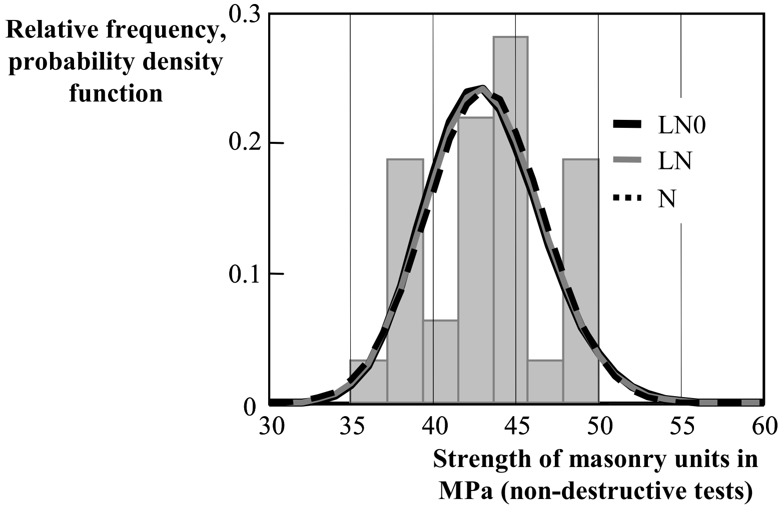

Figure 4: Histogram of the masonry unit strength obtained by the non-destructive tests without the outlier and the considered theoretical models.

by a more general three-parameter shifted lognormal distribution having the lower bound different from zero (LN). Another possible theoretical model is the popular normal distribution.

Probability density functions of these three theoretical models (considering sample characteristics) and a sample histogram without the outlier are shown in Figure 4. It follows that, due to the low sample coefficient of variation and skewness, all the considered models describe the sample data similarly. To compare goodness of fit of the considered distributions, Kolmogorov-Smirnov and chi-square tests described by Ang and Tang [5] are further applied. It appears that no distribution should be rejected at the 5% significance level; however, the lognormal distribution LN0 seems to be the most suitable model. Therefore, this distribution is considered hereafter.

The conversion factor η_b is further taken into account to determine normalised compressive strength of masonry units f_b:

$$\eta_b = f_b / f_b^{'} \tag{1}$$

where $f_b^{'}$ denotes strength of masonry units estimated from the non-destructive tests. Previous experience indicates that the coefficient of variation of the conversion factor may be assessed by the value 0.2. Using a limited number of measurements the mean value of the conversion factor was estimated by the value 0.45.

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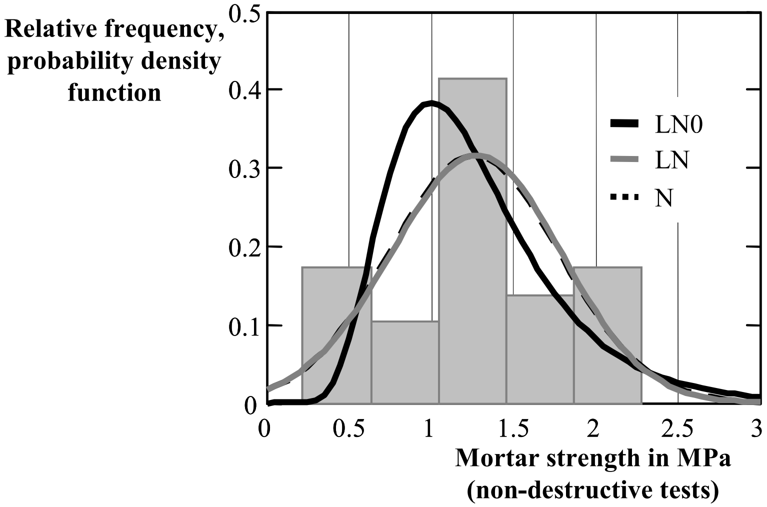

Figure 5: Histogram of the mortar strength obtained by the non-destructive tests and the considered theoretical models.

2.2 Mortar strength

Estimation of mortar strength may be a complicated issue since sufficiently large specimens for destructive tests can rarely be taken. Therefore, non-destructive testing based on relationship between hardness and strength of mortar was developed in the Klokner Institute of the Czech Technical University in Prague.

This method is used in the assessment. Histogram of 29 measurements is indicated in Figure 5. Point estimates of the sample characteristics given in Table 1 are estimated using the method of moments. The sample coefficient of variation of mortar strength is considerably greater than that of the strength of masonry units. The sample distribution seems to be nearly symmetric as the skewness is of about zero. This indicates that a normal distribution might be a suitable model. However, normal distribution is not recommended for description of the variables with the coefficient of variation exceeding, say, 0.20 as negative values can be predicted. Due to the zero skewness, a three-parameter lognormal distribution yields the similar model as the normal distribution. Therefore, the lognormal distribution LN0 is assumed hereafter for the mortar strength estimated by the non-destructive tests. Probability density functions of the theoretical models are shown in Figure 5.

