ABUAD Journal of Engineering Research and Development (AJERD)
ISSN (online): 2645-2685; ISSN (print): 2756-6811

Volume 7, Issue 2, 163-171

Reliability-based Assessment of the Structural Integrity of some Existing Reinforced Concrete Columns

Samuel Lambe AKINGBONMIRE, Joseph Olaseinde AFOLAYAN

Department of Civil Engineering, Federal University of Technology, Akure, Nigeria
sakingbonmire@futa.edu.ng/joafolayan@futa.edu.ng

Corresponding Author: *sakingbonmire@futa.edu.ng*, *+2348030898039*

Date Submitted: *29/04/2024*
Date Accepted: *09/08/2024*
Date Published: *14/08/2024*

Abstract: *Abnormal loading can initiate the progressive collapse of a reinforced concrete building. A progressive collapse may start as a local failure, followed by a sequence of reactions leading to a massive portion failure of an entire structure. Reinforced concrete columns are significant structural elements in ascertaining the integrity of framed buildings. This paper presents the report on the structural integrity of reinforced concrete columns of two selected university buildings labelled A and B investigated by using non-destructive testing techniques. First-Order Reliability Method (FORM) was deployed to process the data from the field in order to generate the implied safety indices for all accessed columns in the two buildings. The computed safety indices decrease as the simulated designed practical axial loads/moments increase for all the assumed steel ratios (0.4%, 1.59% and 6%) based on BS 8110:1997:1. When compared with the target safety level of 3.8 according to BS EN 1990:2002+A1:2005 for 50 years reference period of Class RC2 structural members in the ultimate limit state, almost all the columns passed the reliability test except the columns labelled 71 in building A; and C81A and C85 for building B. The highlighted critical columns show the direction for immediate repairs to forestall the initiation of eventual progressive failure of the buildings.*

Keywords: *Target Reliability, Structural Integrity, Cal-REL, Safety Indices, Reinforcement Ratio.*

1. INTRODUCTION

Good engineering design of structures is germane as it averts failure/collapse during construction or in service and so, engineers need to pay more attention during design [1]. The use of limit states (ultimate and serviceability) [2] which accommodates partial factor of safety to produce design values from material strength and the applied load help to fulfil the design objectives. The objectives are that the structure must not collapse, has less repair in case of accidental load(s), shall not cause displeasure on its appearance and shall be fire-resistant for escape [3]. Therefore, structural system must be rigid, solid, and must be connected in such a way that failure will be impossible except intense natural occurrence like earthquake with high magnitude. This implies that structural elements such as columns, beams and slab must be well designed and be able to function well throughout their working lives. The loads from columns, beams and slabs from the superstructure are transferred into the foundation and then into the surrounding soil. Columns, which are one of the structural elements, are compression members that carry all the loads from the slabs and the beams in the structures and transfer them into foundation [4]. The periodic check for the structural integrity of columns should therefore not to be overlooked. This is because the failure of any of the structural components can lead to progressive collapse. Progressive collapse refers to the failure of a main vertical structural element within a building or structure, which can subsequently lead to the failure of adjacent elements. This chain reaction of failures may ultimately result in a partial or complete collapse of the entire structure [5]. The initial failure will be local before spreading into other parts of the structural members and final collapse of the structure. The final failure is usually disproportionate to the initial failure [6]. With columns as structural elements, the modes of failure can be compression and bending failure, torsion and shear failure, creep damage, joint failure of longitudinal reinforcement, etc. [7]; and so, their failures in some critical position(s) in the structure may lead to the total collapse of the structure as witnessed in the 21-storey Ikoyi building collapse (Nigeria) [8]. One of the survivors affirmed that they were working on a particular cracked column (initial failure point) on the first floor when the entire building eventually collapsed, the final failure state is far disproportionate to the initial failure. Therefore, structural health monitoring is very important. However, apart from the non-destructive means of ascertaining the structural integrity of columns, reliability-based prediction provides means of predicting the status of columns in buildings so that their failures are known at a glance and means to rescue the situation can be provided.

2. LITERATURE REVIEW

Errors in construction are sometimes inevitable [9] and the major reason for critical defects is human error [10]. Some design and construction errors are architectural design errors, civil design errors, errors caused by management and staff of the consulting company, errors caused by construction plans, errors caused by construction inspection, errors due to civil construction, errors due to construction materials, errors due to construction machinery and errors due to technical specifications [11]. These errors may lead to collapse of the structure if not promptly attended to. Testing for examples the compressive strength of a column in a structure at different points by any non-destructive equipment will produce different values, hence it is considered as random variables and not deterministic. Therefore, the reliability approach of finding the integrity of any structural element is noteworthy.

