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Original Article

Reliability and Structural Performance Assessment of Solid Concrete Block Masonry Prisms using Compressive Strength Modelling and Monte Carlo Simulations

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Abstract *- Solid concrete block masonry is widely used in construction, but its performance is affected by variability in material properties, workmanship, and block quality. Traditional deterministic design methods often fail to capture these uncertainties, potentially leading to unsafe designs. This research proposes a reliability approach to assess masonry prism compressive strength through the integration of predictive modelling and probabilistic analysis. The objective is to perform a reliability analysis of masonry prisms and determine the Probability of failure. Five cement-sand mortar ratios (1:3 to 1:7) were experimentally evaluated, and Multiple Linear Regression (MLR) models were developed to estimate prism strength as a function of block and mortar strengths. The developed regression equations were incorporated into a Monte Carlo simulation framework with 40,000 iterations to evaluate the Probability of failure and reliability index for a typical residential building configuration. Results indicate that the 1:3 mortar mix provides superior structural performance, yielding a probability of failure (P_f) of 0.0479 and a reliability index (β) of 1.66, satisfying the adopted target reliability criterion. Floor optimization analysis further revealed that the structure can safely support up to 14 floors while maintaining the adopted Probability of failure limit of 5%. The findings highlight the significant influence of material variability on masonry reliability and demonstrate the effectiveness of probabilistic methods for realistic safety assessment and performance-based masonry design.*

Keywords *- Masonry reliability, Monte Carlo simulation, Probability of failure, Reliability index, Solid concrete blocks, Structural safety, Multiple linear regression.*

1. Introduction

Concrete Block Masonry (CBM) prism is one of the most widely used construction elements in low to mid-rise buildings because of its economic feasibility, ease of transportability, and flexibility to suit different architectural plans [1]. The CBM prism, having concrete blocks with mortar joints placed between the blocks, forms the primary unit for construction purposes in the case of walls, partitions, and load-bearing structures [2]. The performance properties, namely, the compressive strength, stiffness, and deformability properties, are mainly dependent on the strengths and properties of the concrete blocks, the Mortar, and the combination or effect between the two, and hence the masonry [3, 4]. A lot of experiments have been conducted to determine the effects and results regarding the compressive strength and the deformability properties of the CBM prism under laboratory conditions [5]. Furthermore, with the advent of advanced computational models, simulation models have been developed to predict the performance properties by incorporating various factors such as size, strength, and bonding properties between the concrete blocks, and hence the importance to estimate the properties accurately to provide protection and optimization for the materials used, along with sustainable and new construction codes [6, 7].

A number of problems persist in the precise estimation of CBM prisms, even considering the advances in testing and modelling techniques [8]. Material heterogeneity, environmental influences, and workmanship variations introduce uncertainties in compressive strength and deformation response, rendering conventional deterministic analyses insufficient for true representation of the behaviour

[9]. Further, the estimation of the Probability of failure under realistic loading scenarios remains cumbersome, which calls for stochastic methods like Monte Carlo simulations to capture variability for enhanced reliability predictions. Addressing these challenges is of paramount importance for the development of robust assessment methodologies that improve structural safety, inform design decisions, and support sustainable construction [10].

A review of the existing literature reveals that substantial research efforts have been devoted to investigating the compressive behaviour, deformation characteristics, and numerical modelling of masonry prisms. Recent studies have also explored probabilistic approaches for assessing uncertainty in masonry structures using fragility analysis and Monte Carlo simulation techniques. However, most of these investigations focus either on structural vulnerability under extreme loading conditions or on deterministic prediction of masonry strength. Relatively few studies have focused on the integration of experimentally derived masonry prism strength characteristics with reliability-based assessment frameworks for solid concrete block masonry. In particular, the combined influence of block strength variability and mortar strength variability on structural reliability has not been adequately quantified. Furthermore, there is a lack of practical methodologies that directly relate experimentally measured material properties to Probability of failure and reliability indices for masonry design applications.

Another important limitation of previous studies is the absence of reliability-based floor optimization for masonry structures. Existing approaches generally provide strength predictions without evaluating the corresponding level of structural safety under uncertain loading and material conditions.

To address these gaps, the present study develops experimentally calibrated Multiple Linear Regression (MLR) models and integrates them with Monte Carlo simulation to quantify the Probability of failure and reliability index of solid concrete block masonry prisms. The proposed framework provides a practical reliability-based methodology for evaluating masonry performance and establishing safe design limits for multi-storey masonry construction.

Several significant studies related to solid concrete block masonry and masonry reliability are reviewed in this section.

Thamboo, J. et al., [11] investigated the compressive strength values for the grouted concrete masonry structure by examining the prevailing methodologies for predicting the strength based on experimental prism values. The authors pointed out the inadequacies in the prevailing unit strength relationships, as they were found to be quite sensitive to the values of the concrete units, Mortar, and grout strength. Although improved correlations were identified through statistical evaluation, the work was constrained by reliance on experimental databases and did not fully capture variability arising from construction practices.

Oddo, M.C. et al., [12] assessed the vulnerability of masonry structures to tsunamis using an analytical methodology modified for the calculation of fragility curves and the evaluation of the resultant uncertainties. The work proved the efficacy of the Monte Carlo simulation in the assessment of the uncertainty of the predicted damage without necessitating regression assumptions. Yet the methodology was noted to be simple because it considered only a few classes of structures and basic models of coastal loading.

Shi, T. et al., [13] examined the impact of random imperfections in the compressive performance of dry-stacked interlocking block walls using a stochastic Monte Carlo simulation model. The findings showed that the more variable and random the imperfections, the lower the compressive strength of the walls, with varying levels of imperfections affecting load transfer. The study has the limitation of assumed distributions of imperfections and the assumed conditions of the wall.

da Silva, L.C. et al., [14] presented a probabilistic numerical procedure for seismic fragility analysis of masonry buildings using a discrete macro-element model along with meso-scale homogenization. Their procedure considered uncertainties related to material properties, geometric parameters, and loads. It also significantly reduced the cost of the analysis using the incremental dynamic procedure. Their procedure proved efficient and effective on the English bond masonry mock-up structure.

