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Reliability-based Appraisal of Existing Reinforced Concrete Building

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Abstract: The challenges of incessant rate of building collapse, due to environmental effects calls for structural integrity assessment of existing reinforced concrete building. Therefore, this study presents the structural reliability assessment of an existing reinforced concrete building. The building was assessed by performing Rebound hammer tests on randomly selected beams, which was calibrated using calibrated by mean of freshly prepared concrete cubes. A fundamental limit state equations based on the ultimate limit state design requirements of BS 8110 (1999) for beam has been developed for the reliability estimation based on First Order Reliability Method (FORM). The mean and standard deviation of the compressive strengths of beams were obtained and used in estimating the probabilities of failure of the elements. Afterwards, the implied reliability levels of the beams were compared with those obtained using standard compressive strength of 20 N/mm^2. Considering the simulated loading, reinforcement conditions and target reliability indices adopted in this study, it was observed that some beams have very low reliability levels compared to others.

Keywords: Existing building, beams, reliability index, probability of failure, non-destructive testing, load ratio, reinforcement conditions.

1. Introduction

Several existing buildings have been built with reference to the safety requirements of the period in which they were built. Hence, depending on the time of their construction, these buildings have different safety levels. As a result of this, to continue using these buildings for the same functions without considering the effects of degradation that has occurred may be problematic, in some extreme cases catastrophic. If the condition of existing buildings will not be improved in accordance with contemporary requirements and safety level, there may be a rise in the occurrence of accidents (Drukis et al. 2017). Furthermore, adaptive reuse of existing structures has become very important in the preservation of heritage structures. This involves changing the previous function of an existing structure to a different one. It is therefore, often important to test an existing concrete structure in order to determine whether it is suitable for its current or future use.

It has also become very important to consider the effects of climate change on the condition of existing buildings, as well the need for improvement of energy efficiency of buildings. The challenges that these needs pose to the present condition of existing buildings, thus, necessitate adequate structural assessment of existing buildings (Ma et al. 2012).

Structural assessment can be conducted by completely non-destructive methods, partially destructive or utterly destructive methods. Non-destructive testing methods over the years have played a major role in structural assessment. Several research efforts have been made towards the improvement of the assessment of existing structures using this approach. Actually, non-destructive testing may be applied to both new and existing structures. With respect to new structures the principal application is for quality control, whereas for existing structures non-destructive testing is carried out to assess structural integrity. Wang et al. (2017) asserted that reliability analysis is an important tool frequently used in evaluating and managing structural safety and serviceability, with the aim of providing quantitative information that a structure can withstand future extreme events with an acceptance level of reliability during its future service life.

There will always be need for structural reliability analysis. According to Fabera and Stewart (2003), focus on risks are not likely to decrease in the future. The future development and the preservation and maintenance of the civil structures in the society will likely demand an intensified focus on risk. It is therefore, imperative to engage in development of the methods of structural reliability assessment of existing buildings.

The incessant rate of building collapse in Nigeria today presents a major need for adequate research and review of the causes with a view to proffering a viable solution to the problem. Several existing buildings are either substandard in construction and material specifications, or subjected to higher load carrying capacities than they were originally designed for. Besides, the environmental conditions of several buildings today pose undeniable threat to the occupants. In addition, the need for modification and adaptive reuse of existing structures is gradually being substantially with the current economic situation being experienced in the country. The need for structural reliability assessment of existing buildings is hence substantiated by these stated reasons.

The current building codes in the country (BS 8110: Parts 1, 2 and 3), however, have not made adequate provisions for the assessment of existing structures. This is why this study is essential, with a view to providing a basis for examination and assessment of existing structures using non-destructive techniques. Holicky et al. (2014) also emphasized the importance of introducing more detailed information concerning procedures for the specification of design values of basic variables, the load-bearing capacity of existing structures and determination of reliability level with respect to the consequences of failures (categorization of structures) and remaining working life of structures.

The use of Rebound hammer method, a non-destructive test of concrete, offers a cost-effective, easy and reliable solution for the structural assessment of existing structures. This proffers a means of ascertaining reliability of the structures to continue in its functional state or to be adapted for a new function, for the initial or extended period of time, and/or to be remediated or completely demolished, as the case may be. These reasons corroborate the need for this study and are also evident from some previous investigations (Kaura and Afolayan, 2011; Abubakar et al., 2014; Quadri and Afolayan, 2016).

