Calibration of brick masonry partial safety factors for the South African Code

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ABSTRACT: The current South African Code of Practice for structural use of masonry uses four partial safety factors γ_m, for materials depending on construction control and quality control. With the boom in the construction industry, new entrants in the industry lack skills and the construction quality, particularly of masonry structures, is compromised. This has been proven by a number of structural failures and poor workmanship in the home building industry. However, the values of γ_m are based on the British Standards with some slight modifications to take into account local conditions. In this paper, focus is on establishing the reliability level as prescribed in the current code. The parametric calibration is based on current stochastic models and on statistical data collated by the National Home Building Registration Council (NHBRC) using a well researched quality assessment tool (Building Quality Index for Houses). Highlights are also made on the current work-in-progress in testing masonry walls so as to establish a South African material resistance stochastic database. The paper describes the format of the South African code, the stochastic models based on the test results and the resulting partial safety factors.

1 INTRODUCTION

Brick masonry is one of the building materials commonly used in the construction industry of South Africa. The material is used as part of load bearing structures, in housing and infill in framed construction. Masonry is widely used in the home building industry because it provides a combined structural and architectural element which is attractive and durable, has good thermal and sound insulation and excellent fire resistance.

With the boom in the construction industry of South Africa, new building contractor entrants in the industry that lack skills and the construction quality. The quality of masonry structures in particular is compromised. This is evidenced by a number of structural failures and poor workmanship (Mahachi et. al, 2001, Mahachi & Goliger, 2006). Bond strength has been identified to be of prime importance for unreinforced masonry, particularly with regard to flexural and shear performance. The achievement of satisfactory bond between mortar and brick is essential if adequate masonry performance at both ultimate and serviceability limit states are to be obtained. Masonry bond is affected by many factors including the properties of the masonry unit, mortar and workmanship effects.

The current South African Code of Practice for Structural Use of Masonry (SABS 0164, 1980) uses four partial safety factors for materials (γ_m), depending on construction and quality control. These factors are reproduced in Table 1.

Table 1: Partial material factors

Manufacturing Control	Construction Control	
	Category I	Category II
Category A	2.9	3.2
Category B	3.2	3.5

The values of γ_m range from 2.9 to 3.5. The “special” category (i.e. Category A – Manufacturing Control and Category I – Construction Control) is applicable where a designer makes frequent site visits or where there is a permanent design representative on site and tests of mortar strength, for every 150m^2 of wall built, are performed. The γ_m value of 3.5 is applicable where no strict quality control is exercised during manufacturing process and construction.

However, the values of γ_m are based on the British Standards (BS5268: 1978) with some slight modifications that take into account local conditions. With the upsurge of untrained builders in South

Africa and a high frequency of structural failures, it is necessary to review both the design input requirements and construction quality control. In this paper, focus is made on establishing the reliability level as prescribed in the current code. Highlights are also made on the current work-in-progress in testing masonry walls so as to establish South African material resistance stochastic database. The database will be used in the near future to re-calibrate the partial material factors as stipulated in the code.

2 CODE FORMAT

The Load and Resistance Factor Design adopted in most South African design codes is in the format:

$$R_d \geq Q_d$$

$$i.e.\ \phi R_n \geq \sum \gamma_i Q_{ni} \qquad (1)$$

Where

Q_d	Design load effect
R_d	Design Resistance
ϕ	Resistance factor
R_n	Nominal resistance
γ_i	i^{th} partial load factor (including combination factor)
Q_{ni}	nominal load

The factors ϕ and γ_i are calibrated based on a target reliability index (β) adopted by the code. The South African partial load factors were calibrated using a load index (α) approach (Milford, 1987, 1988). The load index was defined as a measure of the actual load exceeding the design load Q_d, and calculated as:

$$\alpha = -\log[p_Q)] \qquad (2)$$

Where p_Q is the probability of exceeding the design load during the life of the structure. The load factors that were adopted in the South African loading code SABS 0600 (1988) were then selected on the basis of achieving a uniform load index α for all possible load ratios. At the ultimate limit state, a load index of 2.0 was adopted, i.e. a probability of exceeding the design load of 1% in 50 years. The procedure that was used was independent of statistics of the resistance of the member.

At the ultimate limit state, the following combinations of self-weight D_n, imposed floor loads L_n and wind loads W_n were obtained and are stipulated in the code SANS 10600:

$$\begin{aligned}&1.5D_n\\&1.2D_n + 1.6L_n\\&1.2D_n + 0.5L_n + 1.3W_n\\&0.9D_n + 1.3W_n \qquad (3)\end{aligned}$$

Note that in the structural steel code SANS 10162 (2006), the nominal resistance R_n does not include any partial material factors, while in the masonry code SABS 0164 the partial material factors are incorporated in the nominal resistance with $\phi = 1$.