Cho, H.C. et al., [15] examined the safety inspection regulations for reinforced concrete structures in South Korea and concluded that the general importance factors tended to have a conservatively low value for the effect of worn-out beams and worn-out concrete slabs. Case studies have been performed to revise the importance factors based on member reliability, which resulted in a more practical method for the safety inspection of the floor and overall structural deterioration. However, the approach was limited to the specific evaluation framework and member types considered, which may restrict its general applicability to other inspection standards or structural systems.

Guamán-Naranjo, M. et al., [16] evaluated the seismic vulnerability and economic impact of reinforced concrete frame structures with masonry infills in Quito by applying a probabilistic model. Nonlinear time history analyses were applied to parametric models to model variability, and fragility curves were calculated efficiently. The outcome indicated that the repair difficulty and vulnerability of the typical structure were high. Moreover, the validation was only done for a structural type and seismic data that limit its generalizability to other structures.

Abdelrahman, M.Z. and Galal, K., [17] presented an experimental study on the shear and compressive behaviour of dry-stacked interlocking masonry with varying levels of grouting and reinforcement. Several unreinforced walls, without horizontal reinforcement, exhibited premature failure, whereas several walls that were both reinforced and fully grouted exhibited better ductility and strength. There was increased performance with increased vertical and horizontal reinforcement. The DSIM behaviour was poorly predicted by conventional masonry design equations; thus, dedicated models need to be developed. The study was limited to specific block types and reinforcement layouts, restricting wider applicability.

Zorainy et al., [44] investigate the stress–strain behavior of masonry boundary element prisms subjected to axial compression, with the aim of understanding their contribution to the overall performance of masonry structures. Experimental testing was carried out on masonry prism specimens to evaluate key mechanical properties, including compressive strength, stiffness, and deformation characteristics. The results indicate that masonry boundary elements exhibit nonlinear stress–strain behavior, characterized by an initial linear elastic region followed by progressive cracking and eventual failure. The study highlights the influence of material properties and confinement effects on the load-carrying capacity and ductility of the prisms. It is observed that boundary elements can significantly enhance the compressive strength and deformation capacity of masonry systems.

A comparative assessment of the reviewed literature indicates that previous studies have primarily focused on either experimental evaluation of masonry strength, empirical prediction of prism behaviour, or probabilistic assessment of structural performance under specific loading conditions. Although Monte Carlo simulation and reliability concepts have been applied in masonry research, their application has largely been limited to fragility assessment, seismic vulnerability studies, and idealized structural systems.

In contrast, the present study combines experimentally calibrated MLR models with Monte Carlo simulation to establish a practical reliability-based assessment framework for solid concrete block masonry. Furthermore, the study introduces a reliability-based floor optimization approach for multi-storey masonry construction, which has received limited attention in existing literature. Therefore, the present research extends conventional strength prediction methodologies towards a practical reliability-based design and assessment framework for solid concrete block masonry structures.

The objective of this study is to evaluate the reliability of solid concrete block masonry prisms under material variability and to quantify their Probability of failure using a probabilistic framework. Through MLR, predictive equations based on block and mortar strengths are first developed. Monte Carlo simulations are then used to evaluate structural reliability quantitatively.

The proposed framework integrates experimentally calibrated MLR models with Monte Carlo simulation to quantify the Probability of failure and reliability index under material and loading uncertainties. The framework also facilitates reliability-based floor optimization for multi-storey masonry construction.

Major Contributions are summarized as follows:

- Developed MLR models to predict masonry prism compressive strength as a function of block and mortar strengths for different mortar mixes.
- Incorporated material variability by modelling Mortar and block strengths as normally distributed random variables.
- Performed Monte Carlo simulations to generate a statistically significant dataset for masonry compressive capacity.
- Computed Probability of failure and reliability index to quantify structural reliability.
- Demonstrated the effect of mortar mix and material variability on masonry performance, providing guidance for safer and more informed masonry design.

The rest of the manuscript is structured as follows: Section 2 describes the materials and methods; Section 3 describes the proposed methodology; Section 4 illustrates the results and discussion; Section 5 illustrates the conclusion.

2. Materials and Methods

The overall process of reliability assessment of solid concrete block masonry prisms is shown in Figure 1. The overall process involves the selection of crucial materials like cement and M-Sand, as well as varying proportions of Mortar, which then helps in preparing the masonry prisms. The prepared masonry prisms are used to perform three different tasks.

The first task involves the prediction of the strength of the masonry prism using multiple linear regressions. The second task involves the reliability assessment of the structural strength of the masonry. The final task involves Monte Carlo analyses, which help in determining the failure probability of the materials.

2.1. Binder and Fine Aggregate Properties

2.1.1. Cement

In every mortar mix, OPC is the primary binder. OPC-based mortar cubes baseline compressive strength was considered as the input parameter of simulations. Random variables have been considered as the average and standard Deviation of mortar strength of each cement-to-sand ratio.

2.1.2. Sand (M-Sand, Zone II)

Manufactured sand confirming to Zone II of IS:383 was utilized as fine aggregate in all mortar mixes. Differences in packing, grading of the particles and texture on the surface also affect mortar strength. Rather than making these effects modelled on a one-by-one basis, the effects are implicitly included in the statistical variability (mean and standard Deviation) of the experimentally observed Mortar compressive strength.

2.2. Solid Concrete Masonry Blocks

Prism construction was done by using solid concrete masonry blocks with nominal dimensions of 400 mm × 200 mm × 200 mm. The blocks had been purchased in three manufacturing sources to ensure that they captured the natural variability that comes with the practices of production, quality of the raw material, compaction efficiency and curing conditions. This was to guarantee natural variability of block strength in the experiment program.