The overall aim of structural reliability analysis is to quantify the reliability of structures under consideration of the uncertainties associated with the resistances and loads. In this paper, First-Order Reliability Form (FORM) (Alabi et al. 2019; Afolayan 2005; Afolayan, and Abdulkareem 2005) based on non-destructive testing using Schmidt Rebound hammer was extended to the assessment of reinforced concrete beam. The positive results in the case study clearly show the practical value of the proposed method and its potential in integrity assessment of beams in service.

2. Experimental setup

The existing institutional office building as shown in Fig. 1, was assessed by performing Rebound hammer tests on structural elements which includes slabs, beams, and columns. A total of at least 12 readings were taken on the beams, with the average rebound number obtained. ASTM C805-02 (2002) specifies at least 10 readings to be taken on each structural element. After the average rebound values were obtained for beams, values differing by more than 6 units from the average were discarded and a new average was obtained. The standard deviation and coefficient of variation of these readings were obtained, and then using the regression equation, a corresponding value of the compressive strength of the beam was obtained. Also, the dimensions and section properties of the tested structural members were obtained for use in the reliability analysis.

Twelve (12) different concrete cubes were prepared according to BS 1881: Part 108 (1983) using mix ratio 1:2:4. These cubes were then cured in portable water for 7, 14, 21 and 28 days. For each of the specified, a total of 18 blows were made on each cube with each face receiving 3 blows and reading indicated on the Schmidt hammer was recorded. Then, each of the cubes was crushed using compressive strength testing machine. The compressive strength of each cube was recorded against the average rebound number. Therefore, a graph of the compressive strength was plotted against rebound number and the suitable regression equation was obtained as in Eq. (1). The aggregates and cement used were tested and the workability of the concrete mix was also determined.

$$f_{cu} = 1.6515\,\mathrm{RN} - 22.985 \qquad (1)$$

where f_{cu} and RN are compressive strength and Rebound number respectively.

Figure 1. Target Existing Institutional Office Building.

3. Theoretical Development

The reliability of structural member can be determined when the probability level exceed certain value in an operational loading case. Consider a structure with ultimate moment capacity, M_c, subjected to maximum moment, $M_{\max}$, if both M_c and $M_{\max}$ are statistically independent normally distributed random variable, then the limit state function or safety margin, G, can be expressed as in Eq. (2)

$$G(\boldsymbol{\theta}) = M_c - M_{\max} < 0 \qquad (2)$$

where $\boldsymbol{\theta} = \theta_1, \theta_2, \ldots \theta_N$ denote N basic random variables and $G(\boldsymbol{\theta})$ denotes a function of all design variables. In general, the function $G(\boldsymbol{\theta})$ can take any form provided that the structure is defined failure, when $G \le 0$ and the survival of the structure is defined when $G > 0$. Thus, the probability of failure P_f can be determined as

$$P_f = P\left\{G(\boldsymbol{\theta}) < 0\right\} = \int_{G(\boldsymbol{\theta})<0} f_{\boldsymbol{\theta}}(\boldsymbol{\theta})\, d\boldsymbol{\theta} \qquad (3)$$

The probability of failure in terms of the reliability index can be written as

$$P_f = \Phi(-\beta) = 1 - \Phi(\beta) \qquad (4)$$

or

$$\beta = -\Phi^{-1}\left(P_f\right) \qquad (5)$$

3.1 Beams

3.1.1 Singly Reinforced Sections

The maximum moment, $M_{\max}$, for a simply supported beam can be expressed in Eq. (6) as

$$M_{\max} = 0.125\omega l^2 \qquad (6)$$

where ω and l are the ultimate load and length of the beam element and;

$$\omega = 1.4 g_k + 1.6 q_k \qquad (7)$$

where g_k and q_k are characteristic dead and characteristic imposed loads hence eq. (6) becomes:

$$M_{\max} = 0.125\left(1.4g_k + 1.6q_k\right)l^2 = \left(0.175g_k + 0.2q_k\right)l^2 \quad (8)$$

Taking the load ratio to be α, which is expressed as $\alpha = g_k/q_k$ and substituting in Eq. (8), $M_{\max}$ becomes

$$M_{\max} = \left(0.175\alpha + 0.2\right)q_k l^2 \quad (9)$$

The ultimate moment capacity, M_c of the beam is given as follows:

$$M_c = 0.156 f_{cu} bd^2 \quad (10)$$

Therefore, the limit state function, G, for a singly reinforced rectangular section can be given by substituting Eqs 9 and 10 into Eq. (2). This is express as a functional relationship between the moment-capacity and ultimate moment capacity.

