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Probabilistic Assessment of Structural Integrity of Reinforced Concrete Rectangular Beams Based on Material Failure

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ABSTRACT :*Structural health monitoring using reliability concepts is a powerful tool in maintenance planning for reinforced concrete buildings. Structural integrity entails an assurance that either a structure or structural component is adequate for its purpose under normal operating conditions and is safe even under conditions outside the original design. When considering the entire lifespan of a structure, extreme events other than those considered in the design are pertinent. This paper focused on probing the structural integrity of two existing reinforced concrete university buildings. The in-situ strength of all accessible reinforced concrete beams was measured using Schmidt rebound hammer and Ultrasonic pulse velocity tester (Pundit Lab equipment). The calibration of the measuring equipment rested on twelve specimens of concrete cubes of grade 20 N/mm^2. At ages 7, 14, 21, and 28 days, three concrete cube specimens were tested with the rebound hammer, Pundit Lab equipment and compression machine for their respective rebound numbers, pulse velocities and crushing strength. The rebound numbers, pulse velocities and the crushing strength were subjected to regression analysis to generate a model for predicting concrete strength. The model formed the basis for the computation of the reliability index for each structural element assessed. The first-order reliability method (FORM), in a coded algorithm (CalREL), performed the computation of reliability indices as measures of the probability of violation of the limit states associated with each structural element. The limit state for each beam was a function of multidimensional random variables. A target reliability value of 3.8 for a 50-year design life for residential reinforced concrete buildings according to EN 1990 (2002) was the basis for comparison. The results showed that the safety of all the structural elements decreased with increasing simulated accidental loads/moments for all the criteria for serviceability and ultimate limit states. The beams carried the loads in varying proportions of the moment of resistance of the concrete section. Some only sustained between 30% and 80% of their designed loads; a few others can carry as much as twice their designed loads for the two buildings. In addition, for all practicable steel ratios, all the beams satisfied the condition of ultimate yielding resistance of steel with high-reliability indices. The findings of this investigation advocate extreme caution in the usage of the assessed buildings to avoid undue progressive collapse.*

KEYWORDS: *reinforced concrete, structural integrity, CALREL, reliability indices.*

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I. INTRODUCTION

Structural integrity is the ability of a structure to withstand its intended loading without failing due to fracture, deformation, or fatigue. It is often used in engineering to produce items that will serve their designed purposes and remain functional for a desired service life (Kayode, 2015). Therefore, the importance of structural integrity assessment of reinforced structures can never be overemphasized. With conduction of integrity of structural components of structures, the extent of distress or damage is located before failure. It will determine how reliable the structure is to carry both the present and future load (Ehiorobo *et al.*, 2013). For effective conduction of structural integrity, site inspection (visual inspection) is carried out by which any area of distress such cracks, scaling, deflection, delamination, and spalling is quickly identified so that appropriate actions are taken to prevent failure. For deep assessment, non-destructive tests on the structural components are necessary. Non-destructive testing (NDT) involves the non-destruction of the serviceability of the part or system of the structure through proper inspection, testing and evaluation of the components of the materials (ASNT, 2021).

With NDT, conditions of reinforcement, compressive strength of concrete and any other properties of concrete are determined. Non-destructive equipment such as Schmidt Rebound hammer, Ground Penetrating Radar (GPR), Ultrasonic Thickness Gauges, Pundit Lab equipment, Profoscope and Concrete Tester and Surveyor (CTS) are commonly available (Jedidi and Machta, 2014, Sakshi, 2018). With these equipment, relevant information for assessing the conditions of the structure is obtained. Moreover, the data from the use of these equipment may not be enough to fully harness the real condition of the structure. Structural reliability updating technique provides the platform of analysing the desired properties so as to identify the components that violate the limit state (ultimate and serviceability) (Salma *et al.*, 2017, Wasiu and Adedeji, 2018).

II. LITERATURE REVIEW

One of the problems of nature is uncertainties (Xianqi, 2019) and these must be, at least, solved by formidable systems and policies. This is why in structural engineering design, the major aim is to achieve an acceptable probability that structures being designed will perform satisfactorily during their intended life and that with an appropriate degree of safety, they must sustain all the loads and deformations of normal construction and use and have adequate durability and resistance to the effects of misuse and fire (BS8110, 1997). Reliability analysis methods offer the theoretical framework for considering uncertainties in a comprehensive decision scheme. The main goal of reliability analysis methods is to evaluate the ability of systems or components to remain safe and operational during their life cycle (Arteaga-Bastidas and Soubra, 2014) i.e., it helps to predict the behaviour of structural elements whether they are in good standing or at the verge of collapse. Therefore, the importance of reliability application in predicting the safety of a system cannot be over-emphasized.

For reliability analysis, the performance function of space of random variables, $G(\mathbf{X})$, is expressed as the difference between the resistance $R(\mathbf{X})$ and the demand or solicitation on the system $S(\mathbf{X})$ as shown in Equation (1).

$$G(\mathbf{X}) = R(\mathbf{X}) - S(\mathbf{X}) \quad (1)$$

If $G(\mathbf{X}) \leq 0$, it is the failure region and $G(\mathbf{X}) > 0$ is the safety region. However, the $G(\mathbf{X}) = 0$ is the boundary between failure and safety regions and it is called the *limit state surface*. Several methods exist for solving structural reliability problems. Some of them are first order reliability method (FORM), second order reliability method (SORM), Monte Carlo Simulation, etc. (Achintya, and Sankaran, 2000; Afolayan and Abubakar, 2003; Afolayan and Opeyemi, 2010; Gangli *et. al.*, 2013; and Sule, and Okere 2020).However, many researchers adopted FORM to predict the reliability indices of a particular parameter. This is because FORM is capable of handling non-linear performance functions, and correlated non-normal variables and it is also referred to as mean value first order second moment method (MVFOSM). FORM linearizes the performance function using Taylor series approximation; hence it is a first order approximation. It uses only mean and standard deviation of the variables (Manoj, 2016).