2.3. Mortar Mix Proportions and Testing

The ratios of cement to sand taken into consideration were five, that is, 1:3, 1:4.5, 1:5, 1:6 and 1:7. Mortar was prepared by mixing cement with M-sand in the required proportions, and then water was added to bring about the required workable proportions. Nine cubes of Mortar were cast in total to each mix ratio. Demoulding and wet curing of the specimens were done after a period of 24 hours and 28 days, respectively. Compressive strength tests were carried out according to IS:2250, and the test results obtained were used to determine the average compressive strength of each mix. Table 1 shows the mean compressive strengths obtained for different mortar mixes.

The results indicate a progressive reduction in compressive strength with an increase in sand proportion, with the 1:3 mix exhibiting the highest strength and the 1:7 mix showing the lowest strength.

Table 1. Mean Compressive Strength of mortar mixes

Mortar Mix Ratio	Mean Compressive Strength (MPa)
1: 3	36.24
1: 4.5	25.50
1: 5	25.11
1: 6	16.19
1: 7	11.92

2.4. Concrete Block Testing

The samples were made up of concrete blocks, which were procured from three sources and subjected to uniaxial compression to find out their compressive strength. A total number of 54 blocks were to be tested, with 18 blocks of each source. The compressive strength was computed as a ratio of the ultimate load to the loaded area of the block. Table 2 summarizes the compressive strengths of block of various sources.

Table 2. Compressive Strength of concrete blocks from different sources

Block Source	Dimensions (mm)	Compressive Strength (MPa)
Source A	400 × 200 × 200	12.85
Source B	400 × 200 × 200	11.66
Source C	400 × 200 × 200	12.86

The overall mean compressive strength of the blocks, calculated from all tested specimens, was 12.62 MPa. The variation among the sources reflects practical manufacturing differences and provides a realistic basis for probabilistic modelling.

2.5. Masonry Prism Preparation and Testing

The concrete blocks that had been tested were used to construct a masonry prism using the mortar mixes. In the construction of the prism, bed joint thickness was kept as uniform as possible to reduce variability as a result of workmanship. The prisms were constructed and left to dry in moist conditions and tested after 28 days.

Axial compression tests were conducted on the masonry prisms using a calibrated loading frame of 60-tonne capacity. The specimens were tested after 28 days of curing under concentric axial loading conditions. The ultimate load at failure was recorded, and the prism compressive strength was calculated by dividing the failure load by the gross cross-sectional area of the prism. The testing procedure was carried out in accordance with relevant Indian Standard recommendations for masonry compression testing. To verify that the results were statistically reliable, 54 prisms were used in each mortar ratio. Prism strengths obtained experimentally were then utilized to build predictive regression models and to act as input parameters of reliability analysis.

3. Proposed Methodology

The predictive modelling and probabilistic analysis are employed to determine masonry prism strength and reliability. Regression models determine the strength of the block and Mortar materials, and Monte Carlo with varying material strengths is used to assess the likelihood of failure and the reliability index, which reflects the impact of material variability on structure performance.

3.1 Predictive Modelling using Multiple Linear Regression (MLR)

Multiple linear regression was used to develop predictive equations for prism compressive strength (f_p) as a function of block strength (f_b) and mortar strength (f_m). The general form of the model is:

$$f_p = af_b + bf_m \quad (1)$$

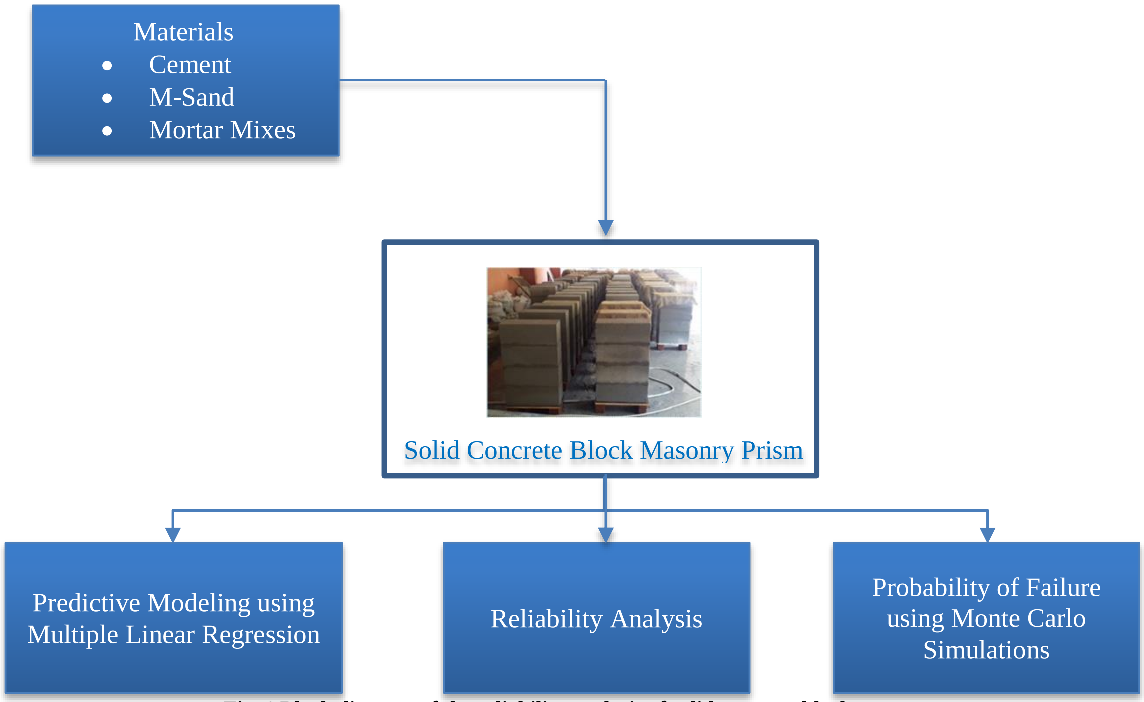

Fig. 1 Block diagram of the reliability analysis of solid concrete block masonry

Coefficients for each mortar grade are summarized in Table 3.

