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, 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 $\gamma_m$ 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.

The current South African Code of Practice for Structural Use of Masonry (SABS 0164, 1980) uses four partial safety factors $\gamma_m$, 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 $\gamma_m$ are based on the British Standards with some slight modifications that take into account local conditions.

The values of $\gamma_m$ 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 150$m^2$ of wall built, are performed. The $\gamma_m$ value of 3.5 is applicable where no strict quality control is exercised during manufacturing process and construction.

However, the values of $\gamma_m$ 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. \( \phi R_n \geq \sum \gamma_i Q_{ni} \)  

Where
\begin{align*}
Q_d & \quad \text{Design load effect} \\
R_d & \quad \text{Design Resistance} \\
\phi & \quad \text{Resistance factor} \\
R_n & \quad \text{Nominal resistance} \\
\gamma_i & \quad i^{th} \text{partial load factor (including combination factor)} \\
Q_{ni} & \quad \text{nominal load}
\end{align*}

The factors \( \phi \) and \( \gamma_i \) are calibrated based on a target reliability index (\( \beta \)) adopted by the code. The South African partial load factors were calibrated using a load index (\( \alpha \)) 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:

\[ \alpha = -\log[p_Q] \]  

(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 \( \alpha \) 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{align*}
1.5D_n \\
1.2D_n + 1.6L_n \\
1.2D_n + 0.5L_n + 1.3W_n \\
0.9D_n + 1.3W_n
\end{align*}

(3)

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 \( \beta \). 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 \( \beta \) is determined as follows:

\[ \beta = -\phi^{-1}(p_f) \]  

(4)

Where \( \phi^{-1}(\cdot) \) 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:

\[ P(Q \geq R) \]  

(5)

where \( Q = D + L + W \)

The wind load ratio \( \chi \) is as defined as

\[ \chi = \frac{W_n}{D_n + L_n + W_n} \]  

(6)

and dead load ratio \( \xi \) as

\[ \xi = \frac{D_n}{D_n + L_n} \]  

(7)

Let \( \gamma_d \), \( \gamma_l \) and \( \gamma_w \) 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 \( \chi \) and dead load ratios \( \xi \), from which the \( \beta \) 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:

\[
\overline{R}/\varphi R_n = 3.20 \quad \text{and} \quad V_R = 0.18 \quad (8)
\]

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) 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:

\[
\overline{R}/\varphi R_n = 3.20 \quad \text{and} \quad V_R = 0.18 \quad (8)
\]

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.

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>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient of Variation</th>
<th>Distribution Type</th>
<th>Mean/No. minal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead</td>
<td>0.10</td>
<td>Log-normal</td>
<td>1.05</td>
</tr>
<tr>
<td>Live max</td>
<td>0.25</td>
<td>Type I</td>
<td>0.96</td>
</tr>
<tr>
<td>Live a.p.t*</td>
<td>0.25</td>
<td>Gamma</td>
<td>0.71</td>
</tr>
<tr>
<td>Wind max</td>
<td>0.52</td>
<td>Type I</td>
<td>0.52</td>
</tr>
<tr>
<td>Wind a.p.t</td>
<td>1.08</td>
<td>Weibull</td>
<td>0.052</td>
</tr>
</tbody>
</table>

*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:

\[ \phi \bar{R}_n \geq 1.2D_n + 1.6L_n \]  

(9)

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

\[ R_d = \phi \cdot R_n \left( \frac{f_k}{f_m} \right) \]  

(10)

where

- \( R_n() \) is the nominal resistance that includes the partial material factor \( \gamma_m \).
- \( f_k \) is the characteristic compressive strength of masonry, and
- \( \phi \) is the resistance factor and \( \phi = 1.0 \)

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

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

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

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

The first scenario corresponds to the “special” category, where \( \gamma_m \) 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 \( \gamma_m \) of 4.6. Performing a Monte Carlo using equation (5) for the three scenarios, the safety index \( \beta \) was determined for different dead load ratios as presented in Figure 2.

It is observed that the change in \( \beta \) 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, \( \beta \) is about 4.0 for all resistance ratios. This ties in with the recommendation by Milford (1988) of adopting a \( \beta \) value of 4.0 for brittle failures.

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

(b). Dead + Live + Wind

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

\[ \phi \bar{R}_n \geq 1.2D_n + 0.5L_n + 1.6W_n \]  

(11)

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

(c). Variation of \( \beta \) with \( V_R \)

Figure 4 shows the variation of \( \beta \) with \( V_R \) for a fixed resistance ratio of 5.12. For a \( V_R \) of 0.18, \( \beta \) is of the order of 4.0. However, for \( V_R \) of 0.25 and 0.35, \( \beta \) 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 \( \beta \) value of 4.0 will not be achieved unless the partial material factor \( \gamma_m \) is increased. In order to achieve uniform \( \beta \) 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.
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 $\gamma_m$ values show fairly uniform $\beta$ 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 $\beta$ 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 $\beta$ is therefore compromised with the current $\gamma_m$ values.

6 REFERENCES


Annexure

Figure 1: BQIH for wall elements

Figure 2: Variation of Safety Index $\beta$ with $\frac{\bar{R}}{\phi R_n}$

Figure 3: Variation of Safety Index $\beta$ with Wind Load Ratio $\chi$ for resistance ratio of 5.12
Figure 4: Variation of Safety Index $\beta$ with $V_R$ for resistance ratio of 5.12