CalREL (Cal-RELiability), which is a general-purpose structural reliability analysis program, is designed to compute the probability integrals of the form:

$$P_f = \int_{\Omega} f(\boldsymbol{x})\boldsymbol{dx} \quad (2)$$

where $\boldsymbol{x}$ is a vector of random variables with joint probability density is function $f(\boldsymbol{x})$ and Ω is the failure domain defined by:

$$\Omega \equiv \{g(\boldsymbol{x}) < 0\} \quad (3)$$

CalREL computes the generalized reliability index defined as:

$$\beta_g \equiv \phi^{-1}(1 - p_f) \quad (4)$$

where ϕ^{-1} (.) denotes the inverse of the standard normal cumulative probability, and the sensitivities of the first-order estimates of P_f and β_g with respect to deterministic parameters defining the probability distribution or the limit-state functions.

CalREL incorporates four techniques for computing the above quantities, namely (a) The first-order reliability method (FORM); (b) The second-order reliability method (SORM); (c) Directional simulation with exact or approximate surfaces; and (d) Monte Carlo and importance simulation (Pei-ling *et al.*, 1989).

Abubaka *et al.*, (2018) adopted Euro Code 4 to carry out the reliability analysisofconcrete-steelcompositebeamsusingFORMthrough a developedMATLABprogramme. The fourfailuremodes that were considered were bending, shear, deflection and shear connectors'capacity with the assumption that the random variables were the loadsandresistancesofthesectionsinthelimitstateequations.Thesafety indexwasfoundtobeaffectedby parameterslikesteelyieldstrength, concretestrength,effectivewidth of theslab,web thickness,ultimatetensile strength, shank diameterof theshearconnectors, loadratio,liveloadandspan of thebeam.From thefailuremodeconsidered,Eurocode4 was found tobeconservativewith respectto shear,safe fordeflection,satisfactoryforbending,whileshearstudcapacitywascritical.

Sule and Okere (2020) conducted research on reliability analysis of a singly reinforced concrete rectangular beam with uncertain parameters and found out that the reliability indices increased with increase depth of beams and that the design was conservative in shear. However, assessing the findings above, it is considered fit to use more than one NDT equipment and also apply reliability approach to ascertain the real condition of the structural components of the buildings considered.

III. METHODOLOGY

3.1. The Structural Layout

The structural layouts of the two investigated building are as presented in Figs. 1 and 2. Building A has 44 accessible beams while Building B has 89.

3.2. Research Equipment

The two NDT equipment used were the Schmidt Rebound hammer (Fig. 3) and ultrasonic pulse velocity tester (UPV) (Fig. 4). ASTM C805 (2013) and ASTM C597 (2016) were followed for the use of Schmidt Rebound hammer and UPV respectively. Every accessible beam in the buildings was tested with the equipment and rebound numbers from Schmidt hammer and pulse velocities from Pundit Lab equipment were obtained.

3.3. Casting of concrete cubes

The materials needed for casting of the twelve concrete cubes of grade 20 were Portland cement (Superset brand of grade 42.5, locally purchased), fine aggregate (natural sand obtained from River Ogbese in Ondo State, Nigeria) and coarse aggregates, 19 mm sizes (obtained from Akinchang Quarry Company located at Owena in Idanre Local Government, Ondo State, Nigeria). The sand was washed and cleaned using 0.075 mm sieve to remove dirt, clay and silt. It was spread and air dried to reduce the moisture content. Portable water, which was fit for drinking, was used (Sheelan, *et al.*, 2019). The moulds were cleaned and oiled for easy demoulding. Proper mixing of the concrete ingredients was done and twelve concrete cubes of 150 mm × 150 mm × 150 mm for the calibration of rebound hammer and Pundit Lab were produced, as shown in Fig. 5. The concrete cubes were cured in water for 28 days.

3.4. Correlation of Rebound Number, Pulse Velocity and Cube Compressive Strength

The real values of the compressive strength of the structural beam elements of the two selected buildings depend on the correlated equation obtained from the measurements of the values of the rebound numbers, pulse velocities and compression test of the concrete cubes. Each concrete cube is tested with rebound hammer, UPV and compression test machine The values obtained were subjected to regression analysis and the best fit equation was obtained. The structural elements of the two buildings as shown in the building layoutswere then tested with rebound hammer and UPV to obtain their rebound numbers and pulse velocities respectively. The values obtained were substituted into the best fit equation to produce the actual compressive strength of the tested structural elements.

3.5. Formulation of Limit States for Reliability Analysis

The structural integrity of a building depends on the integrities of its structural members. Having determined the estimated compressive strength of the structural members, the reliability analysis will show further the ability of the structural members to withstand the applied loads. The applied axial loads and moments were obtained from the theoretical design using Orion Software known as Orion 17.0. The limit state equations for the reliability analysis are as given in Equations 5 – 8.

Case A: Ultimate Moment of Resistance Based on failure of Concrete about the Neutral Axis

The limit state equation or the performance function for this case is

$$g = M_{ult} - M_{app} \tag{5}$$

where M_{ult} is the ultimate moment and M_{app} is the applied moment ; and

$$g = 0.156 f_{cu} b d^2 - \alpha M \tag{6}$$

where f_{cu} is the characteristics strength of the concrete, b is width of the section, d is the effective depth of the section, M is the applied moment, and α is the percentage of applied moment.