Table 3. MLR models for prism strength prediction

Mortar Mix Ratio	Model Coefficients (a, b)	Coefficient of Determination (R^2)
1 : 3	0.4105, 0.2036	0.97
1: 4.5	0.4060, 0.1927	0.95
1: 5	0.4090, 0.1552	0.94
1: 6	0.4103, 0.1497	0.93
1: 7	0.4068, 0.1091	0.92

3.2. Probabilistic Modelling of Material Properties

Mortar strength and block strength were taken as random variables to consider uncertainty in the means of behaviour of the material. Goodness-of-fit tests using the Chi-square technique were performed on the experimental data to determine the most appropriate probability distribution for the strength parameters.

The test results confirmed that mortar strength, block strength, and consequently the derived prism compressive strength follow a normal distribution at a 5% significance level. Although compressive strength is a strictly positive value, the Normal distribution is justified in this case because the means are sufficiently large relative to the standard deviations, ensuring that the Probability of negative values is negligible. For all material parameters in this research, the condition $\mu > 3\sigma$is satisfied, confirming that negative strength values have negligible Probability. Table 4 shows the statistical parameters of the mortar strength of various mix ratios.

Table 4. Statistical parameters of mortar strength

Mortar Mix	Mean Strength (MPa)	Standard Deviation (MPa)	Coefficient of Variation (COV)
1: 3	36.25	0.5919	0.0163
1: 4.5	25.50	1.284	0.0511
1: 5	25.11	0.3448	0.0135
1: 6	16.20	0.7907	0.0488
1: 7	11.92	0.6705	0.0562

The findings show that mortar mixes with more richness have less variability than their leaner counterparts in the form of lower COV values of a higher strength mortar. On the same note, block compressive strength is a normal random variable with experimentally measured means and standard Deviation.

The mean block strength, which was utilized in the reliability analysis, was 12.62MPa with a standard deviation of 0.857MPa. The condition $\mu > 3\sigma$ is satisfied (12.62 > 2.57), confirming that negative strength values have negligible Probability.

3.3. Load Modelling

A typical section of a residential building in Figure 2 with known geometric dimensions was considered for analysis. The chosen masonry wall has reinforced concrete slabs of 3.23 m and 3.71 m across, respectively. The load on the wall was determined to be the axial load on the wall in terms of tributary slab areas. Live Load (LL) and Dead Load (DL) were considered as randomly variable. Table 5 summarizes the statistical parameters to be used for load modelling.

Table 5. Statistical parameters of loads

Load Type	Mean	Coefficient of Variation (COV)	Standard Deviation	Distribution
Dead Load (DL)	26.48	0.026	0.6885	Normal
Live Load (LL)	6.94	0.01	0.0694	Log Normal (18)

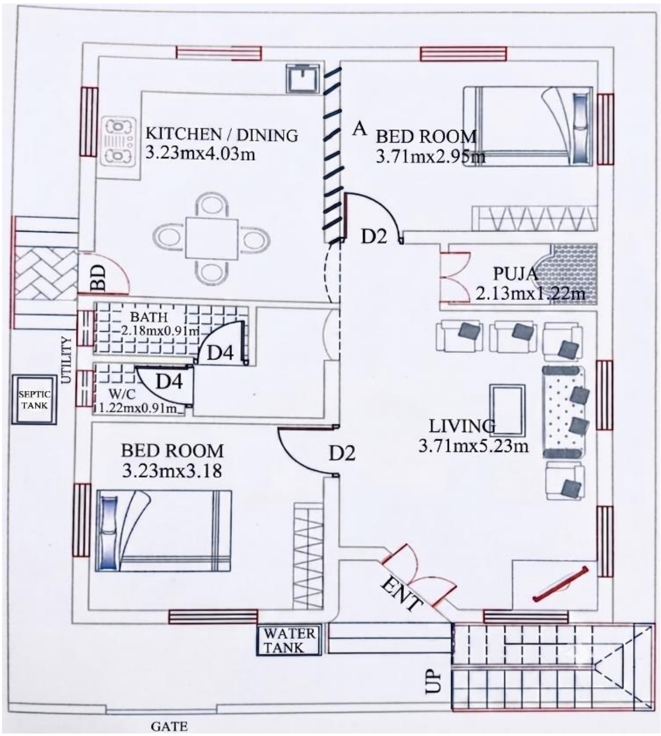

Fig. 2 Plan of a typical residential building

3.4. Structural Modelling and Limit State Formulation

The prism compressive strength f_p is calculated using the regression equations developed in Section 3.1 for the mortar ratio of 1:3. The basic compressive strength of masonry $(B_c)$is determined as specified in IS:1905-1987 (Clause B-2, Page 22) using equation (2).

$$B_c = 0.25 f_p \quad (2)$$

The resistance of the masonry wall $(R)$is computed as:

$$R = B_c \times A \quad (3)$$

where A is the cross-sectional area of the wall.

The load effect $(S)$is calculated as the sum of dead load and live load:

$$S = DL + LL \quad (4)$$

Both resistance and load effect were expressed in terms of uniformly distributed load (kN/m).

The structural performance is evaluated using the limit state function in equation (5):

$$Z = R - S \quad (5)$$

Where R represents the masonry compressive capacity obtained from the regression model, and S represents the applied stress due to combined dead and live loads.
Failure is considered to occur when $Z < 0$.

The Normal distribution was adopted for modelling mortar strength and block compressive strength based on both statistical testing and previous masonry reliability studies. Chi-square goodness-of-fit tests conducted on the experimental data indicated satisfactory agreement with the Normal distribution at a 5% significance level. Similar assumptions have been reported by Balasubramanian et al., [19] and Ranganathan [18] for modelling masonry and structural material properties. Furthermore, the experimentally observed coefficients of variation were relatively small, and the mean values were significantly greater than three times the standard Deviation, ensuring that the Probability of obtaining physically unrealistic negative strength values was negligible.

