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Reliability Analysis of Nano Engineered Reinforced Concrete Beam

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ORIGINAL RESEARCH

Abstract— This work presents reliability analysis of Nano Engineered Reinforced Concrete (NERC) beam designed according to EN1992-1-1(2008) and its reference standard. In the reliability analysis, variability in load, geometric properties, Optimal Nano Engineered Concrete (ONEC) grade and other design variables were considered. The reliability analysis utilized FORM (First Order Reliability Method) with FORTRAN subroutine programs developed for the NERC beam failure modes at ultimate limit state. Results indicated that NERC beam behaves in a similar manner to conventional reinforced concrete beam on strength aspect. At design point, the NERC beam failed to meet the target safety index values provided by EN1990: 2002 (EC0) as a reference standard of EN1992-1-1 (2008) for all the failure modes considered. Furthermore, variations in span and reinforcement ratio have been found to be capable of changing the criticality of failure modes of NERC beam. Also, variation in characteristic yield strength of steel was found to severely affect NERC beam safety. This study recommends that unnecessary variation of span, reinforcement ratio and characteristic yield strength of steel should be avoided in NERC beams at project implementation stage so as to reduce the possibility of unforeseen structural failures. The work suggested that the safety margin provided by EN1992-1-1 (2008) and its reference standards for the design of singly reinforced concrete sections without shear reinforcement be improved. Finally, the study observed the need for incorporation of reliability-based design in Civil Engineering design standards.

Keywords—nano engineered concrete, nano engineered reinforced concrete beam, safety index, ultimate limit state, EN1992-1-1(2008), EN 1990 (2002).

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1 INTRODUCTION

The foundations of infrastructure to support human civilizations have been made of cement based materials which kept evolving in order to maintain their function in our lives as human activities advances (Karkarna *et al.*, 2023). One of the most recently developed concrete materials for use in civil engineering applications is called Nano Engineered Concrete (NEC) which contains nano materials such nano silica (Sobolev and Sanchez, 2010; Sobolev *et al.*, 2016). NEC also known as nano concrete is a product of nanotechnology which has the potential of providing increased load bearing ability, reduced brittleness, increased toughness, reduced permeability and high durability (Adamu *et al.*, 2020a; Adamu *et al.*, 2020b; Adamu *et al.*, 2023).

One of the most commonly used structural solutions in Civil Engineering design and construction is Reinforced Concrete (RC) whose popularity is mostly linked to its efficiency, cost effectiveness and versatility with many performance criteria and design guidelines (Karkarna *et al.*, 2023).

Adamu *et al.* (2023) described RC as a composite material formed by embedding reinforcing steel in concrete at desired location in line with the requirements of resisting applied bending and shear stresses. Further, the arrangement in RC, as a composite material, was meant to utilize the natural ability of concrete in resisting compressive stresses within its carrying capacity as an artificial rock, and to cater for its weakness in resisting excessive applied bending and shear stresses; meaning that RC depend on the contribution of concrete in compression and shear, and reinforcing steel in tension and shear to support applied stresses that are above the carrying capacity of mass concrete sections.

The fast development in the field of civil engineering design and construction to meet growing infrastructural development needs have promoted great scientific and technological leap, but many RC structures show unsatisfactory performance due to aspects such as involuntary failures, imperfections, misuse of materials, natural ageing, errors in designs or unsafe designs, and problems of implementation (AntounNetto *et al.*, 2023). The development of material technology has brought the 'world of science' to develop up-to-date concepts related to effective and efficient structural capacities, which means that a structural design must fulfill safety and economic considerations (Patty *et al.*, 2023).

Uncertainties are inherent in engineering systems which affect reliability and safety (Kumar, 2020). Uncertainties in reliability analysis include aleatory (inherent variability), epistemic (knowledge-based), and model uncertainty (approximation errors) (Kumar, 2020; Zhang, Yang & Zhao, 2019; Li, Wang & Chen, 2018). Methods of reliability analysis include First Order Reliability Method (FORM) (Kumar, 2020), Second Order Reliability Method

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Section E- CIVIL ENGINEERING & RELATED SCIENCES
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(SORM) (Zhang, Yang & Zhao, 2019), and Monte Carlo Simulation (MCS) (Li, Wang & Chen, 2018). FORM is preferred in reliability analysis due to its computational efficiency and accuracy, requiring less effort than MCS (Li, Wang & Chen, 2018) and outperforming SORM in certain problems (Zhang, Yang & Zhao, 2019).