The statistics for the designed variables and the parameters in Equation (6) are summarised in Table 1.

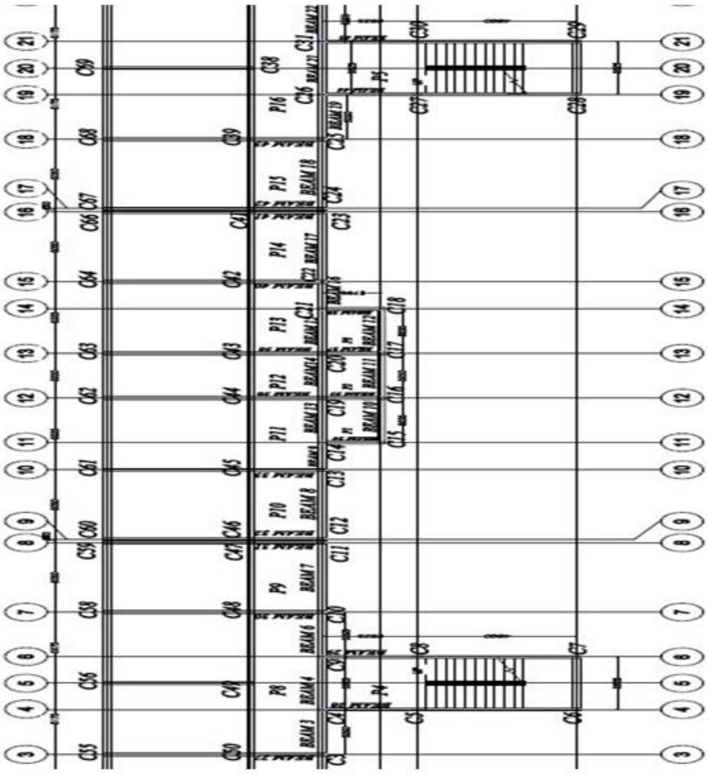

Fig 1: The structural layout of the Building A

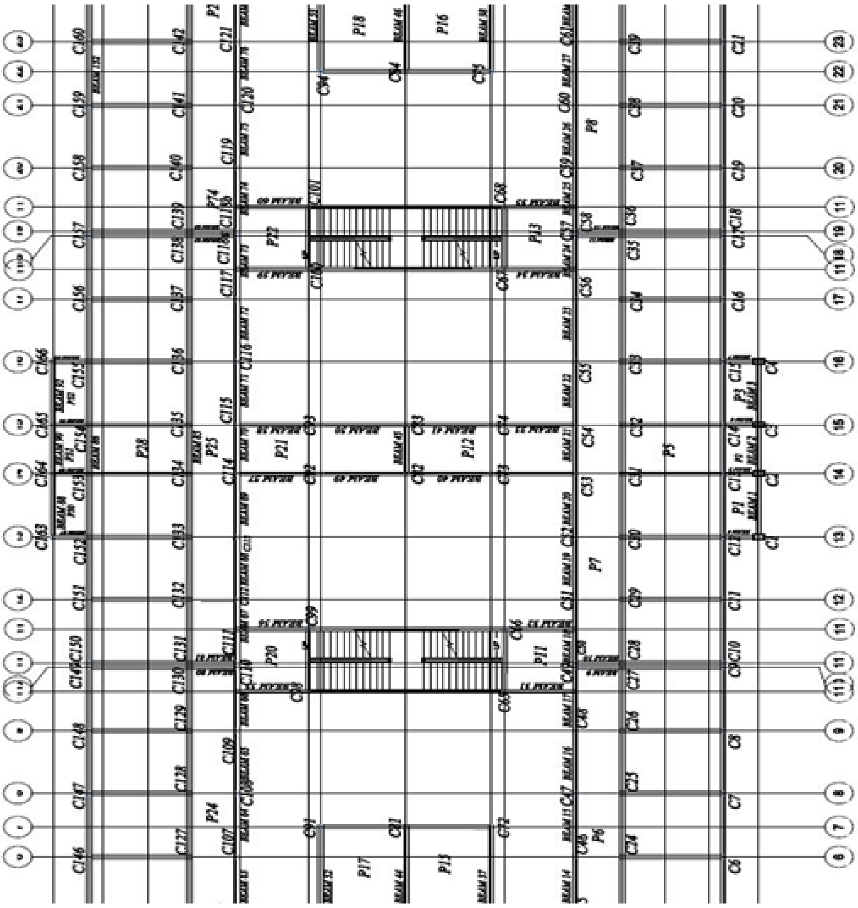

Fig. 2: The structural layout of the Building B

Fig. 3: Schmidt Rebound Hammer Fig. 4: Pundit Lab Equipment

Fig. 5: Already prepared concrete cubes

Table 1: Statistics for the relevant designed variables based on failure of concrete about the neutral axis

Variables	Distribution Type	Mean	Standard deviation
f_{cu} (N/mm^2)	Log normal	33.38	3.07
b (mm)	Normal	225.00	22.50
d (mm)	Normal	393.00	39.30
M (Nmm)	Log normal	67680000.00	20304000.00

Case B: Ultimate Moment of Resistance Based on failure of Steel about the Neutral Axis
The performance function for this case is:

$$g = 0.95 f_y A_s Z - \alpha M \quad (7)$$

where f_y is the characteristics strength of the steel, A_s is cross sectional area of the tension reinforcement, Z is the lever arm, M is the applied moment, and α is the percentage of applied moment.
According to Table 3.25 of BS 8110-1:1997, clause 3.12.5.3 and clause 3.12.5.3, steel percentage for beams is $0.13\% \leq \frac{100 A_s}{bh} \leq 4\%$;
If $\rho = \frac{A_s}{bh}$ is the reinforcement ratio, $A_s = \frac{\rho b h}{100}$ and $Z = 0.95d$, $h = d + 0.5\emptyset + \emptyset_{links} + cover$, then

$g = 0.95 f_y A_s Z - \alpha M = 0.009025 f_y \rho b d(d + 0.5\emptyset + \emptyset_{links} + cover) - \alpha M$ (8)

The statistics for the designed variables and the parameters in Equation 8 are summarised in Table 2.

