Reliability-Based Assessment of an Existing RC Building

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Abstract

One method of ensuring the sustainability of historic buildings and engendering innovation is adapting existing structures to a different form or function. However, this requires utmost consideration for the safety and reliability of such structures. This study examined the structural reliability of the beams, slabs, and columns of an existing reinforced concrete building to evaluate its suitability for use after being abandoned for some time. Nondestructive tests were carried out on selected slabs, beams, and columns of the building under evaluation after calibrating a Schmidt Rebound hammer. Limit state equations were developed in accordance with the provisions of BS 8110 (1990) for the assessment of the beam, slabs, and columns. The failure probability and reliability indices for each of the examined structural members were determined with Cal-Reliability (CALREL) software using the First Order Reliability Method (FORM). All the beams assessed showed satisfactory reliability levels. However, one of the slab panels examined showed reliability levels below the target reliability index and a very high probability of failure if the loading is less than half the design load. The examined columns also showed high levels of probability of failure, with their reliability indices well below the target reliability index. It is advised that necessary retrofitting strategies should be adopted to strengthen the columns before adapting the structure for the planned use.

Keywords: Structural reliability, FORM, Non-destructive testing, Limit State, CALREL

1. Introduction

The fundamental concept of design requires that structures meet the safety and serviceability criteria for their projected purpose during their lifespan. Nevertheless, in actuality, every structure is likely to fail, regardless of the safety measures and factors taken into account or applied during its design and construction. Furthermore, the structural integrity and rigidity of several civil infrastructure facilities gradually decline over time due to their prolonged exposure to harsh operational or climatic conditions during their lifespan (Wang *et al.*, 2017). Several structural failures have been documented due to environmental factors and unforeseen incidents, leading to severe damage and financial losses for the facility owners. Chendo and Obi (2015) observed that many building collapses are a result of human errors such as faulty design, poor construction, and the use of low-quality construction materials. Other causes include carelessness, errors, inexperience, quackery, graft, subversion, and natural events like floods, earthquakes, and strong winds. Hence, assessment of a building's structural condition is critical in mitigating this rising problem. While safety is of the essence, one important way of implementing sustainability in construction is through the innovative transformation of existing buildings to suit a new purpose. However, having been constructed over a long period, the safety levels in the many old buildings change with time, and thus, failing to account for such changes may be disastrous when adapting the buildings for a different use. Moreover, the adaptive use of existing buildings (Ajgwi *et al.*, 2023) necessitates assessing the structure's adaptability for an alternative purpose. All these considerations have contributed to the need to assess the structural conditions of existing buildings to ascertain their ability to continue to maintain their functionality.

Evaluating the structural condition of a building can be done using fully destructive, partially destructive, or nondestructive approaches. Nondestructive testing (NDT) technologies have considerably contributed to the evaluation of structures over time. Multiple research initiatives have been undertaken to enhance the evaluation of current structures with this approach. Diaferio and Vitti (2021) investigated reinforced concrete (RC) buildings in Bari (Italy) using both nondestructive (ultrasonic pulse velocity) and destructive (drilled core) tests. The structural safety of an Italian school building was evaluated by Minutolo *et al*. (2019), who applied SonReb, UPV and coredrill methods to assess the strength of structural members in a school building. Rebound hammer and chemical tests were utilised by Jedidi *et al*. (2017) in the diagnosis of an RC building in Tunisia, and a jacketing method was proposed for the repair of the defective columns. In spite of these records, there have been drawbacks to using only nondestructive methods for evaluating structures. This is because NDT techniques may not always provide a comprehensive assessment of the structure's long-term durability and future performance (Tworzewski *et al*., 2021).

However, by employing structural reliability analysis, it is possible to not only assess the conditional structural integrity and serviceability but also to provide quantitative predictions about a structure's capacity to withstand future events (Wang *et al*., 2017). Structural reliability analysis thus enables the prediction of future development, preservation, and maintenance of infrastructure while minimising possible risks and ensuring safety, sustainability, and innovation in construction.
This study, therefore, sought to evaluate the reliability of an existing RC structure that was proposed for use after being abandoned for a period of time.