The European reinforced concrete standards, which rely mostly on deterministic and semi probabilistic approach, have incorporated numerous scientific research and experience of prominent scientist from various countries (Seyfullaev, 2023). With the presence of uncertainties in analysis and design of reinforced concrete structures (Adamu *et al.*, 2023; Abubakar, Afolayan & Osinubi, 2014; Abejide and Adamu, 2013) and deterministic or semi probabilistic nature of Eurocodes (Seyfullaev, 2023; Abejide, 2014), which rely on the use of partial safety factors to take care of uncertainties (Halder and Mahadevan, 2000; Abubakar, Afolayan & Osinubi, 2014; Adamu *et al.*, 2023), as well as structural collapse and failures recorded as a result of under estimating uncertainties (Carino *et al.*, 1983; Igba, 1996),a probabilistic structural safety assessment approach adopted in this work is essential for a better understanding of the safety of nano engineered reinforced concrete designs made according to Eurocode 2 and its reference standard. The need for reliability analysis of structures and structural elements was buttressed by Qianru and Ann (2013) where they stated that ensuring consistent safety level requires a probabilistic approach that reconciles uncertainties.

In order to facilitate application of nano engineered concrete as a new construction material in civil engineering designs and construction, its level of safety according to design standards and on some selected structural elements needs to be determined. Therefore, this study carried out reliability analysis of nano engineered reinforced concrete beam, with beam defined by AISC (2005) as a structural member with the primary function of resisting bending. The reliability analysis was done at ultimate limit state in line with Eurocode 2 and its reference standards considering bending and shear failure modes. A singly reinforced concrete beam model was adopted in the study to ensure lesser reinforcement in the concrete beam section which can enable better assessment of the contribution of NEC in resisting applied bending and shear stresses at ultimate limit state. The considerations presented herein are motivators for the research work as there are presently no studies conducted in this aspect to the best knowledge of the authors.

Nigeria as a former British colony and as member of commonwealth nations has over time adopted British Codes of Practice such as BS 8110 and the likes for reinforced concrete design. Recent development has shown that all British Standard Codes of Practice have been withdrawn and replaced with Eurocodes released by European Committee for Standardization (Adamu *et al.*, 2023).These developments tilt the fate of concrete design and construction in Nigeria and commonwealth nations to Eurocodes as guiding documents. Therefore, the structural safety analysis of nano engineered reinforced concrete beam presented herein was done according to Eurocodes.

3 METHODOLOGY

3.1 PROCEDURE FOR FIRST ORDER RELIABILITY ANALYSIS

Reliability is commonly described as the probability or likelihood of a structure performing its purpose adequately for a period of time intended under the operating condition encountered (Uche & Afolayan, 2008). In structural reliability analysis, consideration is given to the effect of carrying capacity (Q) and structural strength/response (R) which are functions of design variables. For safe design, Q must be greater than R. The relationship between performance function G(X_i), R and Q is given by Eq. (1).

$$G(X_i) = Q - R \qquad (1)$$

Another way of expressing the performance function is as given by Eq. (2)

$$G(X_i) = G(X_1,\ X_2, \ldots\ldots..X_n)\ = 0 \qquad (2)$$

With X being values of the basic design variables

Value of performance function G(X_i) = 0 indicates the element under consideration is on the failure surface boundary, with G(X_i) < 0 corresponding to failure region and G(X_i) > 0 representing safe region.

When the set of standardized variables are introduced Eq. (3) is obtained

$$X_i^1 = \frac{X_i - \mu_{xi}}{\sigma_{xi}}, \quad i\ 1,2\ldots.n \qquad (3)$$

By substituting Eq. (3) in (2) we obtain

$$G(\sigma_{xi} X_i X_1^1 + \mu X_i \ldots\ldots, \sigma_{xn} X_n X_n^1 + \mu X_n) = 0 \qquad (4)$$

Where μ and σ are the respective mean and standard deviation of the decision variables.