3 CALIBRATION OF PARTIAL SAFETY FACTORS

Having defined the load factors, the resistance factors and partial material factors are calibrated in such a way that uniform margins of safety satisfying the criterion of Equation (1) are attained. This uniformity is measured by a safety index β. For a given set of load factors and load combinations, the uniformity in the safety index will depend upon, amongst others, the level of the target safety index and the coefficient of variation V_R of the resistance of the member.

The safety index β is determined as follows:

$$\beta = -\phi^{-1}(p_f) \qquad (4)$$

Where $\phi^{-1}()$ is the inverse of the cumulative normal distribution and p_f is the probability of failure at the ultimate limit state. The probability of failure is calculated from:

$$P(Q \geq R) \qquad (5)$$

where $Q = D + L + W$

The wind load ratio χ is as defined as

$$\chi = \frac{W_n}{D_n + L_n + W_n} \qquad (6)$$

and dead load ratio ξ as

$$\xi = \frac{D_n}{D_n + L_n} \qquad (7)$$

Let γ_d, γ_L and γ_W be the partial load factors for dead load, live load and wind load respectively.

Equation (5) is then solved using any reliability techniques or Monte Carlo simulation for different parametric values of wind load ratios χ and dead load ratios ξ, from which the β value is obtained from Equation (4).

It has been mentioned that the values of the partial material factors in the South African code range from 2.9 to 3.5 for unreinforced masonry. The code distinguishes between inspected and uninspected workmanship. For example, when the workmanship of a wall is inspected, then wall alignment, thickness of joints, effects of partially filled joints and other factors, which would reduce the probable strength and increase its variability, are more carefully controlled. However, data on the effect of inspection on R_n and V_R, and on the variability in construction quality control in South Africa is not available. Current partial resistance factors based on the modified British stochastic models therefore do not apply. Stochastic models for the resistance of masonry walls are based on:

$$\bar{R} / \phi R_n = 3.20 \quad and \; V_R = 0.18 \quad (8)$$

The above statistics are based on brick masonry walls in compression plus bending and $e/t \leq 1/3$, where e = eccentricity and t = thickness of wall. The statistics assume “special” category, where workmanship is inspected and the manufacturing quality control is high. The distribution type of the statistics is normally distributed.

4 TESTS AND QUALITY OF WALLS

Since stochastic models for brick masonry resistance are not available, the National Home Builders Registration Council (NHBRC) has embarked on a testing programme, conducted on wall structures.

Several tests are being conducted in order to determine the strength of single walls subject to compression plus bending. Parameters that are being varied include wall slenderness, eccentricity of load and end restraints. Specimens are being built by home builders who are both experienced and inexperienced. There are more than 20,000 registered home builders on the NHBRC database. For inexperienced or new entrant builders, tests are conducted before and after training the builders on bricklaying and other relevant skills. The results of the above tests were not yet available at the time of publishing this paper.

For the purpose of calibration in this paper, Building Quality Index for Houses statistics was used. NHBRC has collated data on the quality of houses using a well researched tool (Building Quality Index for Houses, BQIH – Mahachi & Goliger, 2006). The philosophy and principles of BQIH are based on an internationally accepted quality control scheme, CONQUAS 21, which was developed and implemented by the Construction Industry Development Board of Singapore.

BQIH measures the quality of structural components (e.g. foundations, walls, roofs etc) based on a score of 1 to 100, with the highest quality having a score of 100. Using BQIH, more than 2000 walling components of houses were assessed. The results are presented schematically in Figure 1. The statistics fit in a log-normal distribution with a mean of 60% and a variance of 15%. All houses and the walling components were not inspected or signed-off by a competent engineer during construction. The bricks used for construction were either manufactured on site or did not meet the required compressive strength. These structural components would typically fall under Category B - Manufacturing Control and category II – Construction Control as per Table 1 above.

According to BQIH, it is assumed that with proper and thorough inspection, the walls must have a 100% quality. The uninspected walls therefore have a mean quality of approximately 60% of the inspected walls. The assumption has been adopted in this paper. The assumption will be verified when the test results currently in progress are completed.