The analysis of reinforced concrete columns using reliability-based rating (first-order second moment integration technique) [12] showed that the requirements of BS 8110 [13], when applied to higher reinforcement ratios, appeared to be inconsistent and excessively conservative. The implied safety indices obtained from the analysis ranged from 0.05 to 8.52, with an average value of approximately 4.29 (i.e., $P_f = 5.5 \times 10^{-6}$)

The research on reliability-based interaction curves of reinforced concrete columns [14] using first order reliability method (FORM) (which was based on FORTRAN language) was conducted and interaction curves were plotted for varying safety indices. On the curves, design decisions relating to ratios of dead to live loads, effective to the gross depth of a section and reinforcement could be made. However, the reliability assessment of reinforced concrete columns with a specific section [15] was conducted based on ultimate limit state requirements. Three commonly used columns with a typical cross-section (400 mm × 400 mm) were probabilistically evaluated, considering random variations in loading geometry and material properties. FORM was utilized to estimate the implied probability of failure for different simulated loading and reinforcement scenarios. The results indicated that the assessed cross-section (400 mm × 400 mm) could only sustain up to 40% of the expected ultimate design load before reaching the limit state violation. Moreover, the performance of reinforced concrete columns was found to be more influenced by the applied load rather than the amount of reinforcement used. It was found that most of the columns designed according to BS 8110 [2] have not experienced failure because they were carrying significantly lower loads than their ultimate design capacities. This suggests that the design requirements in BS 8110 might be conservative, providing an additional safety margin for these types of columns.

Furthermore, the reliability analysis of reinforced concrete columns after exposure to high temperature, considering multiple potential failure paths, revealed significant differences in the reliability assessment when the eccentricity (i.e., the displacement of the load from the centre of the column) is relatively large or small. The analysis demonstrated that the reliability assessment method is not consistent between cases where the eccentricity is significant and cases where it is minimal. [16].

Techniques of reliability analysis exist. The common ones are FORM, first order-second moment reliability and Monte Carlo simulations [17] - [18]. In this paper, the authors conducted a reliability assessment of the accessible columns in two University buildings. The assessment was performed using FORM along with a coded algorithm called CalREL. The main goal was to compute the reliability index, which serves as a measure of the probability of violation of the limit states associated with each structural element in the columns.

2.1 Equation of the Limit State

In the context of reliability analysis, the equation of the limit state (denoted as g) represents a mathematical function that involves basic random variables. It is derived by calculating the difference between the resistance (R) of a structural element or system and the applied load (S) that it is subjected to (Equation 1).

$$g = R - S \tag{1}$$

The performance functions for the columns are shown in Equations (2) – (9)
For a small eccentricity permitted by the Code [2] the ultimate load (N_{ult}) is:

$$N_{ult} = 0.4 f_{cu}\, A_c + 0.8 A_{sc}\, f_y \tag{2}$$

where f_{cu} is the characteristics strength of the concrete, f_y is the characteristics strength of the reinforcement, A_c is the net cross sectional area of concrete in a column and A_{sc} is the area of vertical reinforcement.

$$N_{ult} = 0.4 f_{cu}\,(d + 0.5\emptyset + \emptyset_{links} + cover) + 0.8 A_{sc}\, f_y \tag{3}$$

where b is the width of the section, d is the effective depth of the section, $\emptyset$ is the size of the main reinforcement and $\emptyset_{links}$ is the size of the stirrup.
If $\rho = (100 A_{sc})/bh$, where ρ is reinforcement or steel ratio and
$A_{sc} = \frac{\rho bh}{100}$, $N_{ult} = 0.4b(d + 0.5\emptyset + \emptyset_{links} + cover)[f_{cu} + 0.002 f_y \rho]$
The limit state equation is expressed in Equation (4)

$$g = \{0.4b(d + 0.5\emptyset + \emptyset_{links} + cover)\left[f_{cu} + 0.002 f_y \rho\right]\} - \propto N_A \tag{4}$$

where $\propto$ is the percentage of applied axial load.
For vertically cast column, $0.4 \le \rho \le 6$ [4]
The statistical variables and distribution types are as shown in Table 1.

However, for biaxial columns which are subjected to bending in both axes. The equation of the limit state for such column is given as:

$$g_{(x)} = 1 - \propto \left(\frac{M_c}{M_{uz}} - \frac{N_A}{N_{uz}}\right) \tag{5}$$

where M_c is the applied moment and N_A is the applied load

$$M_{uz} = 0.45 f_{cu} bs(0.5h - 0.5s) + f_{sc} A'_s (0.5h - d') - f_{sc} A_s (d - 0.5h) \tag{6}$$