Computation of reliability index (β) can be done using Hasofer & Lind (1974) invariant solution on Eq. (4) or by utilizing second moment method described in Afolayan & Nwaiwu (2005) on Eq. (4). Based on FORM model, the reliability index can be obtained using Eq. (5).

$$\beta = min_{x\varepsilon F}\sqrt{((X_1^1)^2 + (X_2^1)^2 + \ldots\ldots + (X_n^1)^2)} (5)$$

with X_1^1, X_2^1 .... X_n^1representing random variables in the limit state function represented by G(X) = 0.

To compute reliability index using FORM5 developed by Gollwitzer, Abdo & Rackwiz(1988) over a failure surface (F) represented by G(X) = 0, minimizing Eq. (5) using an optimization method is necessary. FORM5 (Gollwitzer, Abdo & Rackwiz,1988) is a FORTRAN program capable of providing solution to the minimization by transforming non-normal and correlated variables, as

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well as computing the failure probability (P_f) using Eq. (6).

FORM 5 provides approximation to Eq. 6 through transformation, locating β point through optimization, linearizing limit state function at the point and computing failure probability using the standard normal integral.

$$P_f = \mathrm{P}(\mathrm{X} \in \mathrm{F}) = \mathrm{P}\ (\mathrm{G(X)} \leq 0) = \int_{\mathrm{G(X)} \leq 0}^{0} \mathrm{d}\, \mathrm{F_x(X)} (6)$$

$$P_f = \Phi\ (-\beta)(7)$$

Where β and Φ are the reliability index and standard normal integral respectively. According Gollwitzer, Abdo & Rackwiz(1988), the reliability index (β) can be computed from Eq. (7) provided by Thoft-Christensen & Baker (1982).

$$\beta = -\Phi^{-1}(P_f) \qquad (8)$$

In this study, the adequacy or inadequacy of the limit state formulations of EN1992-1-1 (2008) in relation to safety provision in the Nano Engineered Reinforced Concrete Beam (NERC) designed for this study according to its methodology was adjudged using the reliability (safety index) value determined from Eq. (8).

3.2 NANO ENGINEERED CONCRETE CHARACTERISTIC COMPRESSIVE STRENGTH PREDICTIVE MODELS AND NERC BEAM NOTATIONS

The study adopted the characteristic compressive strength predictive models of nano engineered concrete developed by Adamu *et al.* (2024) which are presented herein as Eqs. (9) and (10).

$$f_{ck1} = 6.512 + 5.263 \times 10^{-2} C_T + 5.924 D_{NS} - 2.529 D_{NS}^2 \qquad (9)$$

$$f_{ck2} = 63.561 - 76.136 WC_R + 5.924 D_{NS} - 2.529 D_{NS}^2 \qquad (10)$$

Where f_{ck1}, f_{ck2} , C_T, D_{NS}, WC_R were characteristic cube compressive strengths for model 1 and 2, cement content in kg/m^3, nanosilica dosage in % and water to cementitious materials ratio respectively.

The characteristic cube compressive strengths obtained from Eqs. (9) and (10) were converted to characteristic cylindrical compressive strength according toEN1992-1-1(2008) using Eq. (11) adapted from Domone (2010).

$$f_{cylk} = 0.85 f_{ck(1\ or\ 2)} - 1.6 \qquad (11)$$

Where $f_{ck(1\ or\ 2)}$ andf_{cylk} are characteristic cube compressive strengths and characteristic cylindrical compressive strengths respectively obtained from the predictive models.

Also, the Nano Engineered Reinforced Concrete (NERC) beam notations were adopted from Adamu*et al.* (2020a) and Adamu *et al.* (2020b). The Optimal Nano Engineered Concrete (ONEC) mix notations for grades 30 and 40 concrete are 30NS1.5 and 40NS1 respectively which were named to account for optimal nanosilica dosages of 1.5% and 1% by weight of cementations materials for the two concrete gradesdetermined through laboratory experiments and reported in Adamu *et al.*(2020a) and Adamu *et al.*(2020b) respectively.