Table 2: Statistics for the relevant designed variables based on failure of steel about the neutral axis

Variables	Distribution Type	Mean	Standard deviation
f_y (N/mm^2)	Log normal	460.00	138.00
ρ(%)	Log normal	0.13	0.039
b (mm)	Normal	225.00	22.50
d (mm)	Normal	393.00	39.30
$\emptyset$(mm)	Normal	16.00	1.60
$\emptyset_{links}$ (mm)	Normal	10.00	1.00
Cover (mm)	Normal	39.00	11.02
M (Nmm)	Log normal	67680000.00	20304000.00

IV. RESULTS AND DISCUSSIONS

The correlated relationship of the UPV, the rebound number and the crushing strength of the laboratory concretecubes through regression analysis gives:

$ECS = 0.98532\, N_R - 0.49127\, UPV + 2.85419$ (9)

in which, ECS is the Estimated Compressive Strength (N/mm^2), N_R is the rebound number and UPV is the ultrasonic pulse velocity of the tested structural member. The reliability indices using CalREL software are used to predict the safety of the beams.

4.1. Predicted safety levels of the Beams based on Concrete Failure (Building A)

The estimated reliability indices for the beams based on failure of concrete are as shown in Figs. 6 – 8. The target reliability (TR) has been fixed at 3.8 for 50 years' reference period (EN 1990, 2002). The trends for all the beams are the same, reliability indices decrease with increasing loads effect and most of the beams are safe within the ultimate limit state condition. Beams 1, 2, 7, 8, 17, 18, 23, 24 and 38 only carried 60% of their designed loads while beams 25, 26 27, 30,33, 36, 40, 43, 46 and 47 have carried up to 80% of their designed load when their safety is compared with the target reliability. Any attempt to carry extra or additional accidental load may lead to their violation of the limit states. Similarly, the beams that may fail after carrying their designed loads are beams 4, 19, 21, 22, 31, 32 and 42. Obviously, these beams can remain in service in as much as any additional accidental load beyond the design load is not imposed. Likewise, beams 6, 9, 10, 11, 12, 13, 14, 15, 16, 28, 29, 34, 35, 37, 39, 41, 44, 45 and 48 can carry above their designed loads of which beams 10 and 41 can carry twice their designed load while beams 34, 35 and 37 can carry more than their designed load. As the ultimate moment based on the criterion of failure of concrete depends largely on the concrete characteristic strength and the section parameters of the beam (the sizes), the concrete strength and quality may be the reasons why beams 1, 2, 7, 8, 17, 18, 23, 24, 38, 25, 26 27, 30, 33, 36, 40, 43, 46 and 47 may fail if they carry the exact value of the designed load. There might be some internal voids within the concrete matrix which may adversely affect the strength of the concrete, as well as inadequate compaction of the concrete during construction and improper mixing during casting. Apart from these, other factors such as the cement content, aggregate quality and water quality used during construction may cause the reduction of the reliability indices of those beams (Mohamed, 2015). Therefore, concrete strength and quality play vital roles in reliability of a reinforced concrete beam and must be given adequate attention.

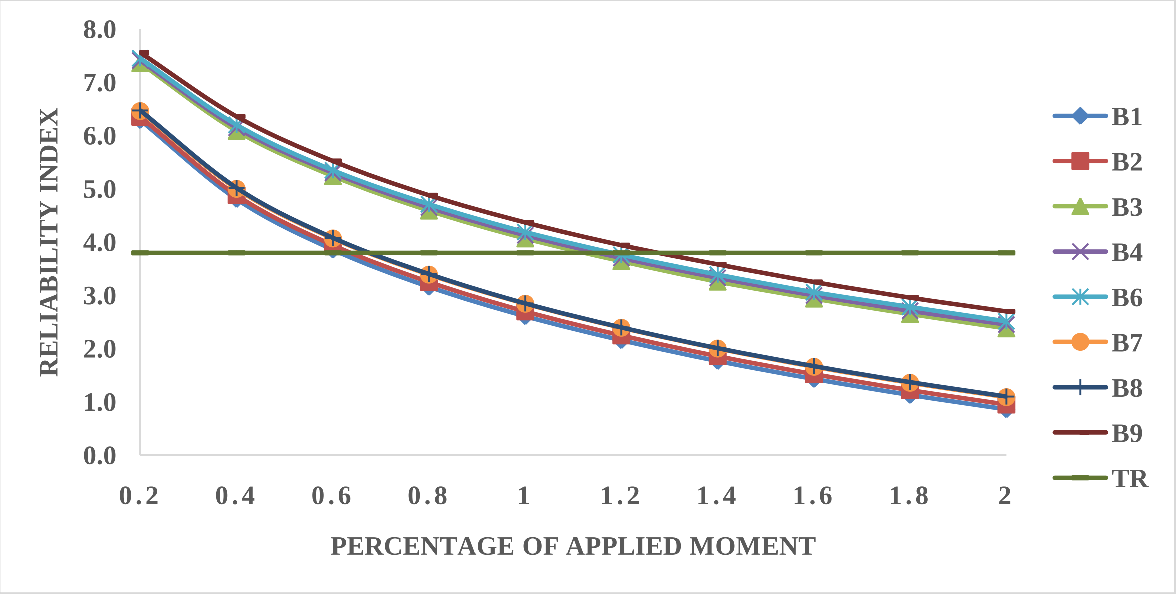

Fig. 6: Reliability index against percentage of applied moment for B1 – B9 of Building A (capacity of beam based on concrete failure)