$$G = 0.156 f_{cu} bd^2 - \left(0.175\alpha + 0.2\right)q_k l^2 \quad (11)$$

where f_{cu}, b, d and l are characteristic strength of concrete, width of the beam, effective depth of the beam, and effective length of the beam.
The probability of failure given in Eq. (3) becomes

$$P_f = P\left(0.156 f_{cu} bd^2 - (0.175\alpha + 0.2)q_k l^2 \le 0\right) \quad (12)$$

The reliability index can be obtained by substituting Eq. (12) into Eq. (5)

$$\beta = -\Phi^{-1}\left[P\left(0.156 f_{cu} bd^2 - (0.175\alpha + 0.2)q_k l^2 \le 0\right)\right] \quad (13)$$

3.1.2 Doubly Reinforced Sections

For a doubly reinforced rectangular section, the limit state function is derived in Eq. (14) as

$$G = 0.156 f_{cu} bd^2 + 0.95 f_y A_s^{'}\left(d - d^{'}\right) - \left(0.175\alpha + 0.2\right)q_k l^2 \quad (13)$$

The reliability index is obtained as in Eq. (14)

$$\beta = -\Phi^{-1}\left[P\left(0.156 f_{cu} bd^2 + 0.95 f_y A_s^{'}\left(d - d^{'}\right) - (0.175\alpha + 0.2)q_k l^2\right)\right] \quad (14)$$

where $A_s^{'}$, ρ, and $d^{'}$ are area of steel in compression and is given as $A_S = \rho bd$; reinforcement ratio, given as $0.2\% \le \rho \le 4\%$; and effective depth of the compression reinforcement, and is given as $d^{'} = h - d$.

3.2 Reliability Estimates

The reliability models considered contains a specified set of basic variables. The variables represent the physical quantities characterizing actions and environmental influences, and material properties, imperfections and geometrical quantities. For each variable, the uncertainties are considered very important, therefore, they are represented as a random variable, which are described by probability distribution. In terms of assessment and design of the existing reinforced concrete beams based on BS 8110: Part 1, the compressive strength of the concrete, reinforcement bars, dimensions, as well as the action forces (i.e., live loads) are primary basic variables. Table 1 shows the assumed general statistical data for the analysis of the structural elements, which are adopted based on previous studies and engineering judgment. Considering that the building examined is singly storey buildings, the expected imposed loads on the slabs were fixed at 3.0 kN/m^2 for building which is serving institutional purpose.
Target reliability index (β_T) level for all beams as 3.5 based on recommendation according to ACI 318-99 (1999) and Szerszen and Nowak (2003).

Table 1. Statistical model for the analysis of the structural elements.

Variable	Distribution	Mean Value	Standard Deviation
Characteristic strength of concrete, f_{cu} (N/mm^2)	Lognormal	Varying	Varying
Characteristic strength of steel, f_y (N/mm^2)	Lognormal	385	115.5
Length, L (mm)	Normal	Varying	Varying
Width, b (mm)	Normal	Varying	Varying
Depth or Thickness, h (mm)	Normal	Varying	Varying
Effective Depth, d or d' (mm)	Normal	Varying	Varying
Live load q_k (kN/m^2)	Lognormal	1.5, 3.0	0.45, 0.9
Load ratio, α	Normal	$0.5 \le \alpha \le 3.0$	$0.05 \le \alpha \le 0.3$
Reinforcement ratio, ρ	Normal	$0.2 \le \alpha \le 4.0$	$0.02 \le \alpha \le 0.4$

4. Results and Discussions

Fig. 2 and 3 shows the effect of change in load action on the reliability levels of the existing singly reinforced beams using measured and designed strength. For a singly reinforced beams, a decrease in reliability index was observed as the load ratios increased from 0.5 to 5.0. This could be attributed to the fact that the carrying capacity of the beams were exceeded therefore, leading to the possibility of failure. A maximum of load ratio of 5.0 was adequately sustained by B2, B4, B7 and B8 with in-situ strength of 26.42 N/mm^2, and B2, B4, and B8 with designed strength of 20 N/mm^2. Again, the decrease in safety index, β as the load ratio increased. This trend could be attributed to the fact that dead load, g_k, increases with increase in unit weight, therefore, increase in g_k, will definitely reduce the safety of the beams. It is observed that the effect of unit weight on the reliabiility index was very insigificant excpet for B2, B4, B7 and B8 with in-situ strength of 26.42 N/mm^2, and B2, B4, and B8 with designed strength of 20 N/mm^2.