3.3 DERIVATION OF PERFORMANCE FUNCTIONS

*3.3.1*Bending criterion

EN1992-1-1(2008) provides that the tensile and compressive capacities of a beam section (simply supported beam with point load at midspan in this case) can be determined from Eqs. (12) and (13) respectively.

$$M_c = 0.167 f_{cylk} b d^2 \qquad (12)$$

$$M_T = 0.87 f_{yk} A_s (d - \frac{0.87 f_{yk} A_s}{1.134 f_{cylk} b}) \qquad (13)$$

Where f_{cylk}, b, d, A_s, f_{yk}, M_T, and M_C are characteristic cylindrical compressive strength, breadth of beam section, effective depth of beam section, area of tension steel, characteristic strength of steel, tensile and compressive moment capacities for the beam respectively.

To enable determination of the actual safety provided in EN 1992-1-1 (2008) design formulations, the respective partial safety factors of 1.15 and 1.5 provided to take care of uncertainties in reinforcing steel and concrete were removed from Eqs. (12) and (13). The re-derived equations are given as Eqns. (14) and (15) for compressive and tensile bending respectively.

$$M_{RC} = 0.251 \phi_R f_{cylk} b d^2 \qquad (14)$$

Where M_{RC} is resistance compressive moment, f_{cylk} , d, b are as defined above with ϕ_R being the compressive moment capacity resistance model uncertainty.

$$M_{RT} = \phi_R f_{yk} \rho b d (d - \frac{f_{cylk} \rho b d}{1.7 f_{cylk} b}) \qquad (15)$$

Where M_{RT} is tensile moment resistance,f_{yk} is steel yield strength,ρ is reinforcement ratio,f_{cylk},d, b are as defined above while ϕ_R is the tensile resistance moment model uncertainty.

To take care of the effect of action, the maximum applied bending moment for a simply supported beam with point load at midspan considering self weight was derived and presented as Eq. (16).

$$Ma = \phi_S (0.25 \mathrm{P} L + 0.125 \gamma_c b h g L^2 \times 10^{-9}) \qquad (16)$$

Where M_a is applied moment, P is point load at midspan, γ is concrete unit weight, g is gravitational acceleration, b is beam breath, L is span of beam,h is beam depth and $\phi_S$is load model uncertainty.
The performance functions for tensile and compressive bending failure are given by Eqs.

The respective performance functions for compressive (G_{MC}) and tensile (G_{MT}) bending failure modes are given by Eqs. (17) and (18) derived from the above equations.

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$$G_{MC} = M_{RC} - M_a \qquad (17)$$

$$G_{MT} = M_{RT} - M_a \qquad (18)$$

WhereM_{RC},M_a, M_{RT}, are compressive moment resistance, applied moment and tensile moment resistance respectively.

3.3.2 Shear criterion

EN1992-1-1(2008) limit state equation for sections without shear reinforcement is as given by Eq. (19) after the code based substitutions and simplifications.

$$V_c = \phi_R(0.18(1+\sqrt{\frac{200}{\mathrm{d}}})(\rho f_{cylk})^{1/3})bd \qquad (19)$$

Where Vc is shear resistance,
$f_{cylk}$is characteristic cylindrical compressive strength,
b is beam's breadth,
ρ is reinforcement ratiowith $\phi_R$being the shear resistance factor.

Considering the effect of self weight, the maximum shear force obtained from basic structural analysis for the selected loading and beam configuration is given by Eq. (20).

$$V_a = \phi_S(0.5\mathrm{P} + 0.5\gamma_c bh\mathrm{L}g \times 10^{-9}) \qquad (20)$$

Where Va is the maximum shear forceP, b, g and h are as defined above while γ_c isthe concrete unit weight.

The shear failure mode performance function is given by Eq. (21) obtained from the above equations.

$$G_{vx} = V_c - V_a \qquad (21)$$

Where Va and Vc are the applied shear force and shear capacity respectively.

3.4PROBABILISTIC MODEL PARAMETERS

The stochastic model parameters of the study are presented in Table 1 obtained from designs, statistical analysis of experimental data and literature.