Table 1: Statistics for the relevant designed variables for a short column

Variables	**Distribution Type**	**Mean**	**Standard Deviation**
b (mm)	Normal	225.00	22.50
d (mm)	Normal	175.00	17.50
$\emptyset$ (mm)	Normal	16.00	1.60
$\emptyset_{links}$ (mm)	Normal	10.00	1.00
C (mm)	Normal	34.71	14.63
f_{cu} (N/mm^2)	Log normal	26.69	2.92
f_y (N/mm^2)	Log normal	460.00	138.00
ρ	Log normal	1.59	0.48
N_A (kN)	Log normal	250.00	75.00

$$N_{uz} = 0.45 f_{cu} bh + 0.95 f_y A_s \tag{7}$$

$s = 0.9x$ and $x = 0.615d$, therefore, $s = 0.5535d$, $A'_s = A_s$, $h = d + 0.5\emptyset + \emptyset_{links} + cover(C)$, $d' = h - d$, $f_{sc} = 0.95 f_y$, $\rho = \frac{100 A_{sc}}{bh}$, $A_{sc} = \frac{\rho bh}{100}$,

$$M_{uz} = 0.1245 f_{cu} bd(d + 0.5\emptyset + \emptyset_{links} + C - 0.5535d) + 0.0095 f_y \rho b(d + 0.5\emptyset + \emptyset_{links} + C)(-0.5\emptyset - \emptyset_{links} - C) - 0.0095 f_y \rho b(d + 0.5\emptyset + \emptyset_{links} + C)(0.5d - 0.0255\emptyset - 0.5\emptyset_{links} - 0.5C \tag{8}$$

$$N_{uz} = b(d + 0.5\emptyset + \emptyset_{links} + C)(0.45 f_{cu} + 0.0095 f_y \rho) \tag{9}$$

The statistical variables and distribution types are as shown in Table 2.

Table 2: Statistics for the relevant designed variables for a biaxial column

Variable	**Distribution Type**	**Mean**	**Standard deviation**
M_c(kNm)	Log normal	12.60	3.78
f_{cu} (N/mm^2)	Log normal	26.77	2.93
b (mm)	Normal	225.00	22.50
d (mm)	Normal	175.00	17.50
$\emptyset$ (mm)	Normal	16.00	1.60
$\emptyset_{links}$ (mm)	Normal	10.00	1.00
C (mm)	Normal	34.71	14.63
f_y (N/mm^2)	Log normal	460.00	138.00
ρ	Log normal	0.40	0.12
N_A (kN)	Log normal	100.00	30.00

3. THE LAYOUTS OF THE BUILDINGS FOR ANALYSIS

Figures 1 and 2 show the structural layouts of the two investigated buildings. The applied accidental loadings on the columns were derived using Orion Software while the mean cover to the reinforcements in the columns was obtained from the use of Profoscope (Figure 3).

4. RESULTS AND DISCUSSIONS

The predicted safety levels for the columns for both buildings were compared to the target value of 3.8 for 50 years' reference period adopted from [20].

4.1 Predicted Safety Levels for the Columns at Building A

The plots of estimated reliability indices against varying percentages of axial load are as displayed in Figures 4 - 6. The plots show that the safety indices decrease as the accidental loads/moments increase for all the assumed steel ratios (0.4%, 1.59% and 6%). As shown in Figure 4, for all the reinforcement ratios, the columns 23 and 24 can function effectively as their safety indices are well above the expected target safety indices of 3.8. They can withstand as much as 40% above the ultimate designed loading for all the admissible steel ratio before they fall short of the target safety level. However, the identified columns in Figure 5 will be able to sustain 80% of their ultimate designed load for all the steel ratios. It is worrisome that these columns will not be able to resist any accidental loading beyond the designed value to meet the target safety level. With appropriate enforcement of building safety regulations, the owner of the building can be advised to checkmate overloading of floors to avoid excessive load distribution to these columns. The worst column in the building is column 71 (Figure 6). It is under performing vis-à-vis the expected target safety level. The column could only resist 50% of the designed loading to meet the target safety level. A slight increase in the designed load may be catastrophic to the building, occupants and the environments.