2. Literature Review

Reliability refers to the likelihood that a system will successfully carry out its intended function within a defined timeframe and under specific service conditions (El-Reedy, 2013). A building can effectively perform its intended function without experiencing any degradation or loss of functionality within a specific period. Structural uncertainty typically comes from changes in loading and material qualities, proportions, natural and man-made risks, inadequate technical know-how, and human mistakes in the construction and design processes (Ellingwood, 1996). These uncertainties create a legitimate suspicion over the structure's capacity to withstand the anticipated loads, rendering it vulnerable to failure. Structural reliability, therefore, seeks to estimate the probability of failure as a quantitative measure of structural safety. It is important to understand that when we refer to the failure of a structure, it does not necessarily mean a catastrophic breakdown. Instead, the structure does not function as intended (Skrzypczak *et al*., 2017). Reliability-based methodologies combine data on design specifications, material and structural deterioration, accumulation of damage, environmental factors, and nondestructive testing (NDT) approaches to create a decision tool that offers a numerical assessment of structural reliability in anticipated future service conditions (Ellingwood & Mori, 1993; Hackl & Kohler, 2016). Generally, the benefit of nondestructive testing (NDT) is that it allows for evaluating a structure without causing any harm to it. Furthermore, their utilisation is rapid and uncomplicated, and the examination outcomes are accessible on location. NDT procedures rely on physical or chemical principles that can be observed or measured without causing noticeable changes to the appearance or functionality of the analysed structures. The speed, cost-effectiveness, and non-invasive type of assessment that this approach provides make them a preferred option during structural integrity assessments, compared to the traditional destructive approaches (Almasaeid *et al*., 2022).

However, these NDT techniques have some limitations and yield uncertain results. Some of these uncertainties may arise due to the anisotropy and heterogeneity of tested materials, roughness on the surfaces where the test is applied, small test conduction area, equipment inclination, test direction, and human errors. NDT methods do not consider other uncertainties during the building process, such as unpredictability of loads, calculation errors, use of inadequate materials, construction method, overloading, misuse, and others.

This is where structural reliability techniques offer more unique advantages. Structural reliability, being a probabilistic approach, takes account of uncertainties associated with strength, load evaluation, uncertainties of some design parameters, and human errors (Skrzypczak *et al*., 2017). Thus, it enables the development of a better service life prediction model. Some reliability techniques have been used in evaluating structural reliability, such as the First-Order Reliability Method (FORM), the Second-Order Reliability Method (SORM), Monte Carlo simulation, and Importance Sampling. Several researchers have studied the structural reliability of existing buildings using different approaches. Ibrahim and Rad (2023) employed Monte Carlo simulation to predict the deflections and probability of failure in RC haunched beams, considering serviceability criteria. The research demonstrates the relevance of probabilistic numerical computation in structural appraisals. Wang *et al.* (2021) utilised spatial correlation in their evaluation of chloride-induced corrosion in reinforced concrete structures to predict the probability of failure. Their study emphasised the significance of spatial effects in accurately assessing the reliability of such systems. Mankar *et al.*

(2020) performed a fatigue reliability analysis on the Crêt de l'Anneau viaduct, demonstrating the need to consider fatigue when evaluating reinforced concrete structures. Drukis *et al.* (2017) performed a case study on the structural reliability of existing buildings using lightweight roofs in Liepaja and Riga. The study revealed that the safety levels of elements vary between Latvia's regions due to the relative change in climatic snow maps. A probabilistic risk assessment was carried out on the concrete component of an existing building by Sule *et al*. (2015). The study used a beta model for risk assessment, using concrete strength as the primary variable. It was observed that the structure was potentially unsafe and thus recommended for careful demolition. The present study sought to evaluate the reliability of a standing reinforced concrete structure proposed for a different use.

3. Research Methodology

This research adopted the First Order Reliability Method (FORM) to estimate the reliability indices. This is because of its simplicity and straightforward approach to reliability analysis. It is very computationally efficient and makes quick calculations of reliability indices possible (Chowdhury, 2023). It is an approximate method in which the limit state function (failure function) is linearised, and the failure domain to the half-space is defined by means of the hyperplane, which is tangent to the limit state surface at the design point (Kassem, 2015).

In general, structural reliability is defined by the relationship existing between strength and load parameters as follows (Afolayan & Opeyemi, 2008):

$$M = R - L = g\,(X_1, X_2, \ldots, X_n) \tag{1}$$

where M represents the limit state function, also known as the safety margin or performance function, R represents the resistance, L represents the load, X = X_1, X_2, …, X_n. Represent n basic random variables, and g(X) represents a function of all design variables. Generally, the function g(X) takes different forms depending on the structure in consideration, provided that the structure’s failure is defined when M ≤ 0 and the structure’s safety is defined when M > 0.