Table 1: Stochastic Parameters of Design Variables (JCSS: 2001, 2002)

S/No	Basic Variable	Unit	Mean	COV	Distribution
1	Unit Weight of Concrete (Υ_c)	Kg/m³	2400.00	0.100	Normal
2	Breadth of Beam (b)	mm	230.00	0.045	Normal
3	Beam Depth (h)	mm	250	0.086	Normal
4	Span (L)	mm	1200	0.044	Normal
5	Steel Yield Strength (f_{yk})	N/mm²	500	0.200	Normal
6	Compressive Strength(f_{cylk})	N/mm²	28	0.130	Log-normal
7	Reinforcement Ratio(ρ)	%	1.90	0.200	Normal
8	Live Load (P)	kN	50	0.400	Gumbel
9	Nanosilica Dosage(D_{NS})	%	1.50	0.100	Normal
10	Total Binder Content (C_T)	Kg/m³	433	0.100	Normal
11	Water Cement Ratio (WC_R)	Nil	0.45	0.100	Normal
12	Bar Diameter	mm	20	0.200	Normal
13	Resistance Model Uncertainty (ϕ_R)	Nil	1.00	0.100	Normal
14	Load Model Uncertainty (ϕ_S)	Nil	1.00	0.100	Normal

JCSS = Joint Committee on Structural Safety

3.5 Computation of Safety Index (β) and Failure Probability (P_f)

First Order Reliability Method coded in FORM5 (Gollwitzer, Abdo & Rackwiz(1988)) used by researchers (Adamu *et al.*, 2023; Wasiu & Adedeji, 2018; Abubakar, Afolayan & Osinubi,2014; Abejide, 2014; Adamu, 2014; Abejide & Adamu, 2013) was employed in the reliability analysis through development of FORTRAN based subroutines in line with FORM5, EN1992-1-1 (2008) and its reference standard and linking them to the program for computation of safety index and probability of failurefor each of the selected failure modes. Some of the NERC beam design variables provided in Table 1 were varied with other design variable values fixed in the developed subroutines. The results obtained are presented in Figures 1 to 5.

4 RESULTS AND DISCUSSION

4.1 Effect of Applied Load and NEC Grade on Beam Safety

Figure 1 presents results of sensitivity analysis where variation of safety index with change in characteristic compressive strength of Nano Engineered Concrete (NEC) mixes and change in applied load was considered for the Nano Engineered Reinforced Concrete (NERC) beam under shear failure mode. A reduction in safety index of the beam was observed with increase in applied load for the two mixes (30NS1.5 and 40NS1) in accordance with Adamu (2014). This behaviour of the NERC beam could be attributed to the fact that increase in load beyond the carrying capacity of the beam usually lead to incapacitation of the section where the maximum load effect occurs. Respcetive safety index values of 2.26 (P_f= 1.58× 10^{-2}) and 2.49 (P_f= 1.06× 10^{-2}) were obtained at design point (applied load = 50.00 kN), for mixes 30NS1.5 (f_{cylk}= 28.40 N/mm²) and 40NS1 (f_{cylk}= 38.20N/mm²). This indicates 10.18% increase in the beam safety with 35.77% increase in compressive strength. Therefore, it could be concluded that change in compressive strength of the NEC mixes slightly affect shear capacity of the beam. With the two mixes (30NS1.5 and 40NS1), the beam could not meet the target safety

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index of 3.8 specified by Eurocode 0 (EC0) for normal structures, neither did it meet the target safety index values of 3.10, 3.30 and 3.70 recommended by JCSS-1.0 (2001) for minor, moderate and large consequences of failure considering large cost of achieving safety. This calls for reduction of applied load to maximum of 22.00 kN and 25.00 kN for 30NS1.5 and 40NS1 mixes respectively if the beam is to meet the target safety index of 3.8 in shear according to EC0. To this end, a suggestion is made to improve the safety margin of Eurocode 2 (EC2) design formulations for shear design of sections without shear reinforcement so as to enable attainment of EC0 recommended target safety index value at design point (applied load = 50.00 kN). Another way of improving safety of the NERC beam section and countering the effect of excessive shear stress beyond the section carrying capacity is to design and provide shear reinforcement in the NERC beam section according to Eurocode 2.