5 PARAMETRIC STUDIES

Parametric studies were conducted for walling structures in order to establish the current levels of reliability using:

- available current stochastic models, and
- modified stochastic models taking into account the strength reduction due to uninspected poor workmanship.

The stochastic models used for calibration of partial safety factors are presented in Table 2, based on information from (Milford 1988, Kemp et.al, 1998).

Table 2: Stochastic models for loads

Variable	**Coefficient of Variation**	**Distribution Type**	**Mean/Nominal**
Dead	0.10	Log-normal	1.05
Live max	0.25	Type I	0.96
Live a.p.t*	0.25	Gamma	0.71
Wind max	0.52	Type I	0.52
Wind a.p.t	1.08	Weibull	0.052

*a.p.t arbitrary-point-in-time

(a). Dead + Live load

Dead plus live load is a load combination that governs designs in most practical instances and even when it does not, it is frequently used for preliminary sizing of members, which are then checked against lateral load effects.

Using the load factors in SANS 10600, the design criterion of equation (1) is:

$$\phi R_n \geq 1.2D_n + 1.6L_n \qquad (9)$$

The Code of Practice for unreinforced masonry SABS 0164 (1980) gives the design resistance (R_d) in Equation (1) in the format:

$$R_d = \phi \cdot R_n\left(f_k / \gamma_m\right) \qquad (10)$$

where

$R_n()$ is the nominal resistance that includes the partial material factor γ_m.

f_k is the characteristic compressive strength of masonry, and

ϕ is the resistance factor and $\phi = 1.0$

Parametric modelling of walling structures was undertaken for the following resistance ratios:

$$(i) \quad \frac{\overline{R}}{\phi R_n} = 3.2 \quad ; \quad V_R = 0.18 \quad ; \quad \gamma_m = 2.9$$

$$(ii) \quad \frac{\overline{R}}{\phi R_n} = 3.88 \quad ; \quad V_R = 0.18 \quad ; \quad \gamma_m = 3.5$$

$$(iii) \quad \frac{\overline{R}}{\phi R_n} = 5.12 \quad ; \quad V_R = 0.18 \quad ; \quad \gamma_m = 4.6$$

The first scenario corresponds to the “special” category, where γ_m is 2.9, as given in the code (Table 1 above). The second scenario is for $\gamma_m = 3.5$ (uninspected workmanship). The third scenario is based on the assumption that quality (strength) of uninspected masonry units is approximately 60% of the inspected masonry units as discussed in the previous sections. This scenario is not incorporated in the code. The 40% reduction in strength implies a γ_m of 4.6. Performing a Monte Carlo using equation (5) for the three scenarios, the safety index β was determined for different dead load ratios as presented in Figure 2.

It is observed that the change in β is more pronounced for low dead load ratios. This is more apparent for low resistance ratios. However, for common practical dead load ratios in the order of 0.4 to 0.6, β is about 4.0 for all resistance ratios. This ties in with the recommendation by Milford (1988) of adopting a β value of 4.0 for brittle failures.

However, where the dead load ratio is low, β is sensitive to the resistance ratio. With the current partial resistance factor (scenarios 1 and 2) β is below 3.0, and with a partial factor of 4.6 (scenario 3), β is above 3.0.

(b). Dead + Live + Wind

The following study was to perform a parametric analysis with a varied wind load ratio χ, but keeping the resistance ratio constant at 5.12. Using the load factors of SANS 10600, the design criterion is:

$$\phi R_n \geq 1.2D_n + 0.5L_n + 1.6W_n \qquad (11)$$

The results of the study is presented in Figure 3. It can be seen that except for the case where χ is zero, the value of β is fairly uniform between 3.8 and 4.0.

(c). Variation of β with V_R

Figure 4 shows the variation of β with V_R for a fixed resistance ratio of 5.12. For a V_R of 0.18, β is of the order of 4.0. However, for V_R of 0.25 and 0.35, β reduces to 2.0 and 3.0 respectively. Considering the workmanship and quality of construction in South Africa, it is inevitable that V_R will be more than 0.25 (as compared to the 0.18 used in developed countries). If that is the case, then the target β value of 4.0 will not be achieved unless the partial material factor γ_m is increased. In order to achieve uniform β values, the partial material factors for uninspected walls must therefore be reviewed, and will possibly be of the order of 4.6.

6 RECOMMENDATIONS

Based on the initial work done by the NHBRC, the following is recommended:

- a database of stochastic material resistance be created based relevant to local manufacturing and construction processes,
- the database should take into account the effects of skilled and unskilled labourers, and
- The partial material factors be re-calibrated based on local statistical data.