Also, Figs. 4 to 11 shows the effect of change in load action on expected reliability levels for assumed designed doubly reinforcement beams The estimated reliability levels for the beams decrease with increase in load ratio, but increase with reinforcement ratio as seen in Figs. However, only Beams B2, B4, B6, B7, B8 and B9 would be able to perform efficiently at maximum load ratio and minimum reinforcement ratio. The results show that beams B3 and B1 will no longer be efficient beyond a load ratio of 3.0 and 2.0 respectively. Beams B5 and B9 have the least reliability indices and therefore they will need to maximally reinforced for adequate performance beyond a load ratio of 2.0. the reason for the higher reliability indices for Beams B2, B4, B6, B7, B8 and B9 can be attributed to their shorter spans (between 2.1 m and 3.92 m) and higher depth of the sections.

A general consistent increase in reliability index, β was observed as the reinforcement ratio, ρ and load ratio, α increased from 0.2 to 4 and 0.5 to 3.0 at in-situ and designed strength of 26.42 N/mm^2 and 20 N/mm^2, respectively, for doubly reinforeced beams. However, this could be attributed to the increase in moment capacity, M_c, which increased the rigidity and ability to sustained more loads. Under the in-situ strength of 26.42 N/mm^2 and load ratio (i.e. 0.2 to 4), the following beams were safe at a minimum reinforecement ratio of 1.0.

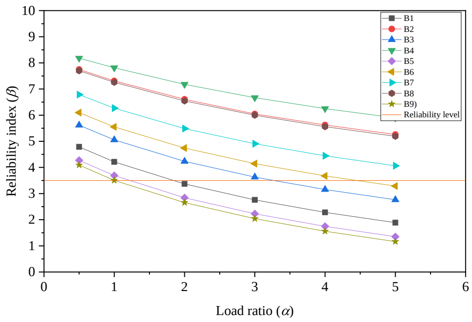

Figure 2. Effect of change in load action on the calculated reliability levels of the existing assumed singly reinforced beams using measured strength (f_{cu} = 26.42 N/mm^2).

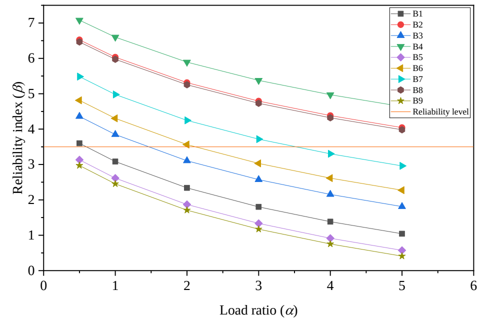

Figure 3. Effect of change in load action on expected reliability indices for designed singly reinforced beams (f_{cu} = 20 N/mm^2).

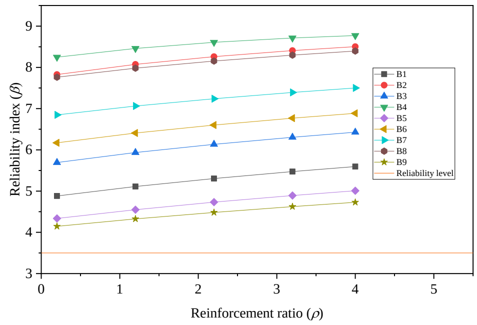

Figure 4. Effect of load action variation on implied reliability levels of the existing assumed doubly reinforcement beams (f_{cu} = 26.42 N/mm^2, α = 0.5)

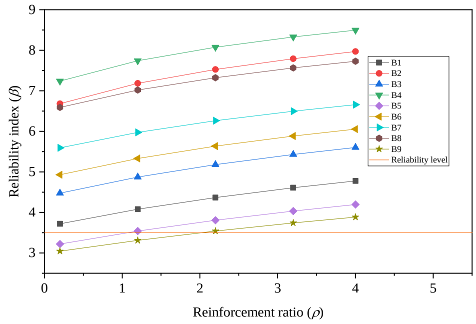

Figure 5. Effect of load action variation on expected reliability levels for assumed designed doubly reinforcement beams (f_{cu} = 20 N/mm^2, α = 0.5)