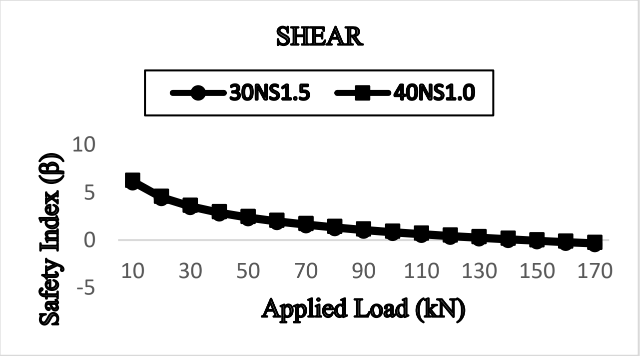

Figure 1: Effect of Applied Load on Safety of beam in Shear

Load increase resulted to decrease in safety index of NERC beam in bending as presented in Figure 2 in line with Adamu (2014). Safety index values of 5.69 and 1.13 were obtained at applied loads of 10.00 kN and 170.00 kN respectively but the 35.77% increase in NERC mix characteristic compressive strength (from 30NS1.5 to 40NS1) did not significantly affect the beams safety and its tensile bending capacity as presented in Figure 2. This could be attributed to lack of role of characteristic compressive strength in computation of beam tensile moment capacity, as it only affects the beam neutral axis position.Respective safety index values of 3.45 and 3.52 were obtained for (f_{cylk}= 28.40 N/mm²) and 40NS1 (f_{cylk}= 38.20N/mm²) NEC mixes at design point leading to 2.03% increase in safety index with 35.77% rise in compressive strength. Restricting applied load to maximum of 50.00 kN, 40.00 kN and 30.00 kN for the NERC beam is necessary if it is to meet the target safety index values of 3.30, 3.80, and 4.30 attached to reliability classes of REC1, REC2 and REC3 at a reference period of 50 years according to EC0.

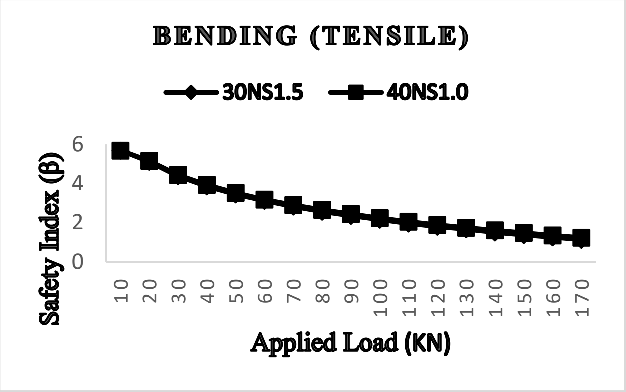

Figure 2: Effect of Applied Load on Safety of beam under Tensile Bending

The results of varying characteristic cylindrical compressive strength of Optimal Nano Engineered Concrete (ONEC) mixes and applied load are presented in Figure 3.At the top fibre where the NERC beam is subjected to compressive bending, increase in applied load led to decrease in safety index with failure probability increasing with increase in applied load in accordance with Wasiu & Adedeji(2018), Abejide(2014), and Adamu, (2014). This indicates that an inverse variation exist between safety index and probability of failure; meaning that less likely hood of failure abound RC elements with better safety index values when compared with those having lower safety index values.

At design point (applied load = 50.00 kN), under compressive bending and for NEC mixes 30NS1.5 and 40NS1, safety index values of 3.51 (P_f= 2.22× 10^{-4}) and 4.15 (P_f= 1.69× 10^{-5}) were obtained. This indicates that there was 18.23% rise in safety index under compressive bending when NEC grade was changed from 30NS1.5 (f_{cylk}= 28.40 N/mm²) to 40NS1 (f_{cylk}= 38.20N/mm²); equivalent to 35.77% rise in compressive strength. This shows that the safety of NERC beam compression strut is reasonably sensitive to change in NEC characteristic compressive strength. Therefore, when compression reinforcement is not provided in NERC beam section, high compressive strengths are essential in avoiding NERC beam compressive failure due to applied bending moment. Compressive bending failure of the NERC beam appears to be the most sensitive to the NEC mixes as more visible difference in safety index values was observed on this failure mode.