The conversion factor η_m is applied to derive compressive strength of masonry mortar f_m from results of the non-destructive tests:

$$\eta_m = f_m / f_m' \tag{2}$$

where f_m' is the mortar strength estimated from the non-destructive tests. Previous experience indicates that the conversion factor has the unit mean and coefficient of variation 0.2 as indicated in Table 1.

3 Masonry strength in accordance with EN 1996-1-1

According to EN 1996-1-1 [1] the characteristic compressive strength of unreinforced masonry made with general purpose mortar can be estimated as:

$$f_k = K f_b^{0.7} f_m^{0.3} = K\,(\mu_{\eta_b}\,\mu_{f_b'})^{0.7}\,(\mu_{\eta_m}\,\mu_{f_m'})^{0.3}$$
$$= 0.55 \times (0.45 \times 43.1)^{0.7} \times (1 \times 1.26)^{0.3} = 4.7 \text{ MPa} \quad (3)$$

where K is the model variable and μ denotes the mean value. In the present study, the Group 1 of masonry units is assumed and the model variable is 0.55. Note that a rather simplified empirical model for the masonry strength considered in EN 1996-1-1 [1] may not fit available experimental data properly. Other theoretical models may then be used to describe the compressive strength of a particular type of masonry. For instance, application of an exponential function similar to that in eqn (3), but with general exponents, may improve estimation of the resulting strength. More advanced models can be found in [6].

Design value of the masonry strength is derived from the characteristic value using the partial factor γ_M:

$$f_d = f_k / \gamma_M = 4.7 / 2.5 = 1.9 \text{ MPa} \quad (4)$$

The partial factor is dependent on a category of masonry units and classes that may be related to execution control. However, EN 1996-1-1 [1] provides insufficient guidance on classification of masonry into the proposed categories of a quality level. Following recommendations of the Czech National Annex to EN 1996-1-1 [1], the partial factor 2.5 seems to be appropriate in this case. Note that dependence of partial factors for masonry and execution control is thoroughly analysed in the study by Holicky et al. [7].

4 Probabilistic model

The international council ICOMOS [8] indicates that present standards and professional codes of practice adopt a conservative approach including the partial factor method to take into account various uncertainties. This may be appropriate for new structures where safety can often be easily increased. However, such an approach may fail for historical structures where requirements to improve the strength may lead to demanding repairs and loss of a cultural and heritage value.

Therefore, probabilistic model for the masonry strength is proposed to estimate the characteristic and design values from the statistical data obtained by the tests and from previous experience and reduce the uncertainties implicitly covered by the model in EN 1996-1-1 [1]. Considering eqn (3), the compressive strength of masonry - random variable f, is given by:

$$f = K\,(\eta_b f_b')^{0.7}\,(\eta_m f_m')^{0.3} \quad (5)$$

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All the variables in eqn (5) are considered as random variables. Statistical characteristics are provided in Table 1.

Considering background information and experimental results provided in [9], the mean of the model variable K is considered as 1.2-times the value given in EN 1996-1-1 [1] and the coefficient of variation is 0.2. Note that variability of the model variable K describes model uncertainties and covers deviations and simplifications related to the model in EN 1996-1-1 [1].

In the previous section the lognormal distribution LN0 is proposed to describe variability of the strength of masonry units and mortar estimated by the non-destructive tests. In the absence of statistical data and considering general experience, the lognormal distribution LN0 is adopted also for the other variables influencing the strength of masonry. However, it is emphasized that if there is any evidence to support another distribution, then such a distribution should be preferably applied.

When all the basic variables included in eqn (5) are described by the lognormal distribution LN0, it can be easily shown that the strength of masonry has also the lognormal distribution LN0. The natural logarithm of the masonry strength is normally distributed with the mean and standard deviation:

$$\mu_{\ln(f)} = \mu_{\ln(K)} + 0.7[\mu_{\ln(\eta_b)} + \mu_{\ln(f_b')}] + 0.3[\mu_{\ln(\eta_m)} + \mu_{\ln(f_m')}]$$
$$\sigma_{\ln(f)} = \sqrt{\{\sigma_{\ln(K)}^2 + 0.7^2[\sigma_{\ln(\eta_b)}^2 + \sigma_{\ln(f_b')}^2] + 0.3^2[\sigma_{\ln(\eta_m)}^2 + \sigma_{\ln(f_m')}^2]\}} \qquad (6)$$

where $\mu_{\ln(X)}$ and $\sigma_{\ln(X)}$ denote the mean and standard deviation of ln(X):

$$\mu_{\ln(X)} = \mu_X - 0.5\ln[1 + V_X^2]; \quad \sigma_{\ln(X)} = \sqrt{\{\ln[1 + V_X^2]\}} \qquad (7)$$

where μ_X and $V_X = \sigma_X / \mu_X$ are the mean and coefficient of a variable X given in Table 1. From eqns (6) and (7), the mean 5.5 MPa and coefficient of variation 0.29 of the masonry strength are derived.