Dead load was modelled using a normal distribution because it is primarily governed by geometric dimensions, material unit weights, and construction details, which generally exhibit limited variability. Since dead load is the cumulative effect of several independent variables, the resulting distribution can reasonably be approximated as Normal according to the Central Limit Theorem. Live load was represented using a Lognormal distribution because occupancy-related loads are inherently non-negative and often exhibit right-skewed behaviour. Previous reliability studies have shown that Lognormal distributions provide a realistic representation of live load variability in residential buildings. The Lognormal model prevents the generation of physically impossible negative load values while adequately capturing the probabilistic characteristics of occupancy loads. Similar assumptions are widely adopted in structural reliability analysis literature [18].

3.5. Monte Carlo Simulation Procedure

Monte Carlo simulation was performed using 40,000 iterations to estimate the Probability of failure. A total of 40,000 Monte Carlo simulations were performed to ensure statistical convergence of the estimated Probability of failure. Preliminary analyses indicated that the Probability of failure stabilized beyond approximately 30,000 simulation cycles, with negligible variation in the calculated reliability index. Therefore, 40,000 simulations were considered sufficient to obtain statistically stable and computationally efficient estimates. The random values of mortar strength, block strength, dead load, and live load were sampled, each time, with respect to the respective probability distribution of each. The regression equation became the method of computing the prism strength, and accordingly, the wall resistance was calculated. The value of the applied load was calculated based on some sampled dead and live load values.

The random variables considered in the reliability analysis were assumed to be statistically independent. This assumption was considered reasonable because mortar strength, block strength, dead load, and live load originate from different physical processes and are not expected to exhibit significant correlation. Similar independence assumptions are commonly adopted in structural reliability analyses when sufficient correlation data are unavailable.

The Probability of failure is calculated as in equation (6).

$$P_f = \frac{n_f}{n_s} \tag{6}$$

Where, n_f is the number of simulations resulting in $Z < 0$, and n_s is the total number of simulations.

The reliability index is determined using equation (7).

$$\beta = -\Phi^{-1}(P_f) \tag{7}$$

where, Φ^{-1} is the inverse standard normal cumulative distribution function.

3.6. Performance Criterion

A target probability of failure (P_f) of 5% was adopted as the acceptance criterion for the present study. The corresponding reliability index ($\beta \approx 1.64$) was calculated using the standard normal cumulative distribution function and is reported as a complementary measure of structural reliability.

The selected failure probability threshold was used as a comparative benchmark for evaluating alternative masonry configurations and determining the maximum permissible number of floors under the considered loading conditions. If the computed Probability of failure exceeded this limit, the applied floor load is reduced and the analysis is repeated. The maximum number of floors satisfying the condition $P_f \leq 0.05$ is determined for each mortar ratio.

4. Results and Discussion

This section presents the experimental results, regression model performance, and reliability analysis of solid concrete block masonry. It discusses the influence of mortar mix proportion on strength and variability, evaluates predictive accuracy, and interprets the Probability of failure and reliability index in relation to structural safety and floor optimization.

4.1. Experimental Strength Characteristics

The findings of the experiment show evidently that compressive strength is strongly dependent on mortar mix proportion. The maximum mean compressive strength was 36.24 MPa of the 1:3 mortar mix, whereas the minimum compressive strength was 11.92 MPa of the 1:7 mix. There was a systematic decrease in strength with increasing sand content, and this confirmed that leaner mixes decrease cementitious bonding and matrix compactness.

The coefficient of variation (COV) moved steadily with an increase in the leanness of the mortar mix. The COV value of the 1:3 mix was found to be 0.0163, and that of the 1:7 mix was 0.0562, which means strong mixes are less likely to be affected by the material inconsistency and workmanship margin.

The concrete blocks that were taken at three manufacturing sources yielded the strengths of 12.85 MPa, 11.66 MPa, and 12.86 MPa with an average of 12.62 MPa. The sources variation was moderate, which implies the consistency of the manufacturing quality, but at the same time offers realistic variability to be used in probabilistic analysis.

4.2. Performance of Regression Models

Multiple Linear Regression (MLR) analysis demonstrated a strong linear relationship between prism compressive strength and the strengths of block and Mortar. The regression coefficients presented in Table 3 showed that the coefficient corresponding to block strength (a) was consistently higher than that of mortar strength (b), indicating that block strength has a greater influence on composite prism strength.

The coefficient of determination (R^2) ranged from 0.92 to 0.97 across different mortar ratios, confirming the high predictive capability of the developed models. The 1:3 mortar mix exhibited the highest correlation ($R^2 = 0.97$), indicating better composite action and load transfer efficiency at higher mortar strengths. A slight reduction in R^2 was observed for leaner mixes, reflecting increased variability and reduced bonding efficiency.

The regression equations provided a reliable basis for estimating masonry compressive capacity in the reliability framework. To further assess the adequacy of the developed models, the predicted prism strengths were compared with the experimentally measured values used for model development.

The high coefficients of determination ($R^2 = 0.92–0.97$) indicate strong agreement between predicted and observed responses.

The close correspondence confirms that the developed MLR equations are capable of reliably estimating masonry prism compressive strength and are suitable for subsequent reliability analysis.

4.3. Reliability Analysis Results for 1:3 Mortar Ratio

Monte Carlo simulation with 40,000 iterations was carried out for the selected residential building configuration for the mortar ratio 1:3. Out of 40,000 simulation runs, 1,916 cases resulted in failure (Z < 0). The Probability of failure was therefore:

$$P_f = \frac{1916}{40000} = 0.0479$$

The corresponding reliability index was calculated as:

$$\beta = -\Phi^{-1}(0.0479) \approx 1.66$$

The mean safety margin (Z) was 162.04 kN, with a standard deviation of 85.48 kN, resulting in a coefficient of variation of 0. 527. Since the computed Probability of failure (4.79%) is slightly below the target threshold of 5%, the structure satisfies the adopted reliability criterion for the selected number of floors. Table 6 shows the reliability results for the 1:3 mortar mix.