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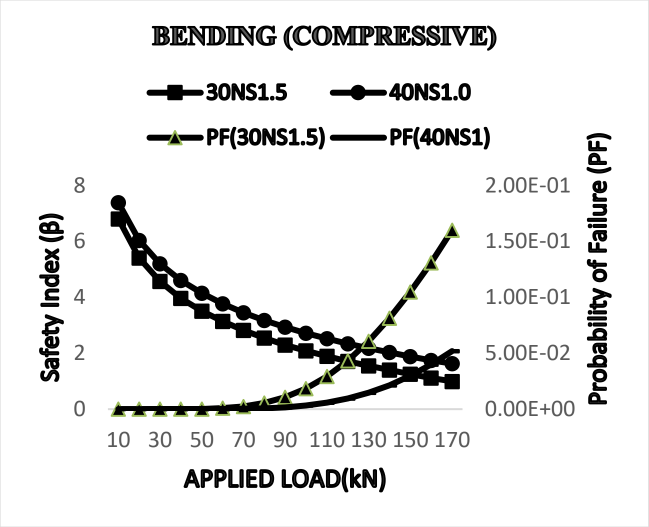

Figure 3: Effect of Applied Load on Safety and Failure Probability of beam in compressive bending

4.2 EFFECT OF REINFORCEMENT RATIO ON SAFETY INDEX AND PROBABILITY OF FAILURE

The results of varying reinforcement ratio on safety of NERC beam with 30NS1.5 designation at design point (applied load = 50.00 kN) considering shear and tensile bending failure modes are presented in Figure 4. From Figure 4, considering the two failure modes (tensile bending and shear), safety index was observed to rise with rise in reinforcement ratio while failure probability reduced with rise in reinforcement ratio in accordance with Othman *et al.*(2014) and Wasiu & Adedeji (2018). Increase in the NERC beam shear and tensile capacity with increase in reinforcement ratio could be attributed to decrease in probability of failure and increase in safety index. The tendency of tensile reinforcement to obstruct path of shear failure propagation could be attributed to the observed increase of NERC beam shear capacity with increase in tensile reinforcement ratio. These indicate that higher tensile reinforcement areaimproves safety and decrease the probability of NERC beam shear failure.

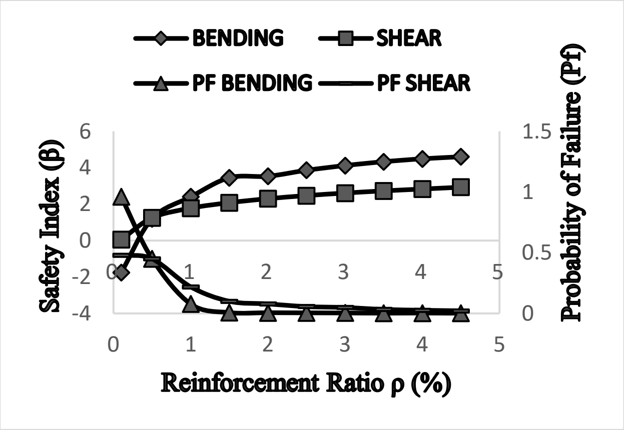

Figure 4: Effect of reinforcement ratio on safety and failure probability of beam in bending and shear

Tensile bending leads the failure modes at reinforcement ratio below the Eurocode 2 calculated value ($\rho < 0.50$ %). This might be due to the fact that the tensile contribution of the concrete in the beam is what could sustain tensile stresses at reinforcement ratio below the required tensile reinforcement ratio. Therefore, inability of concrete in the NERC beam to sustain applied stresses at this stage could lead to catastrophic failure of the beam; being that the calculated safety index at design reinforcement ratio (ρ = 0.50 %) according to Eurocode 2 yielded a safety index value of 1.2 (P_f= 0.116), which was found to be less that the EC0 recommended target safety index of 3.8 for normal structures. This finding indicates that reinforcement ratio above the calculated value is required for the beam to be safe against tensile bending failure. As such, the practice of selecting reinforcement areas greater than calculated values in RCD is a good one, and could be extended to NERC.