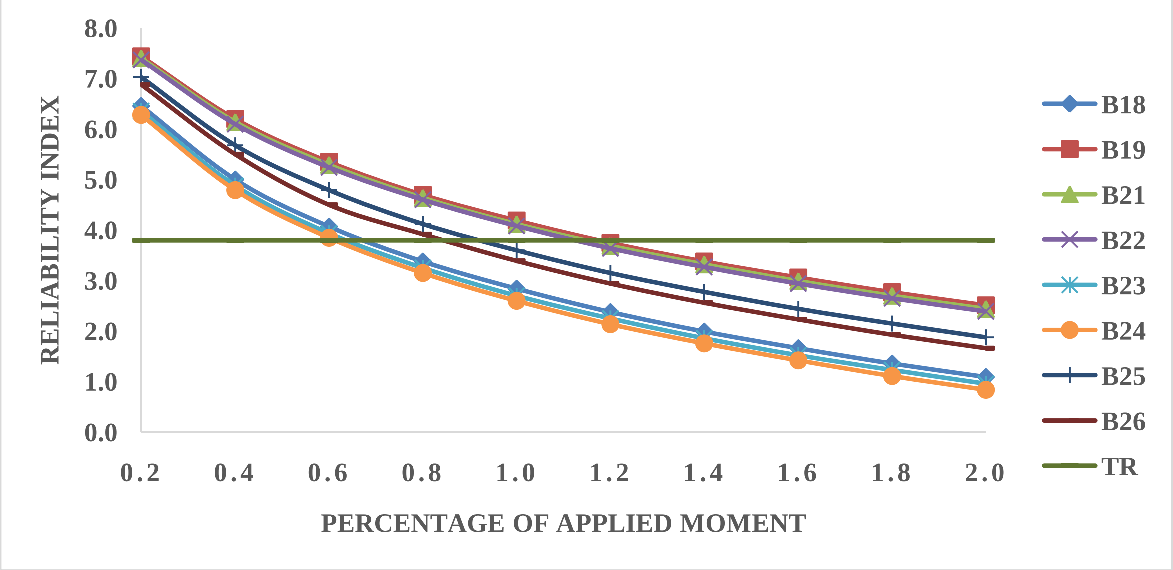

Fig. 7: Reliability index against percentage of applied moment for B18 – B26 of Building A (capacity of beam based on concrete failure)

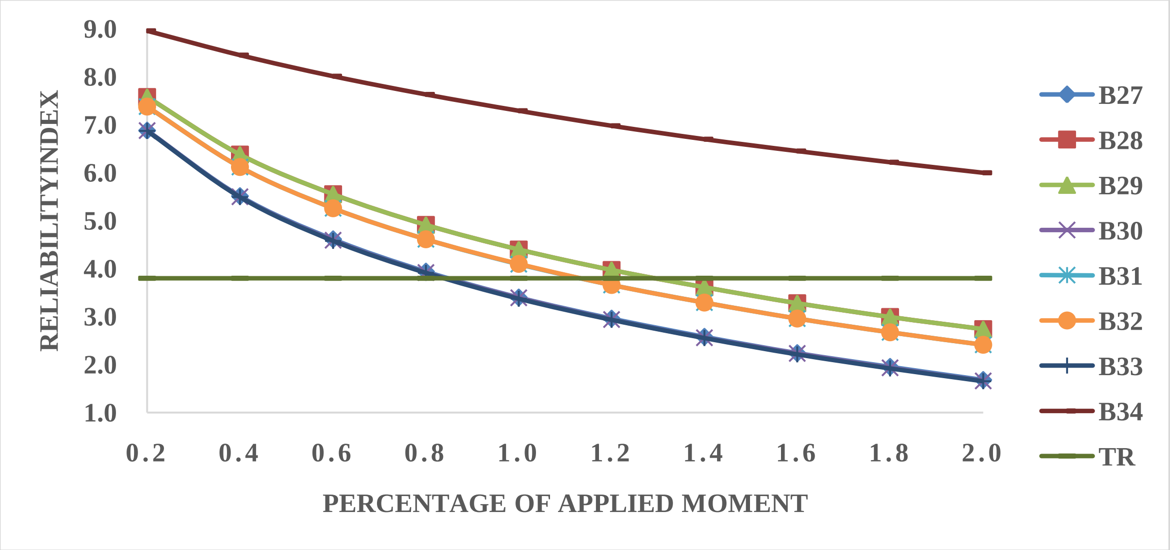

Fig. 8: Reliability index against percentage of applied moment for B27 – B34 of Building A (capacity of beam based on concrete failure)

4.2. Predicted safety levels of the Beams based on Steel failure for Building A

The estimated safety indices reveal that the beams are overdesigned against the yielding of the reinforcements. The indices for all admissible steel ratio are well above the target level. The implication is that the beams are not expected to fail by yielding of the reinforcements. When the safety indices for concrete and steel failure are compared (see Fig. 9), there is indicative that initiation of progressive failure of the beams in the building may be due to loss of ultimate resistance of the concrete section.