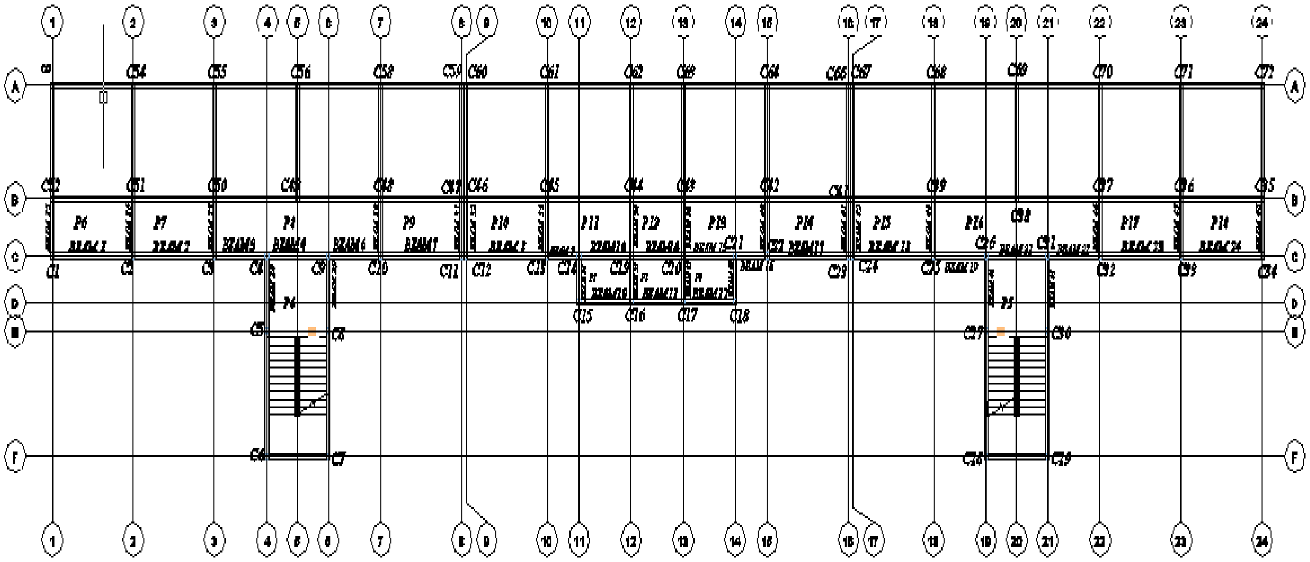

Figure 1: Building A structural layout

Figure 3: Profoscope [19]