The limit state is a condition where a structure or structural element in some way becomes unfit for its intended purposes (El-Reedy, 2013). The limit state function is, therefore, a representation of the boundary between a structure's desired and undesired performance, which is generally represented by equation (1).

When the limit state function has been established, the probability of failure can be calculated by performing the following integration over the region where M ≤ 0, as given in equation (2);

$$P_f = \iint \int f_x\, (X_1, X_2, \ldots, X_n)\; dx_1, dx_2, \ldots, dx_n \qquad (2)$$

where fx is the joint probability density function for the random variables X1, X2, …, Xn, as Afolayan and Opeyemi (2008) reported.

Reliability requirements for both new and existing structures can be defined in terms of the reliability index, β, given in equation (3):

$$\beta = -\Phi^{-1}(P_f) \qquad (3)$$

where Φ-1 is the standard normal probability distribution function,

Pf is the failure probability corresponding to a specified reference period.

When the reliability indices for an existing structure have been determined, they are compared with a specified target reliability index, βT, which is determined based on two parameters: consequences of failure and incremental cost of safety. ISO 13822 (2010) proposed that for a model structure, the target reliability β ≈ 3.8 might be assumed, the related reference period being “a minimum standard period for safety (e.g. 50 years)”.

For this study, nondestructive tests were carried out using a calibrated Schmidt Rebound hammer on randomly selected beams, columns, and slabs in a structure (shown in Figure 1) to evaluate their in-situ strength. The section and dimensional properties of the structural members examined were also recorded and used in the reliability analysis

Figure 1: The building under evaluation

Limit state equations were then formulated for the beams, slabs and columns, represented by equations (4) - (6), respectively, in accordance with the provisions of BS 8110 (1999).

For doubly-reinforced beams:

$$G = 0.156f_{cu}bd^2 + 0.95f_yA_s'(d - d') - q_kl^2(0.175\alpha + 0.2) \quad (4)$$

For two-way slabs:

$$G = 0.156f_{cu}bd^2 - 0.105(1.4\alpha + 1.6)q_kl_x{}^2 \quad (5)$$

For columns:

$$G = 0.35f_{cu}bh + 0.67\rho bdf_y - N\alpha$$

where *α* is the load ratio given by: $\alpha = \frac{g_k}{q_k}$ (6)

FCU is the characteristic strength of concrete

fy is the characteristic strength of steel
b is the width of the beam/column
d is the effective depth of the beam/slab
qk is the characteristic imposed load
l is the effective length of the beam/slab

As' is the area of steel in compression and is given by $A_s = \rho bd'$

ρ is the reinforcement ratio, where 0.2% ≤ ρ ≤ 4% (for beams and columns) and 0.13% ≤ ρ ≤ 4% (for slabs)
d′ is the effective depth of the compression reinforcement and is given by d′ = h – d
N represents the axial load

Using these limit state equations, structural reliability analysis was performed using Cal-Reliability (CalREL), a general-purpose structural reliability software. After that, the reliability levels for the structural members' slabs, beams, and columns at both the design stage and the current as-built state were compared with the target reliability indices. The target reliability index (β_T) level for all slabs was selected as 2.5, for all beams as 3.5, and all columns as 4.0, based on recommendations according to ACI 318-99 (1999) and Szerszen and Nowak (2003). Table 1 presents the general statistical data used to conduct the reliability analysis of the structural elements.

Table 1: General Statistical Data for the reliability analysis of the structural members

Variable	**Mean**	**Distribution**	**Assumed Coefficient of Variation (%)**
Characteristic Strength of Concrete, f_{cu} (N/mm^2)	Varying: 15.34 - 21.3 N/mm^2	Log-Normal	Varying
Characteristic Strength of Steel, f_y (N/mm^2)	385 N/mm2	Log-Normal	30
Length, *L* (mm)	Varying	Normal	10
Width, *b* (mm)	Varying	Normal	10
Depth or thickness, *h, d, or d'* (mm)	Varying: Slabs: 150mm Beams: 450 - 600mm Columns: 230 - 500mm	Normal	10
Live load, q_k (kN/m^2)	1.5, 3.0	Log-Normal	30
Load ratio, α	0.5 ≤ α ≤ 3.0	Normal	10
Reinforcement ratio, ρ	0.2 ≤ ρ ≤ 4.0	Normal	10
Column axial load, N, kN	500	Log-Normal	30

4. Findings

Reliability levels for the slabs, beams and columns are presented in Figures 2 - 4.