7 CONCLUSION

The South African Code of Practice for Masonry (SABS 0164) uses partial material factors based on the British Standards. In this paper, it has been demonstrated that although current γ_m values show fairly uniform β values, the factors need to be reviewed in light of current research being undertaken by NHBRC which takes into account local conditions and the level of skills available in the country. The β values are sensitive to V_R and it is likely that V_R for uninspected structures will be high, increasing the probability of failure of such structures. Uniformity of β is therefore compromised with the current γ_m values.

6 REFERENCES

British Standards Institute (1978). *Use of Masonry. Part 1. Structural Use of Unreinforced Masonry*. BS 5268: 1978. Part 1.

Construction Quality Assessment System (*Conquas 21, 1998*), Construction Industry Development Board, Singapore.

Ellingwood, B., Galambos, T.V., MacGregor, J.G. and Cornell, C.A. (1980), *Development of a probability-based load criteria for American National Standards A58*: NBS Special Publication SP577, National Bureau of Standards, US Dept of Commerce, Washington, 1980.

Goliger, A. and Mahachi, J. (2006), *A Building Quality Index for Houses (BQIH), Part 1: Development*, Proceed. First International Conference on Advances in Engineering and Technology, pp. 31-39, 16-19 July 2006, Entebbe, Uganda.

Kemp, A.R., Mahachi, J & Milford, R.V. (1998), *Comparison of International Loading Codes and Options for South Africa*. South African National Conference on Loading, Midrand, Sept. 1998.

Kemp, A.R., Mahachi, J & Milford, R.V. (1998), *Developing LRFD Codes in South Africa*. Structural Engineers World Congress, San Francisco, USA, pp. P315-3, July 19-23, 1998.

Mahachi, J., Goliger, A.M., and Wagenaar, F., (2002), *Structural Performance of Residential Housing in South Africa*, Proceed. Of the Second International Conference on Structural Engineering, Mechanics and Computation, pp.322, 5-7 July 2004, Cape Town, South Africa.

Mahachi, J. and Goliger (2006), A. *A Building Quality Index for Houses (BQIH), Part 2: Pilot Study*, Proceed. First International Conference on Advances in Engineering and Technology, pp. 31-39, 16-19 July 2006, Entebbe, Uganda.

Milford, R.V. (1988), *Target safety and SABS 0160 load factors.* The Civil Engineer in South Africa, 30(10), October 1988, 475-481.

Milford, R.V., Load factors for Limit State Codes. Technical Note, Journal of the Structural division, ASCE, 113(9), Sept. 1987, 2053-2057.

South African Bureau of Standards, SABS 0164 (1980). *The Structural Use of Masonry. Part 1: Unreinforced Masonry Walling. SABS 0164: Part 1: 1980.* Pretoria

South African Bureau of Standards, SABS 0160 (1989). *Code of Practice for the General Procedures and Loadings to be adopted in the Design of Buildings. SABS 0160:1989,* Pretoria.

South African National Standards, SANS 10162 (2006). *Code of Practice for the structural use of steel. Part 1: Limit States design of Hot-Rolled Steelwork,* SABS, Pretoria.