Table 6. Reliability results for 1:3 mortar ratio

Parameter	Value
Number of Simulations	40,000
Failure Cases	1,916
Probability of Failure (P_f)	0.0479
Reliability Index (β)	1.66
Mean Safety Margin (kN)	162.04
Standard Deviation (kN)	85.48
COV of Safety Margin	0.527

4.4. Influence of Material Variability on Structural Safety

These findings show clearly that both mean strength and variability have a significant effect on structural reliability. The rich mortar mixes are stronger in compressive strength and less variable, and hence the safety margins are better. Leaner mixes, on the other hand, have more dispersion in the values of strength, and consequently, the likelihood of failure in the same load environment is more likely under leaner mixes.

The probabilistic model is useful in addressing the uncertainties associated with material variation, variation in forces and modelling assumptions and can give a more realistic evaluation as opposed to deterministic design methods.

4.5. Sensitivity of Reliability to Material and Load Variations

The reliability performance of masonry systems is inherently sensitive to variations in both resistance and loading parameters. Based on the developed MLR models and the adopted probabilistic framework, it can be observed that changes in block strength, mortar strength, and applied loads directly influence the calculated safety margin and Probability of failure. Since the regression coefficients associated with block strength are consistently higher than those corresponding to mortar strength, the reliability index is expected to be more sensitive to variations in block compressive strength. Similarly, reductions in mortar strength increase the dispersion of masonry resistance and consequently reduce structural reliability. On the loading side, an increase in dead or live load decreases the available safety margin, leading to a higher probability of failure. Therefore, maintaining consistent block quality, adequate mortar strength, and realistic load estimation is essential for achieving satisfactory reliability levels. The present findings indicate that the reliability of solid concrete block masonry is governed not only by the mean values of material properties but also by their associated variability, highlighting the importance of quality control and probabilistic assessment in masonry design.

4.6. Floor Optimization Based on Reliability Criterion

A target probability of failure of 5% (β ≈ 1.64) was adopted as the acceptance criterion for the present study. The selected reliability level represents a practical threshold suitable for comparative assessment of masonry configurations and floor optimization studies. The adopted failure probability threshold is not intended to represent a code-specified target reliability level but rather a comparative criterion for evaluating alternative masonry configurations under identical loading conditions. The Criterion enables identification of acceptable structural configurations while maintaining consistency with reliability-based evaluation procedures commonly adopted in preliminary structural assessment and performance-based design studies. The number of floors was varied, and reliability analysis was repeated until the acceptable limit was reached. Table 7 shows the floor optimization results.

Table 7. Floor optimization results for 1:3 mortar mix

Number of Floors	Probability of Failure P_f	Reliability Index β	Status
13	0.032	1.85	Safe
14	0.0479	1.66	Safe
15	0.061	1.55	Not Safe

The maximum permissible number of floors satisfying the reliability requirement was 14 floors for the 1:3 mortar mix.

4.7. Discussion

The overall findings indicate that the proportion of the mortar mix is decisive in the formation of the strength and structural integrity of the concrete block masonry. Not only do richer mortar mixes increase the compressive strength, but they also minimise variability, which enhances the index of reliability and consequently reduces the chances of failure. The regression analysis proves that the effect of block strength on prism strength is more prevalent compared to that of mortar strength, and therefore, it is necessary to maintain the quality of block uniformity in masonry construction. The Monte Carlo simulation results also indicate that moderate variations in material properties can severely affect the safety margin in case they are coupled with stochastic loading.

The 1:3 mortar mix reliability index of 1.66 meets the adopted target criterion and therefore satisfies the reliability requirement for the selected building configuration. The floor optimization study highlights the practical significance of reliability-based design, demonstrating that the structural system can safely support up to 14 floors without compromising the target probability of failure threshold. By and large, the findings demonstrate that by integrating probabilistic analysis into the masonry design, a more realistic and performance-based evaluation is achieved as compared to the traditional deterministic methods.

5. Conclusion

This research presented a reliability-based evaluation of solid concrete block masonry through the integration of experimental investigation, MLR modelling, and Monte Carlo simulation. The findings confirmed that mortar mix proportion significantly affects compressive strength, variability, and overall structural reliability, with the 1:3 mix demonstrating superior strength characteristics and lower dispersion. The developed regression models exhibited strong predictive capability. A theoretical sensitivity assessment further indicated that variations in block compressive strength exert a greater influence on structural reliability than equivalent variations in mortar strength, emphasizing the importance of maintaining consistent block quality in masonry construction. Reliability analysis showed that the selected configuration achieved a probability of failure of 0.0479 and a reliability index of 1.66, satisfying the adopted target safety criterion. Floor optimization further indicated that the considered building configuration can safely support up to 14 floors while maintaining the adopted Probability of failure limit of 5%. Overall, the study demonstrates that incorporating probabilistic methods into masonry design enables a more realistic and performance-based assessment of structural safety compared to conventional deterministic approaches. The proposed framework can be effectively applied in performance-based design and safe height optimization of masonry buildings by explicitly accounting for material variability. However, the study is limited to compressive strength behaviour under a specific residential loading configuration and does not consider lateral loads or long-term durability effects. Future research may extend the framework to include seismic and wind loads, time-dependent deterioration, and advanced reliability techniques for broader structural applications.