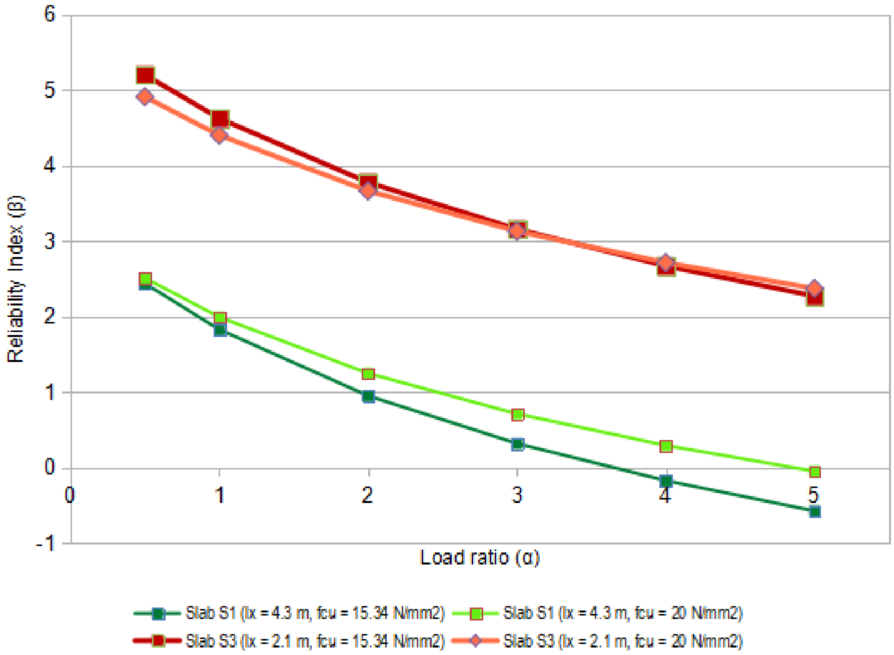

Figure 2: Comparison of the reliability levels for existing and designed slabs

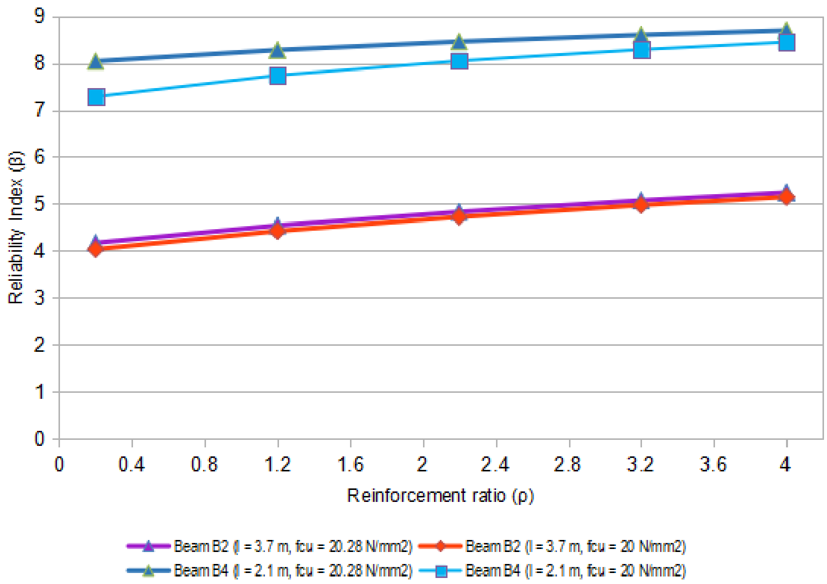

Figure 3: Comparison of the reliability levels for selected existing and designed assumed doubly reinforced beams (α = 1.0)