Annexure

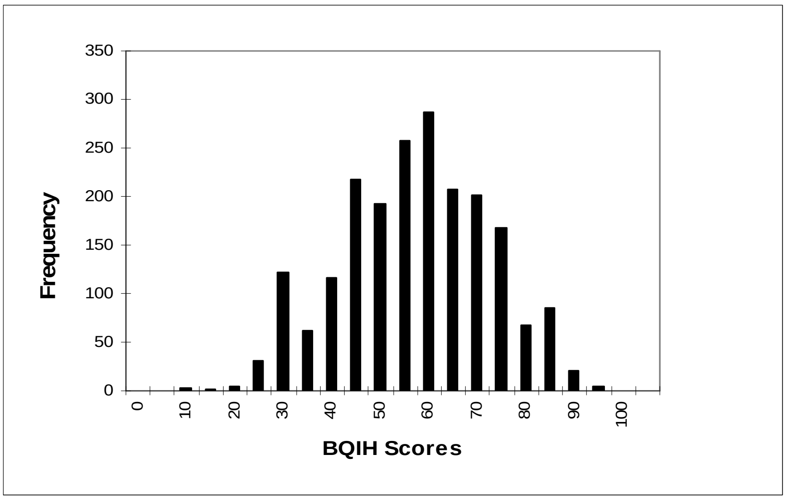

Figure 1: BQIH for wall elements

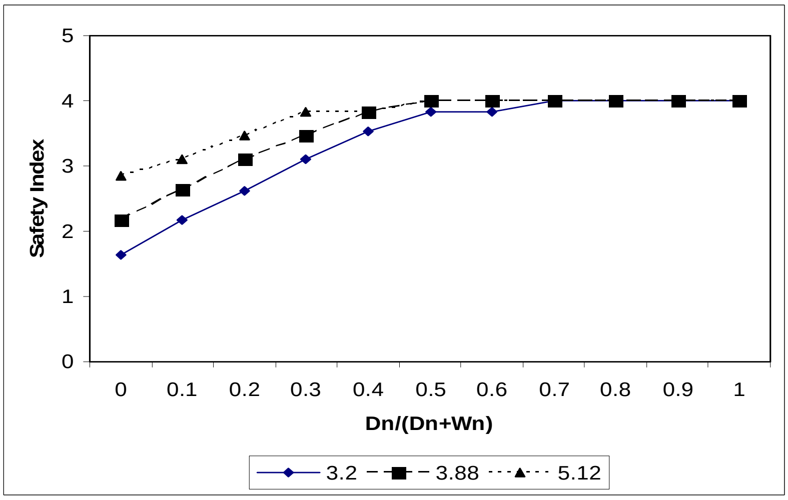

Figure 2: Variation of Safety Index β with $\overline{R} / \phi R_n$

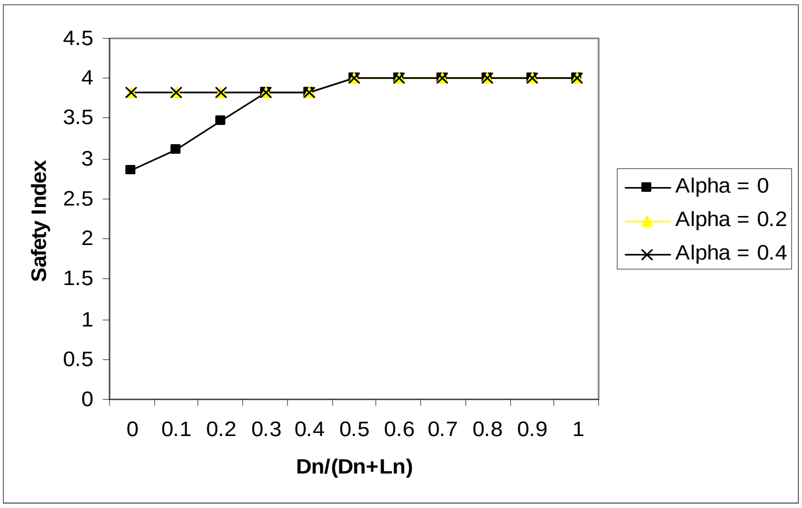

Figure 3: Variation of Safety Index β with Wind Load Ratio χ for resistance ratio of 5.12

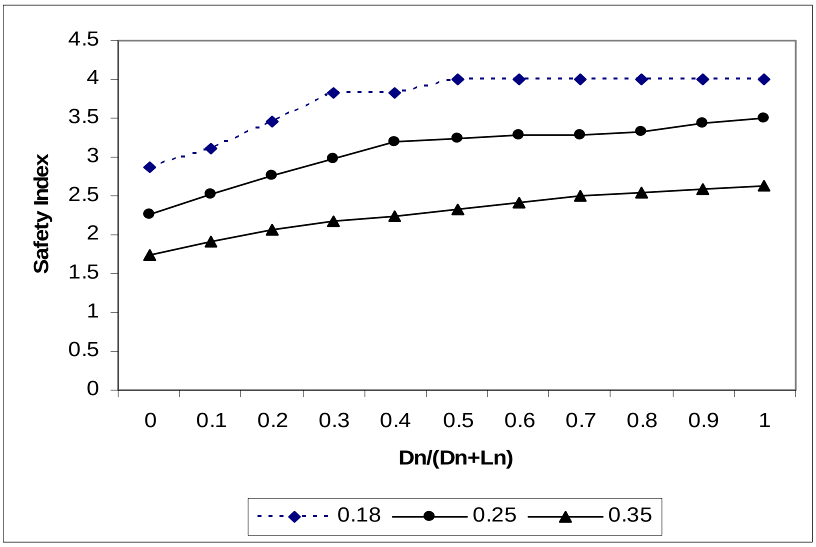

Figure 4: Variation of Safety Index β with V_R for resistance ratio of 5.12