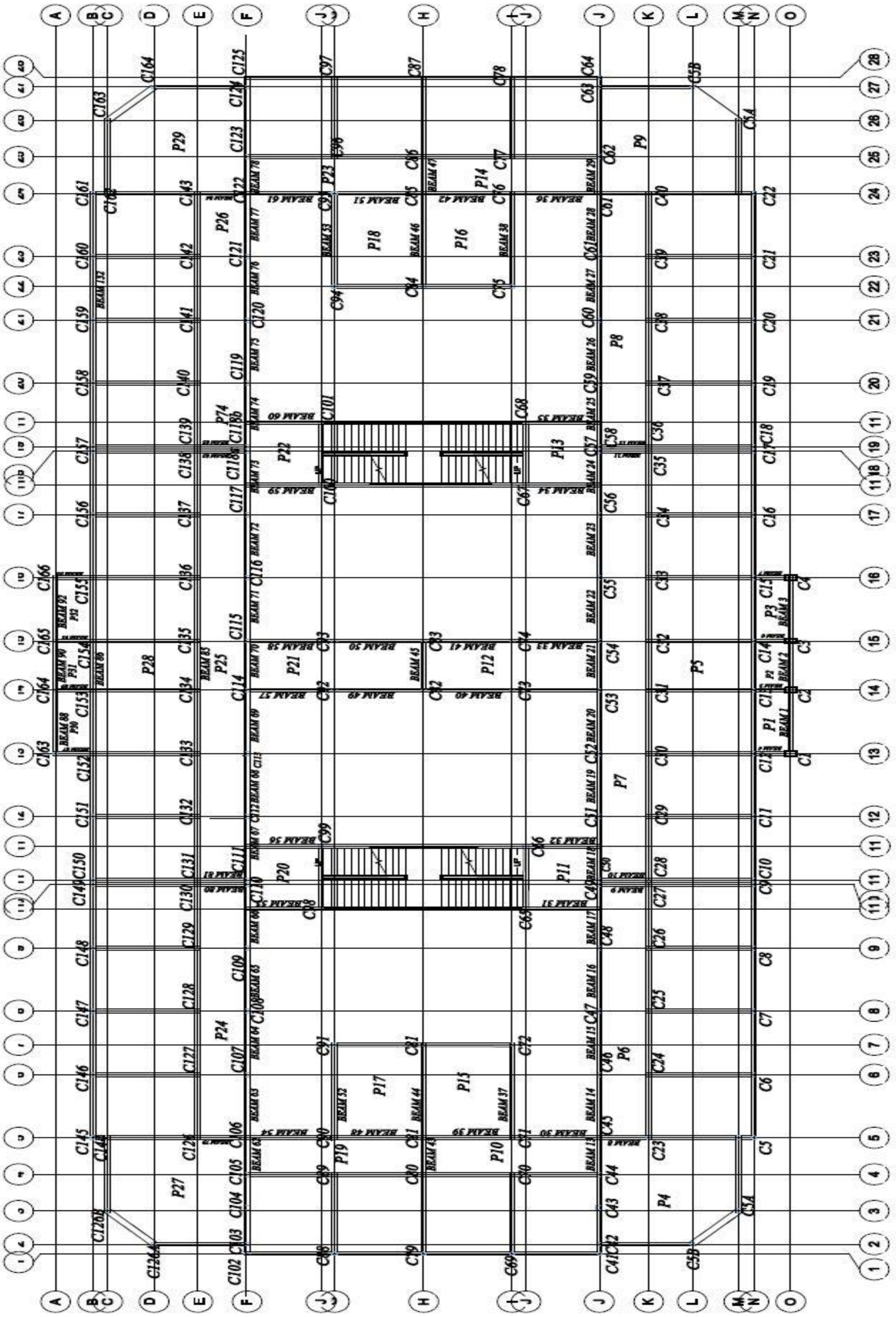

Figure 2: Building B structural layout

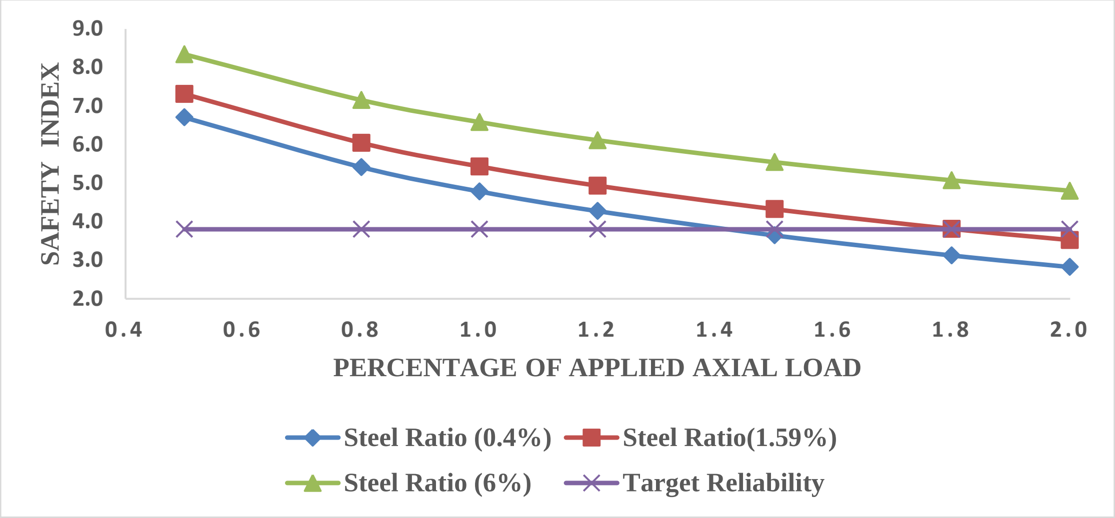

Figure 4: Safety index against percentage of applied axial load (Columns 23 & 24) of Building A

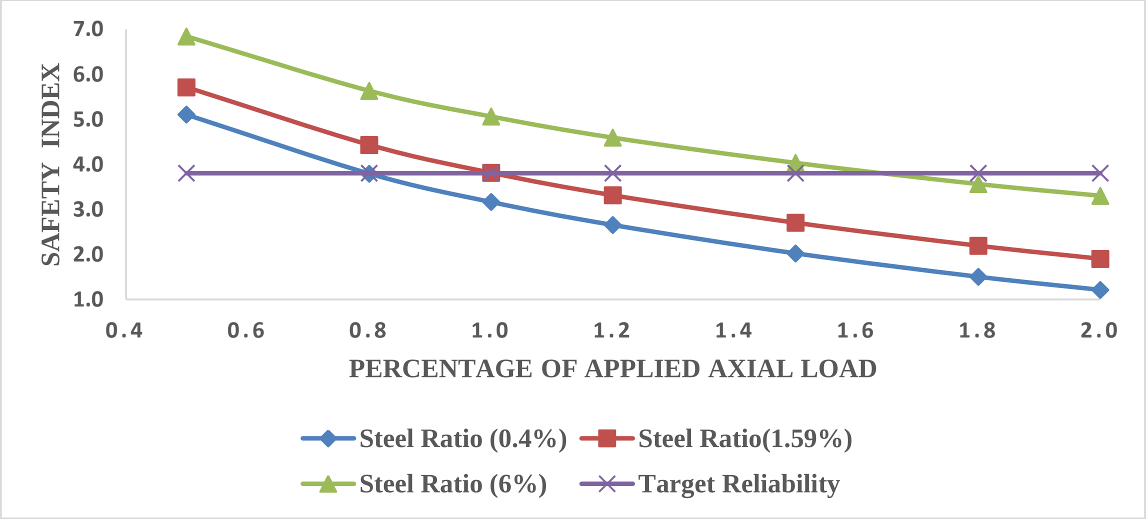

Figure 5: Safety index against percentage of applied axial load (Columns 62 & 63) of Building A