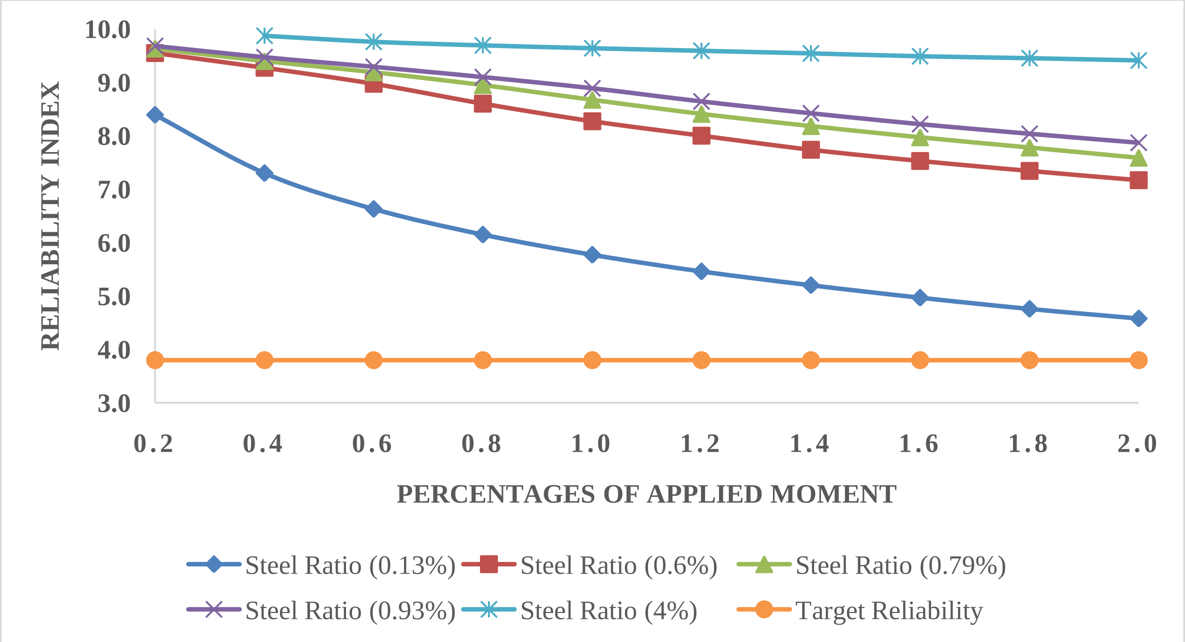

Fig. 9: Reliability index against percentage of applied moment (Beam 1) of Building A (capacity of beam based on failure steel/yielding of steel)

4.3. Predicted safety levels of the Beams based on Concrete failure (Building B*)*

Critical study of the plots of the safety indices of the beams based on concrete failure criterion (Figs. 10 – 13) revealed that beams 43, 44, 46 and 47 would only carry 30% of the designed load to meet the target reliability level. Similarly, some of the existing beams (B24 and B25) in Figure 10 will fail to meet the expected target safety level if they are loaded beyond 60% of their designed loading. On the other hand, none of the beams will meet the target safety level if they are subjected to accidental loading of 20% higher than the designed value. It is worrisome that the beams labelled B37 – B44 are significantly under performing in relation to their expected target safety level. This is obvious from the plots in Figure 11. Beams B73 – B80 in Figure 12 and Beams B85, B86, B87 and B89 in Figure 13 cannot meet the target safety level of 3.8 in their present state as some of them have their safety indices less than this value even at a loading that is between 60% and 80% of their designed value

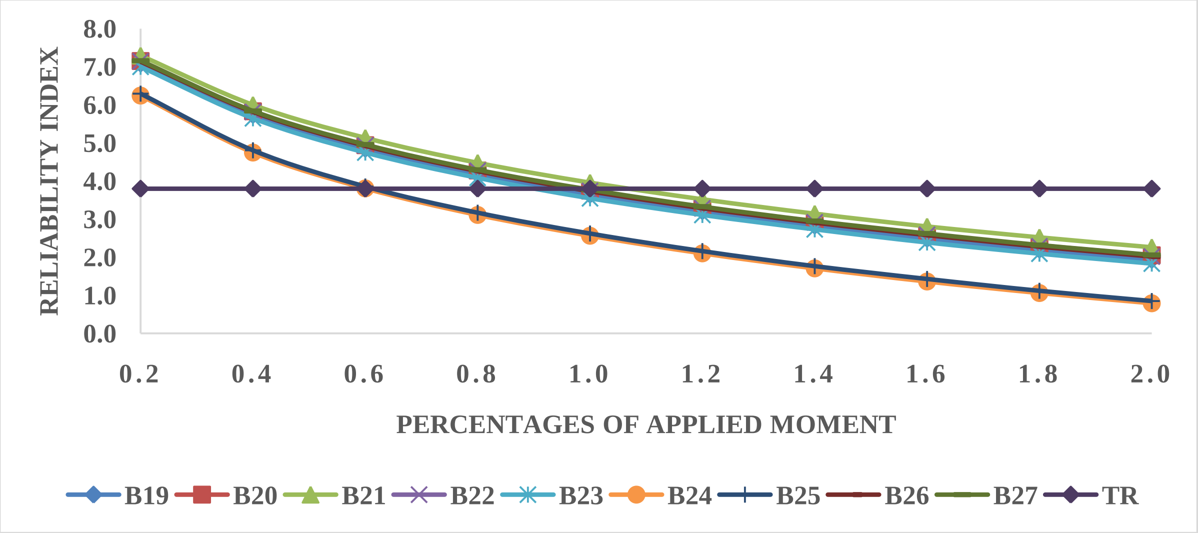

Fig. 10: Reliability index against percentage of applied moment on beams (B19 – B27) of Building B (capacity of beam based on concrete)