Data Availability

The experimental data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Ismail Bello et al., "Complete Stress-Strain Analysis of Masonry Prisms under Compressive Loading-Unloading Cycles through Digital Image Correlation," *Engineering Structures*, vol. 298, pp. 1-31, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[2] Thuany E. S. de Lima et al., "Influence of the Mortar Bedding in Compressive Strength of Masonry Wallets made of Brazilian Concrete Blocks," *International Journal of Civil Engineering*, vol. 22, pp.1945-1959, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[3] Siddharth B. Baeen et al., "Effect of Thin Reinforcement in Bed-Joint on the Compressive and Shear Strength of Brick and Block Masonry-An Experimental Investigation," *Journal of Building Pathology and Rehabilitation*, vol. 10, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[4] Ali Abasi, Bennett Banting, and Ayan Sadhu, "Towards Design of Temporary Bracing for Early-Age Unreinforced Masonry Walls Against Out-of-plane Loading," *Engineering Structures*, vol. 345, pp. 1-13, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[5] Lewis J. Gooch, Mark G. Stewart, and Mark J. Masia, "Model Accuracy for the Prediction of Unreinforced Clay Brick Masonry Shear Wall Resistance," *Bulletin of Earthquake Engineering*, vol. 24, pp.1-29, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[6] Navaratnarajah Sathiparan, "Predicting Compressive Strength of Grouted Masonry using Machine Learning Models with Feature Importance Analysis," *Materials Today Communications*, vol. 41, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[7] Francesco P. A. Portioli, and Paulo B. Lourenço, "Nonlinear Static Analysis of Masonry Structures with Mortar Joints and Cracking units by Optimization-based Rigid Block Models," *Earthquake Engineering & Structural Dynamics*, vol. 53, no. 13, pp. 3963-3982, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[8] Davi Fagundes Leal, Jorge Munaiar Neto, and Cristian Maluk, "Thermal Behavior of Dry-Cast Concrete Blocks Masonry Walls at Elevated Temperatures," *Journal of Building Engineering*, vol. 89, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[9] Gustavo Henrique Nalon et al., "Self-Sensing Concrete Masonry Structures with Intrinsic Abilities of Strain Monitoring and Damage Detection," *Structures*, vol. 59, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[10] Abrahem A. Ali Blash et al., "Evaluating the Behaviour of Axially Loaded Hollow Concrete Block Masonry Walls with Small-Size Openings: Various Opening Positions and their Influence on Experimental Results," *Engineering Structures*, vol. 301, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[11] Julian Thamboo, Mathavanayakam Sathurshan, and Tatheer Zahra, "Reliable Unit Strength Correlations to Predict the Compressive Strength of Grouted Concrete Masonry," *Materials and Structures*, vol. 57, pp. 1-19, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[12] Maria Concetta Oddo, Panagiotis G. Asteris, and Liborio Cavaleri, "Monte Carlo Analysis of Masonry Structures under Tsunami Action: Reliability of Lognormal Fragility Curves and Overall Uncertainty Prediction," *Structures*, vol. 63, pp. 1-15, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[13] Tingwei Shi et al., "Influences of Random Imperfection Distribution on the Compressive Properties of Interlocking Block Wall," *Structures*, vol. 56, pp. 1-19, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[14] Luis C.M. da Silva, Gabriele Milani, and Paulo B. Lourenço, "Probabilistic-based Discrete Model for the Seismic Fragility Assessment of Masonry Structures," *Structures*, vol. 52, pp. 506-523, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[15] Hae-Chang Cho et al., "Structural Safety Inspection of Reinforced Concrete Structures Considering Failure Probabilities of Structural Members," *International Journal of Concrete Structures and Materials*, vol. 17, pp. 1-17, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[16] Mauricio Guamán-Naranjo, José Poveda-Hinojosa, and Ana Gabriela Haro-Báez, "Probabilistic Loss Assessment for the Typology of Non-Ductile Reinforced Concrete Structures with Flat Slabs, Embedded Beams, and Unreinforced Infill Masonry," *Buildings*, vol. 14, no. 10, pp. 1-17, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[17] Mahmoud Zaki Abdelrahman, and Khaled Galal, "Experimental Investigation of In-plane Shear and Compressive Behaviour of Dry-Stacked Interlocking Concrete Masonry," *Construction and Building Materials*, vol. 505, pp. 1-17, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[18] R. Ranganathan, *Structural Reliability Analsis and Design*, Jaico Publishing House, pp. 1-456, 1998. [Google Scholar] [Publisher Link]

[19] S. R. Balasubramanian et al., "Experimental Determination of Statistical Parameters Associated with Uniaxial Compression Behaviour of Brick Masonry," *Current science*, vol. 109, no. 11, pp. 2094-2102, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[20] Dae-Kyung Kim, and Woo-Young Lim, "Correlation between Brick-and-mortar Material Properties and Brick Masonry Prism Compressive Strength and Elastic Modulus," *Journal of Building Engineering*, vol. 111, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[21] Deepa A. Joshi, and R. K. Jain, "Evaluation of Compressive Strength and Basic Compressive Stress of Clay Brick Unreinforced Masonry by Prism Test," *International Journal of Science and Research (IJSR)*, vol. 4, no. 5, pp. 913-916, 2015. [Google Scholar] [Publisher Link]

[22] Fei Zhu et al., "Compressive behavior of Fully Grouted Concrete Bond Beam Block Masonry Prisms," *Materials*, vol. 18, no. 11, pp. 1-16, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[23] C. Freeda Christy, D. Tensing, and R. Mercy Shanthi, "Experimental Study on Axial Compressive Strength and Elastic Modulus of the Clay and Fly Ash Brick Masonry," *Journal of Civil Engineering and Construction Technology*, vol. 4, no. 4, pp. 134-141, 2013. [Google Scholar] [Publisher Link]