In accordance with EN 1996-1-1 [1], the characteristic strength of masonry corresponds to the 5% fractile of the assumed statistical distribution. In the present case the fractile of the lognormal distribution is 3.3 MPa. Probability density function of the masonry strength and the characteristic and design values are indicated in Figure 6. It appears that the 5% fractile of the probability distribution is by about 30% lower than the characteristic value estimated by eqn (3) that seems to be considerably unconservative. Similar findings have been achieved earlier by Holicky et al. [9].

In accordance with EN 1990 [10], the design value of the masonry strength f_d is the fractile corresponding to the probability:

$$p_d = \Phi(-\alpha_R \times \beta) = \Phi(-0.8 \times 3.8) = 0.0012 \qquad (8)$$

where $\Phi(\cdot)$ is the cumulative distribution function of the standardised normal distribution, the FORM sensitivity factor α_R is approximated by the value -0.8 recommended for the leading resistance variable and the target reliability index β is 3.8 for a fifty-year reference period.

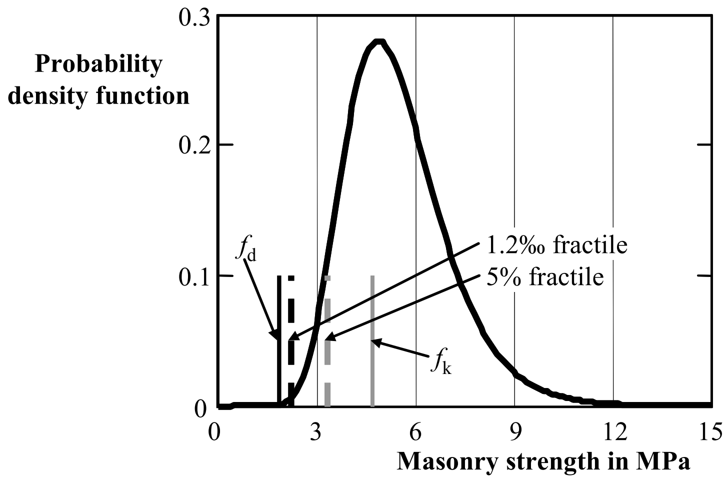

Figure 6: Probability density function of the masonry strength and the characteristic and design values.

Table 2: FORM sensitivity factors of the variables influencing the masonry strength.

Variable	Symbol	FORM sensitivity factor
Strength of masonry units (non-destr. tests)	f_b'	0.20
Conversion factor - masonry units	η_b	0.49
Strength of mortar (non-destr. tests)	f_m'	0.42
Conversion factor - mortar	η_m	0.21
Model variable	K	0.70

The 1.2‰ fractile of the probability distribution is 2.3 MPa. Remarkably, the theoretical design value is by about 20% greater than the design value estimated by eqn (4). It follows that the assumed partial factor 2.5 may be rather conservative as from the probability distribution; the partial factor 1.4 is estimated.

5 Sensitivity analysis

Sensitivity analysis is further conducted to investigate the importance of basic variables on the resulting probabilistic model. FORM sensitivity factors given in Table 2 are evaluated by the software package Comrel®.

Table 2 shows that the model variable K is the most influencing variable. It follows that the proposed model may be improved particularly by reducing variability of this variable.

6 Conclusions

The following conclusions are drawn from the presented assessment of masonry strength of a historical masonry:
(1) Due to inherent variability of historical masonry, information on its actual mechanical properties has to be obtained from tests and estimation of masonry strength from measurements may be one of key issues in assessment of heritage structures.
(2) Available samples should be verified by an appropriate test of outliers as extreme measurements, possibly due to an error, may significantly affect sample characteristics.
(3) Appropriate models for basic variables influencing masonry strength should be selected on the basis of the statistical tests, taking into account general experience with distribution of masonry unit strength.
(4) Lognormal distribution having the lower bound at the origin may be a suitable model for masonry strength.
(5) 5% fractile of a proposed probabilistic model for masonry strength is by about 30% lower than the characteristic value according to EN 1996-1-1.
(6) The partial factor 2.5 assumed in the model of EN 1996-1-1 seems to be rather conservative as compared with the partial factor 1.4 estimated from the probability distribution.
(7) The theoretical design value (1.2‰ fractile) is greater by about 20% than the design value estimated in accordance with EN 1996-1-1.
(8) The model for masonry strength may be improved particularly by reducing the variability of the model variable K.

Acknowledgements

This study has been conducted at the Klokner Institute, Czech Technical University in Prague, within the framework of the research project Assessment of historical immovables A/CZ0046/2/0013, supported by a grant from Iceland, Liechtenstein and Norway through the EEA Financial Mechanism and the Norwegian Financial Mechanism.

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