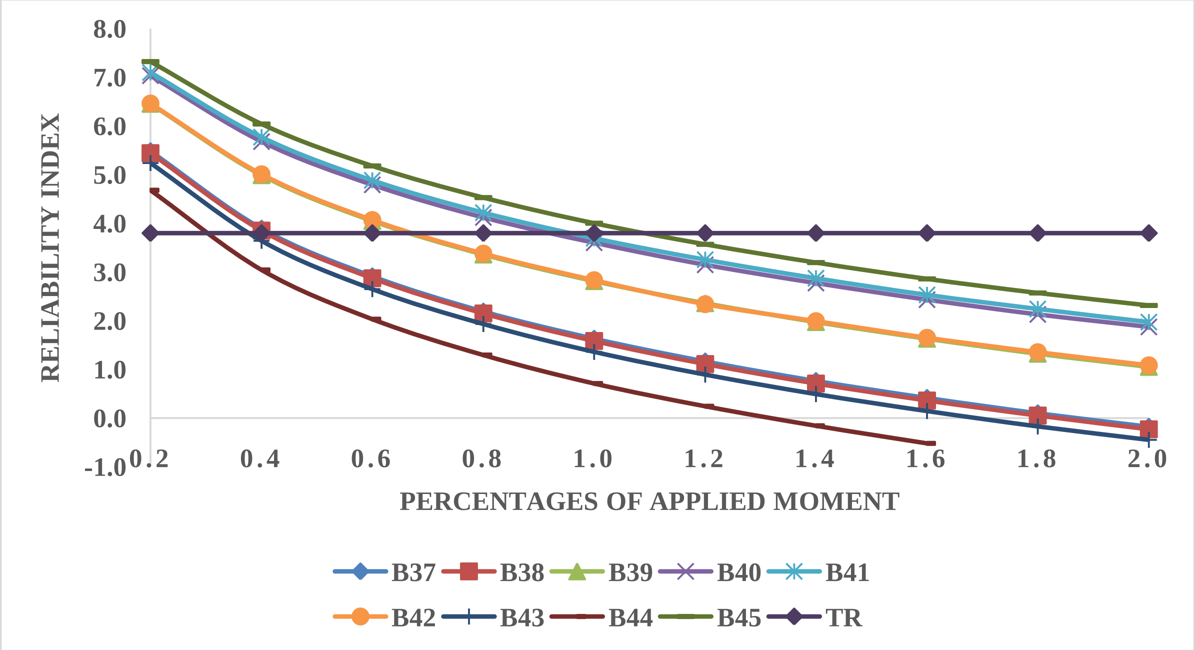

Fig. 11 Reliability index against percentage of applied moment on beams (B37 – B45) of Building B (capacity of beam based on concrete)

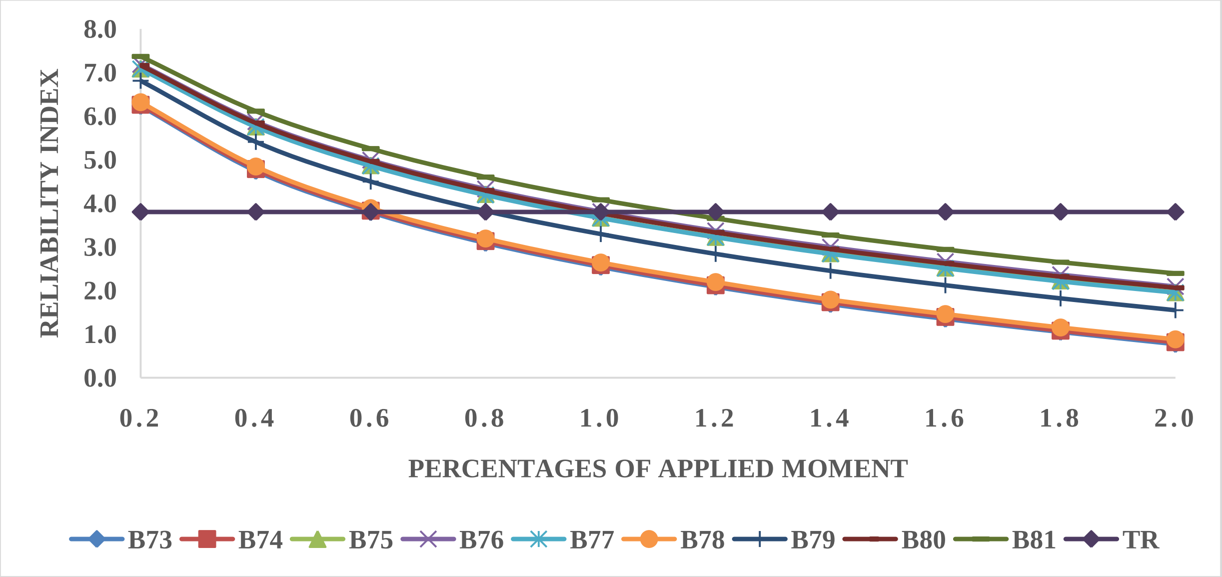

Fig. 12: Reliability index against percentage of applied moment on beams (B73 – B81) of Building B (capacity of beam based on concrete)