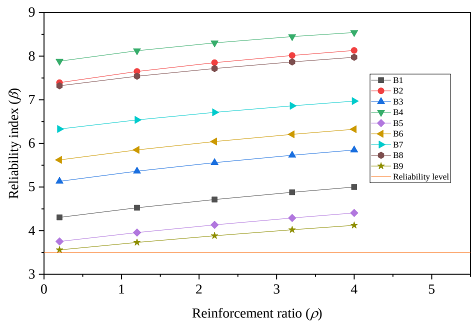

Figure 6. Effect of load action variation on implied reliability levels of the existing assumed doubly reinforcement beams (f_{cu} = 26.42 N/mm^2, α = 1.0)

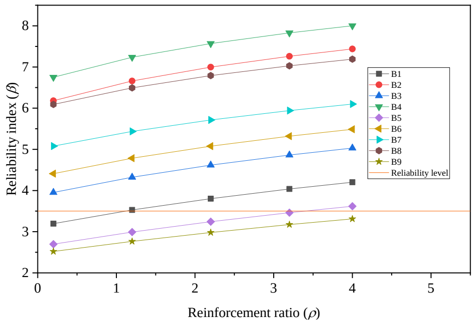

Figure 7. Effect of load action variation on expected reliability levels for assumed designed doubly reinforcement beams (f_{cu} = 20 N/mm^2, α = 1.0)

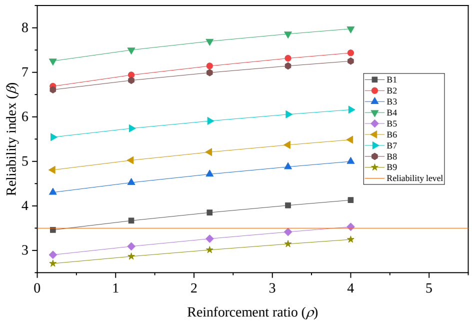

Figure 8. Effect of load action variation on implied reliability levels of the existing assumed doubly reinforcement beams (f_{cu} = 26.42 N/mm^2, α = 2.0)

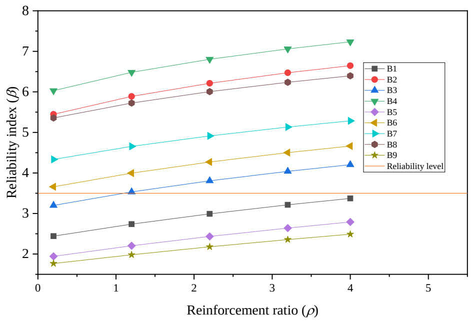

Figure 9. Effect of load action variation on expected reliability levels for assumed designed doubly reinforcement beams (f_{cu} = 20 N/mm^2, α = 2.0)

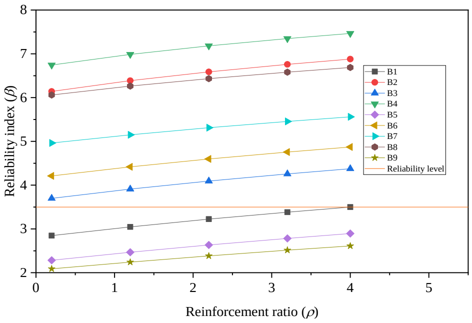

Figure 10. Effect of load action variation on implied reliability levels of the existing assumed doubly reinforcement beams (f_{cu} = 26.42 N/mm^2, α = 3.0)

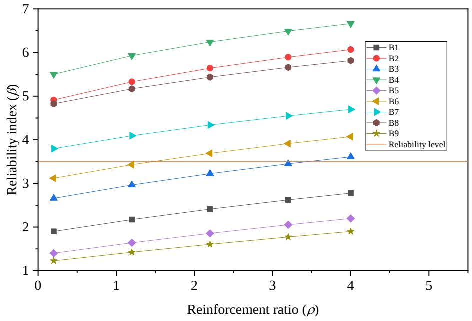

Figure 11. Effect of load action variation on expected reliability levels for assumed designed doubly reinforcement beams (f_{cu} = 20 N/mm^2, α = 3.0)

5. Concluding Remarks

The study has developed a method of assessing the structural reliability of existing buildings using a non-destructive approach. The research has shown that continous monitoring of structural relaibility of exisitng buildings is essential in confronting the health of existing structures and this serves as preventive measures against sudden structural collapse/failure.

Considering the simulated loading and reinforcement conditions adopted in this study, the following can be concluded from the results of the reliability analysis: Specifically Beams B1, B5, and B9 have every low relaibility indeices compared with others.

Based on the findings from this study, the following recommendations are made: Further assessment should be conducted on beams B1, B5 and B9 to examine the current condition of reinforcement in the beams in order to ensure that they are highly reinforced and if necessary the depth of the secions should be increased.

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