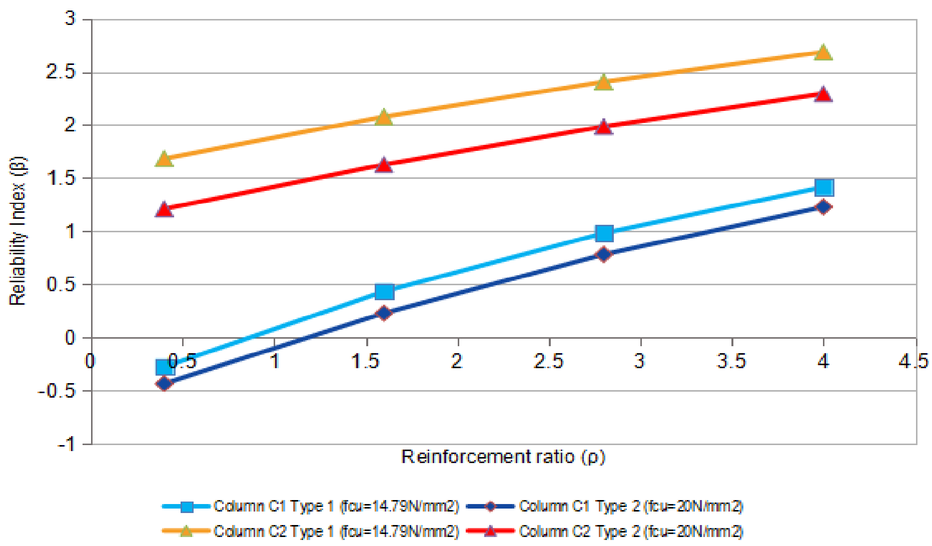

Figure 4: Comparison of implied and expected reliability indices for columns (α = 1.0)

5. Discussion

The results of the reliability estimates for the elements (as shown in Figure 2) show that, generally, as the load ratio increased, the reliability indices decreased. This similar trend was observed by Ozovehe *et al.* (2022). The reliability indices observed from the NDT-measured compressive strength (15.34 N/mm2) were lower than those obtained from the expected design compressive strength (20 N/mm2). It was also observed that only Slab S3 met the target slab reliability index of 2.5 beyond a load ratio of 0.5. This suggests that the Slab S1 shows a considerable level of probability of failure beyond half of its designed load and very high failure probability levels, especially beyond a load ratio of 4.0. This implies that attention needs to be paid to the permissible loading on the slab during its working condition. It is proposed that the slab should not be loaded beyond half its designed load. The average compressive strength of the beams based on the Rebound hammer test results was 20.28 N/mm2. Compared with the expected compressive strength of 20 N/mm2, the beam reliability estimates show that the assessed beams had reliability indices well above the target reliability index of 3.5 at a load ratio 1.0, indicating satisfactory performance. This suggests that the beams were designed and constructed to standard. However, when subjected to higher load ratios beyond 1.0, beam B2 might show considerable failure probability levels. The reliability estimates of the columns show an increasing trend with reinforcement ratio. However, it is seen that at a load ratio of 1.0 (assumed to be

500 kN), the reliability levels of the columns were below the column target reliability index of 4.0. This suggests that the columns show a high probability of failure, and based on the reliability estimates, the columns should not be subjected to loading beyond 250 kN (i.e. load ratio of 0.5).

6. Conclusion and Further Research

This study has assessed the structural reliability of the beams, slabs and columns of an existing reinforced concrete building to see if it is suitable for use after a period of abandonment. After calibrating a Schmidt Rebound hammer, nondestructive tests were conducted on certain building slabs, beams and columns being evaluated. The limit state equations were formulated in compliance with BS 8110 (1990) specifications to evaluate the structural reliability of beams, slabs, and columns. The failure probabilities and reliability indices for each analysed structural element were calculated with Cal-Reliability (CalREL) software using the First Order Reliability Method (FORM). The following conclusions were drawn based on the results obtained:

- The slabs showed a general decreasing trend in reliability levels with increasing load ratios. Slab S3 showed satisfactory performance beyond a load ratio of 0.5, while Slab S1 showed a high probability of failure, especially beyond a load ratio of 4.0.
- It was observed that the reliability indices increased with increasing reinforcement ratios for the beams. All the beams assessed performed satisfactorily at a load ratio of 1.0, with all the reliability indices well above the target beam reliability index.
- The column reliability indices fell below the target column reliability index. Column C2 Type 1 particularly shows a high probability of failure beyond a load ratio of 0.5. It is recommended that essential retrofitting measures be implemented to reinforce the columns prior to modifying the structure for use.

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