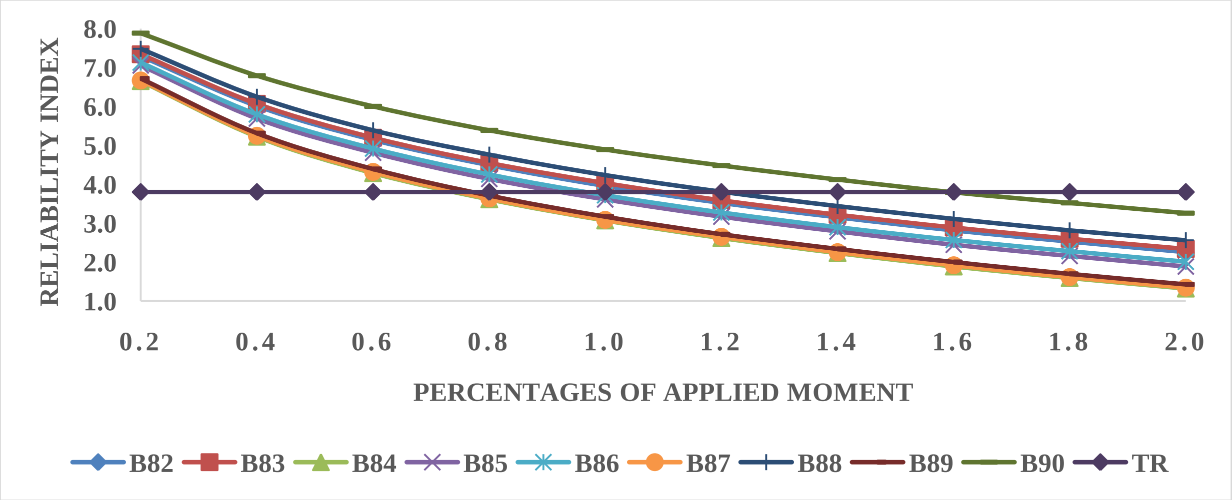

Fig. 13: Reliability index against percentage of applied moment on beams (B82 – B90) of Building B (capacity of beam based on concrete)

4.4. Predicted Safety Levels of the Beams based on Steel failure of Building B

Beam 1 has been presented as a representative of the other beams designed against failure by yielding of the steel reinforcement. The predicted high safety indices for all admissible reinforcement steel ratio are a clear indication of over design of the beams, Similar to the observation in building A, there is a high probability of initiation of progressive failure of building B by loss of ultimate resistance of concrete of the beam sections.

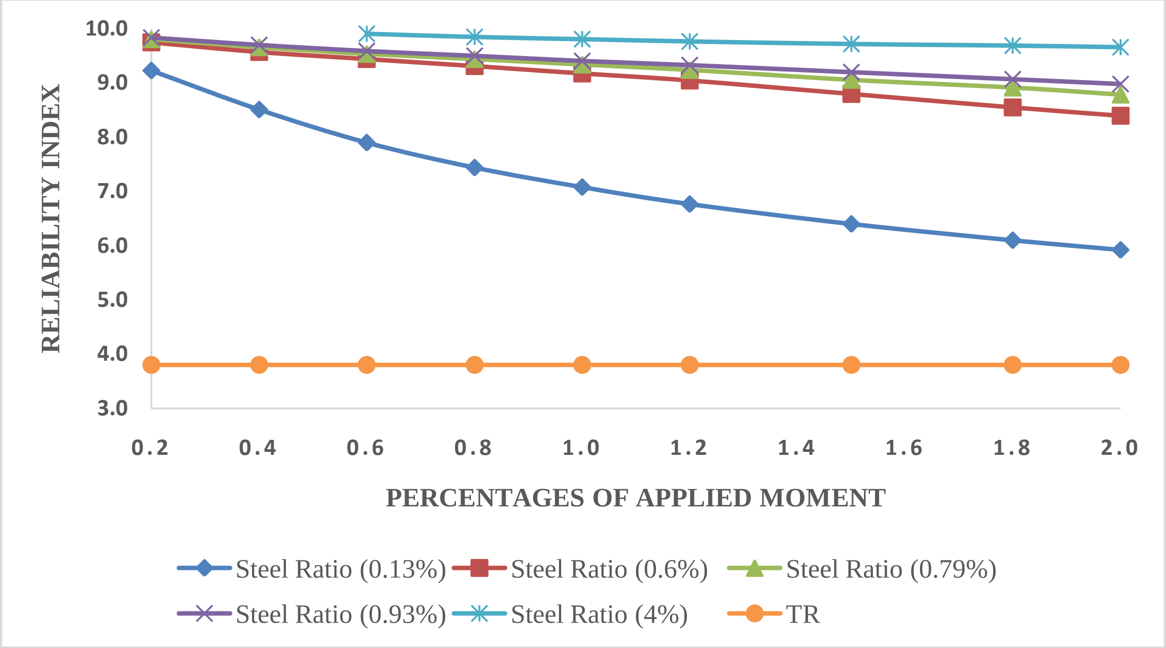

Fig. 14: Reliability index against percentage of applied moment (Beam 1) of Building B (capacity of beam based on failure steel/yielding of steel).

V. CONCLUSION

Field measurements by NDT formed the basis for a probabilistic integrity assessment of the reinforced concrete beams of two existing University buildings. The criteria for ultimate resistance of both concrete and steel reinforcement were subjected to reliability test. There is a clear indication that the beams are well designed against the yielding of the steel reinforcements. However, by safety regulation, most of the beams have fallen short of the target level of safety even at a loading between 60% and 80% of the design values under consideration for ultimate resistance of their concrete sections. By virtue of structural health monitoring, the two buildings stand the risk of progressive failure through the initiation of loss of ultimate resistance of concrete of the beam sections. It is therefore advisable that the buildings be protected against unnecessary overloading.

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