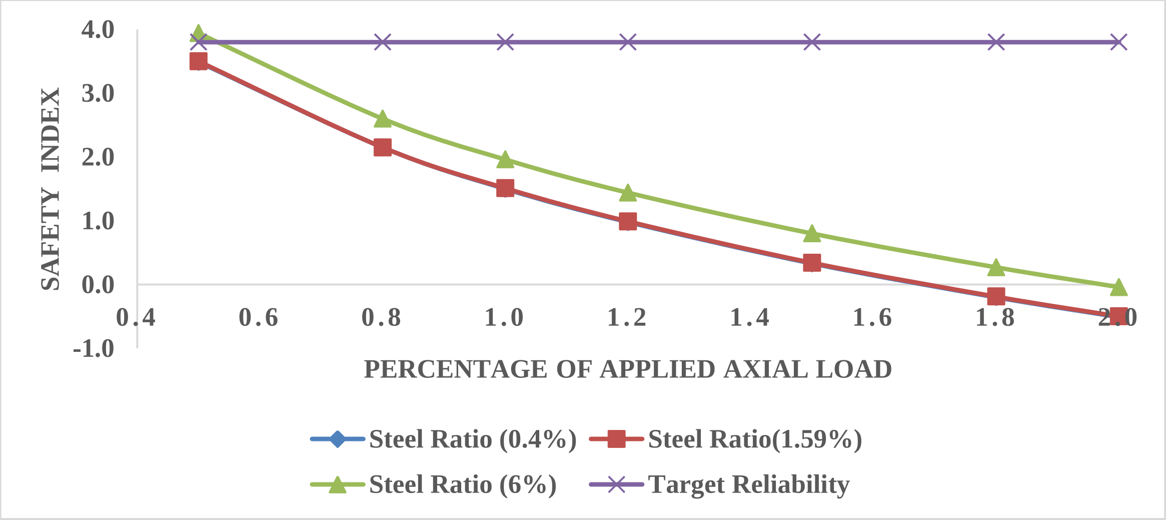

Figure 6: Safety index against percentage of applied axial load (Column 71) of Building A

4.2 Predicted safety levels for the columns at Building B

In general, based on the nature of the plots (Figures 7 - 9), the reliability indices decrease as the axial load increases. The plots (Figure 7) shows that columns 1, 4, 163 and 166 will be able to resist the ultimate design load throughout their service life and even withstand accidental loads twice their ultimate design loads for all the reinforcement ratios. However, Columns 2, 3, 164 and 165 will resist their designed loadings and 30% accidental loadings for target safety level of 3.8 (Figure 8). The most critical columns are C81A and C85 with their axial load summed up to 630 kN. They are critical because the addition of both the imposed loads and the dead load of the slab and the beams on the columns are high and hence, they fell below the target safety level of 3.8 for all the steel ratios (Figure 9). It's perturbing because failure may occur at any moment and hence the authority of the institution should be on the qui vive and look for ways to strengthen the columns in order to avoid progressive failure with its devastating consequences.

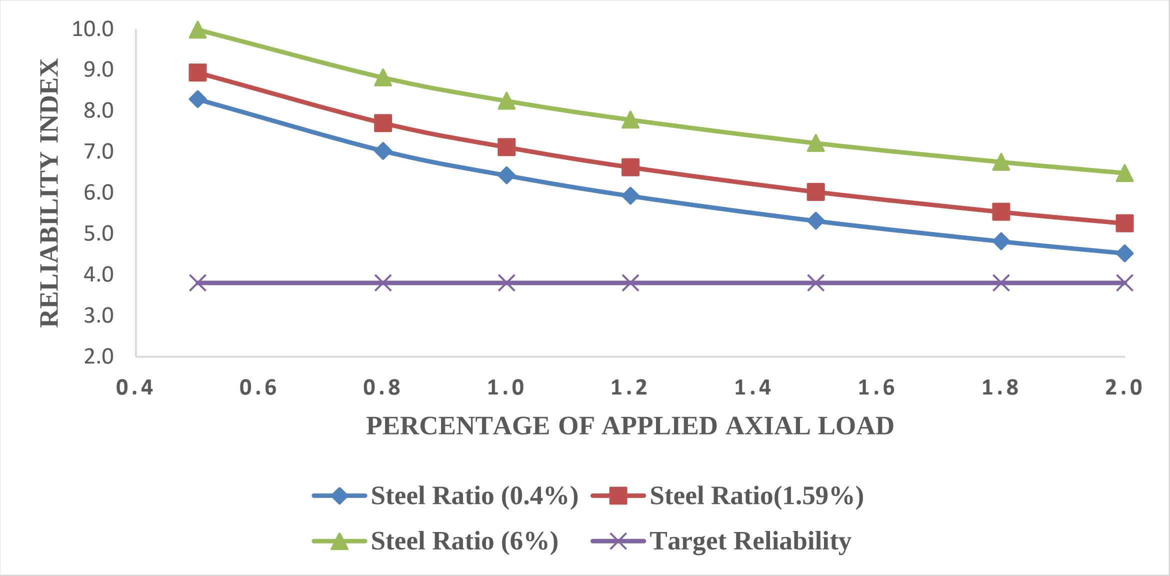

Figure 7: Reliability index against percentages of applied axial load (Columns 1, 4, 163 & 166) of Building B