[24] Julio Garzón-Roca, Creu Obrer Marco, and Jose M. Adam, "Compressive Strength of Masonry made of Clay Bricks and Cement Mortar: Estimation based on Neural Networks and Fuzzy Logic," *Engineering Structures*, vol. 48, pp. 21-27, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[25] Ronald Lumantarna, David T. Biggs, and Jason M. Ingham, "Uniaxial Compressive Strength and Stiffness of Field-Extracted and Laboratory-Constructed Masonry Prisms," *Journal of Materials in Civil Engineering*, vol. 26, no. 4, pp. 1-41, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[26] Mehar Babu Ravula, and Kolluru V. L. Subramaniam, "Experimental Investigation of Compressive Failure in Masonry Brick Assemblages made with Soft Brick," *Materials and Structures*, vol. 50, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[27] S.B. Singh, and Pankaj Munjal, "Bond Strength and Compressive Stress-Strain Characteristics of Brick Masonry," *Journal of Building Engineering*, vol. 9, pp.10-16, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[28] Nassif Nazeer Thaickavil, and Job Thomas, "Behaviour and Strength Assessment of Masonry Prisms," *Case Studies in Construction Materials*, vol. 8, pp. 23-38, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[29] K. S. Gumaste et al., "Strength and Elasticity of Brick Masonry Prisms and Wallettes under Compression," *Materials and Structures*, vol. 40, pp. 241-253, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[30] Hemant B. Kaushik, Durgesh C. Rai, and Sudhir K. Jain, "Stress-Strain Characteristics of Clay Brick Masonry under Uniaxial Compression," *Journal of Materials in Civil Engineering*, vol. 19, no. 9, pp.728-739, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[31] Gihad Mohamad, Paulo B. Lourenço, and Humberto R. Roman, "Mechanics of Hollow Concrete Block Masonry Prisms under Compression: Review and Prospects," *Cement and Concrete Composites*, vol. 29, no. 3, pp. 181-192, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[32] K. S. Jagadish, S. Raghunath, and K. S. Nanjunda Rao, "Behaviour of Masonry Structures during the Bhuj Earthquake of January 2001," *Journal of Earth System Science*, vol. 112, pp. 431-440, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[33] Jahangir Bakhteri, Ahmad Mahir Makhtar, and Shamala Sambasivam, "Finite Element Modelling of Structural Clay Brick Masonry Subjected to Axial Compression," *Journal of Technology*, vol. 41, pp.57-68, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[34] Mangala Keshava, K.V. Vijayendra, and S. Raghunath, "Strength Efficiency of Commonly used Block Work Masonry," *International Journal of Earth Sciences and Engineering*, vol. 3, no. 4, pp. 586-598, 2010. [Google Scholar]

[35] Md Monjur Hossain, Sk Sekender Ali, and M. Azadur Rahman, “Properties of Masonry Constituents,” *Journal of Civil Engineering*, vol. 25, no. 2, pp.135-155, 1997. [Google Scholar]

[36] Hemant B. Kaushik, Durgesh C. Rai, and Sudhir K. Jain, “Uniaxial Compressive Stress–strain Model for Clay Brick Masonry,” *Current Science*, vol. 92, no. 4, pp. 497-501, 2007. [Google Scholar] [Publisher Link]

[37] Navaratnarajah Sathiparan, and Pratheeba Jeyananthan, “Comparative Analysis of Machine Learning Models and Standard Codes for Predicting Compressive Strength in Hollow Block Masonry,” *Journal of Umm Al-Qura University for Engineering and Architecture*, vol. 16, pp. 1806-1838, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[38] Sreedhara B. Marulasiddappa et al., “Strength Assessment of Structural Masonry Walls: Analysis based on Machine Learning Approaches,” *HBRC Journal*, vol. 20, no. 1, pp. 505-524, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[39] Lanh Si Ho, and Quan Tran, “Evaluation and Estimation of Compressive Strength of Concrete Masonry Prism using Gradient Boosting Algorithm,” *Plos one*, vol. 19, no. 3, pp. 1-23, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[40] Abdulelah Al-Ahdal, Belal AbdelRahman, and Khaled Galal, “Compressive, Shear, and Tensile Behaviours of Concrete Masonry: Experimental and Numerical Study,” *Construction and Building Materials*, vol. 458, pp. 1-23, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[41] Md Mohsin M. Dafedar et al., “Evaluation of the Engineering Properties and Sustainability of Solid Masonry Blocks Produced with Recycled Concrete Aggregates,” *Innovative Infrastructure Solutions*, vol. 9, no. 11, pp. 1-19, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[42] Mohamed Y. Zorainy et al., “Stress-Strain Behavior of Masonry Boundary Element Prisms under Axial Compression,” *Structures*, vol. 80, pp. 1-15, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[43] Priyanka Singh et al., “Development of Performance-based Models for Green Concrete using Multiple Linear Regression and Artificial Neural Network,” *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 18, no. 5, pp. 2945-2956, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[44] IS: 383, *Specification for Coarse and Fine Aggregates from Natural Sources for Concrete*, Bureau of Indian Standards, pp. 1-24, 1970. [Google Scholar] [Publisher Link]

[45] IS: 1905, *Code of Practice for Structural use of Unreinforced Masonry*, Bureau of Indian Standards, pp. 1-30, 1987. [Publisher Link]

[46] IS: 2185-1, *Concrete Masonry Units, Part 1: Hollow and Solid Concrete Blocks*, Bureau of Indian Standards, pp. 1-17, 2005. [Publisher Link]

[47] IS: 2250, *Code of Practice for Preparation and use of Masonry Mortars*, Bureau of Indian Standards, pp. 1-36, 1981. [Google Scholar] [Publisher Link]

[48] IS: 4031 (Part 6), *Methods of Physical Tests for Hydraulic Cement Part 6: Determination of Compressive Strength of Hydraulic Masonry Cement*, (First revision), Bureau of Indian Standards, 1988. [Publisher Link]

[49] IS: 5512, “*Specification for Flow Table for use in Tests of Hydraulic Cements and Pozzolanic Materials*,” Bureau of Indian Standards, pp. 1-17, 1983. [Google Scholar] [Publisher Link]