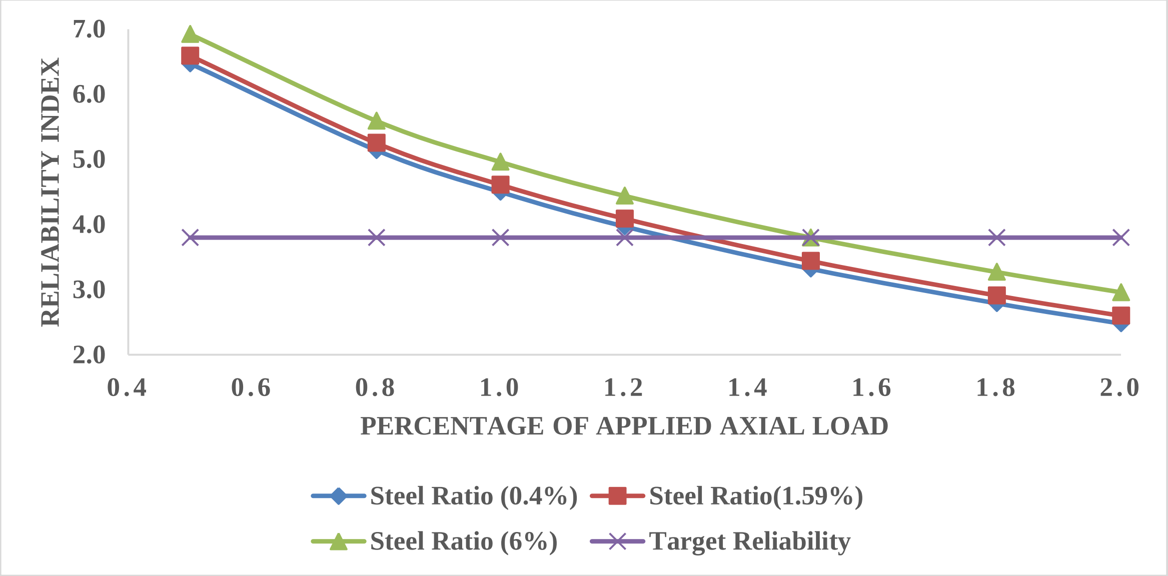

Figure 8: Reliability index against percentages of applied axial load (Columns 2, 3, 164 & 165) of Building B

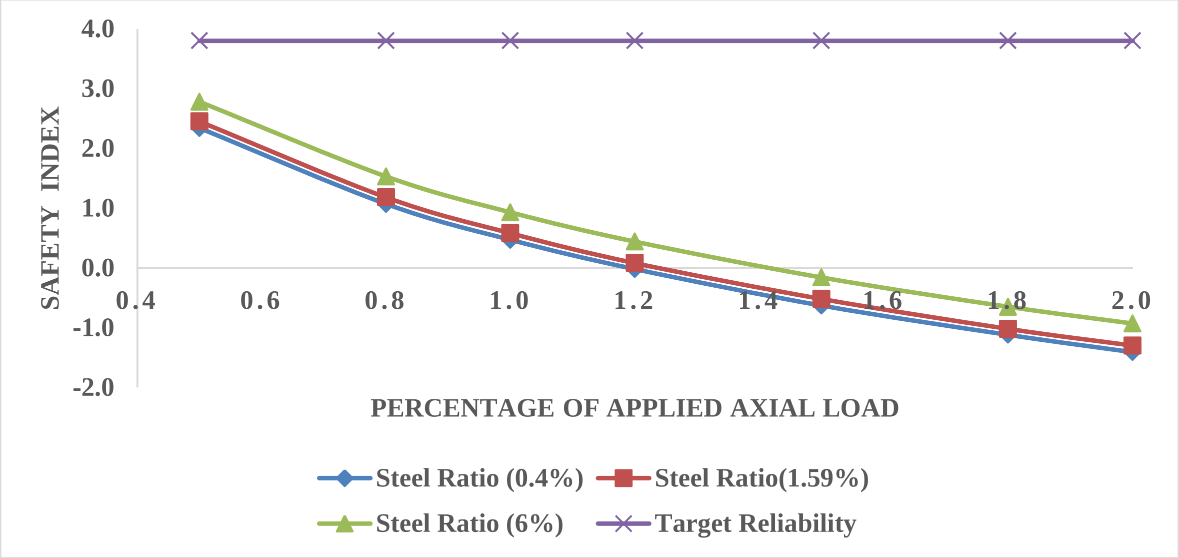

Figure 9: Safety index against percentages of applied axial load (Column 81A and 85) of Building B

5. CONCLUSIONS

Due to the devastating nature of progressive failure most of the times, the failure of a critical column in a building may lead to the total collapse of that building. This necessitates the use of reliability-based assessment of two University buildings so as to access their structural integrities. It was discovered that the safety indices for all the reinforced concrete structural elements of the two investigated buildings decrease as the applied loads/moments increase for all the assumed reinforcement ratios. Low axial loads produce high reliability indices and vice versa. Furthermore, all the accessed columns passed the reliability test within the corridor of simulated practical loading for Building A except column 71 and columns labeled C81A and C85 in Building B, which are prone to violation of the ultimate limit state as suggested by their estimated safety indices.

REFERENCES

[1] Mohammed, A. (2017). Structural Failure of Buildings: Issue and Challenge, *World Scientific News*, 66, 97 – 108.
[2] BS 8110 (1997). *Structural use of concrete; Part 1: Code of practice for design and construction*. 2nd ed.,United Kingdom
[3] Fapohunda, C. A. (2019). *Limit State Design of Reinforced Concrete Structural Elements*, 1st ed., Pelikos, Nigeria.
[4] Mosley, W. H. & Bungey, J. H. (1990). *Reinforced Concrete Design*, 4th ed., Macmillan, London.
[5] Mahrous, A., Ehab, M & Salem, H. (2020). Progressive Collapse Assessment of Post-Tensioned Reinforced Concrete Flat Slab Structures Using AEM, *Engineering Failure Analysis*, 109, 104278.
[6] Kiakojouri, F., De Biagi, V., Chiaia, B. & Sheidaii, M. R. (2020). Progressive Collapse of Framed Building Structures: Current knowledge and Future Prospects, *Engineering Structures*, *206*, 110061.
[7] Dogan, G. & Arsian, M. H. (2016). Failure Modes of RC Columns Under Loading, *International Journal of Scientific and Engineering Research*, 7(12), 1279 – 1300.
[8] Premium Times website. [Online]. (2022). Available: https://www.premiumtimesng.com/news/more-news/494724-ikoyi-building-collapse-how-21-storey-building-collapsed-survivor.html.
[9] Utpreksha, V., Vaibhav, B. & Dr. Virendra, K. P. (2020). Design Errors in Building Construction Projects, *International Research Journal of Engineering and Technology*, 7(7), 3848 – 3855.
[10] Baiburin, A. Kh. (2017). Errors, Defects and Safety Control at Construction Stage, *International Conference on Industrial Engineering*, 206.
[11] Musa, S. & Obaju, B. (2016). Effects of Design Errors on Construction Projects, *International Journal of Scientific and Engineering Research*, 7(2), 1099 – 1114.
[12] Uche, O. A. U. & Afolayan, J.O. (2008). Reliability– Based Rating for Reinforced Concrete Columns, *Journal of Engineering and Technology*, 3(1), 1- 20.
[13] BS 8110 (1985). *Structural Use of Concrete; Part 1: Code of practice for design and construction*. United Kingdom
[14] Akindahunsi A. A., & Afolayan J. O. (2009). Developed Reliability Based Interaction Curves for Design of Reinforced Concrete Columns, *Journals of Theoretical and Applied mechanics*, 47, 943 – 955.
[15] Olusola, J.A., Opeyemi, E. O., & Olaseinde, J. A. (2017). Reliability Assessment of BS 8110 (1997) Ultimate Limit State Design Requirements for Reinforced Concrete columns, *Jordan Journal of Civil Engineering*, 11(3), 512 – 524

[16] Bai, L., Jiang, F. & Fan, B. (2018). Reliability Analysis of Reinforced Concrete Columns after High Temperature under Comprehensive Considering Failure Path, *Journal of Nanoscience and Nanotechnology Applications*, 2(2), 1 – 8.

[17] Nguyen, H. A, T. (2022). Probabilistic Assessment of Bending Strength of Statically Indeterminate Reinforced Concrete Beams, *International Journal of Engineering, Transactions A: Applications*, 35(4), 837 - 844

[18] Dehghani, H., & Fadaee, M. J. (2013). Reliability-based Torsional Design of Reinforced Concrete Beams Strengthened with CFRP Laminate, *International Journal of Engineering, Transactions A: Basics*, 26(10), 1103-1110.

[19] Gilson Company, Inc. website. [Online]. (2019). Available: http://www.globalgilson.com/profoscope-rebar-locators-cover-meters.

[20] *Eurocode – Basis of Structural Design*, BS EN 1990:2002+A1, 2005.