Shear was found to be the most critical failure mode above 0.50 % reinforcement ratio when compared with tensile bending in agreement with Marta *et al.* (2017). At design point (applied load = 50.00 kN, ρ = 1.90 %), the safety index values obtained were 2.26 (P_f= 7.82×10^{-2}) for shear and 3.50 (P_f= 5.90×10^{-3}) for tensile bending respectively; which were 68.14% and 8.57% less than the EC0 recommended target safety index of 3.8 for normal structures. To achieve EC0 target safety index at design point for sections without shear reinforcement, there is need for reviewing EC2 design formulations for shear and tensile bending in accordance with the recommendations of Abejide (2014) on reinforced concrete slab. Another way of improving safety of the NERC beam and countering the effect of excessive shear stress beyond the carrying capacity of the beam section is to design and provide shear reinforcement in the beam section according to Eurocode 2.

4.3 EFFECT OF VARYING NERC BEAM SPAN ON SAFETY INDEX

The effect of span variation on safety index of Nano Engineered Reinforced Concrete (NERC) beam (30NS1.5) with change in failure mode is presented in Figure 5. This sensitivity analysis becomes necessary in order to determine the failure mode most affected by span variation. The span of NERC beam was varied from 200mm to 7200mm with the safety index for each failure mode recorded and compared.

Variation of safety index with span as presented in Figure 5 indicates that safety index drops with increase in span in accordance with Adamu (2014) and Wasiu and Adedeji(2018). Increase in applied bending moment and shear force with increase in span could be attributed to the decrease in safety index with increase in span as concluded by Adamu (2014). The criticality of the failure modes (shear, and bending: tensile and compressive) was found to change with increase in span in accordance with Adamu (2014), as presented in Figure 5. Shear became the most critical failure mode between span of 200mm and

800mm followed by tensile and compressive bending respectively. When span was increased from 800mm to 2200mm, shear led the failure modes in criticality while tensile and compressive bending equate in terms of criticality. Above the span of 2200mm, compressive bending became the most critical failure mode. Therefore, it could be concluded that the NERC beam behaviour between 200mm and 2200mm is that of short span beams in line with the conclusions of Adamu (2014). Further, compression strut failure due to excessive bending stress beyond the carrying capacity of the NERC beam section in the absence of compression reinforcement could be attributed to the NERC beam behaviour beyond the span of 2200mm. As such, it could be said that the intersection of the failure modes represent a transition point between singly and doubly reinforced NERC beam. Moreover, it could be concluded that the failure modes intersection represents the limiting span (2200mm) beyond which the designed cross section cannot be singly reinforced.

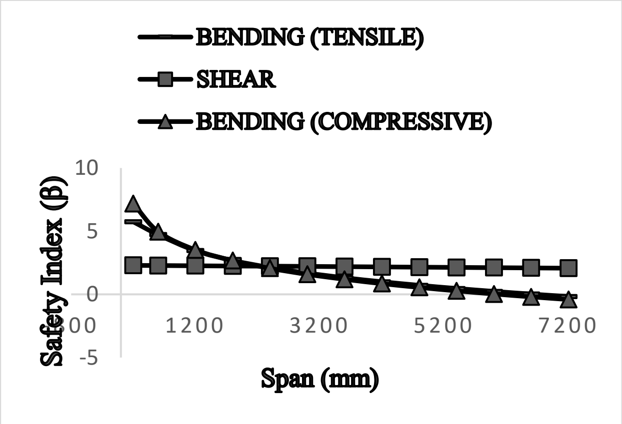

Figure 5: Effect of Span on Safety of NERC Beam in Bending and Shear

The failure mode that was least affected by increase in span was shear, as safety index values of 2.29 and 2.07 were obtained at spans of 200mm and 7200mm respectively signifying a decrease of 0.22 in safety index with an increase of 7000mm in span. This behaviour could be linked to the fact that span does not affect magnitude of applied shear force resulting from the type of applied load (point load located at midspan) and the effect of NERC beam self-weight addition with increase in span on applied shear force, with the type of applied load was negligible.

*4.4*Effect of Steel Yield Strength Variation on Safety Index

Figure 6 presents the effect of steel yield strength variation on safety of Nano Engineered Reinforced Concrete (NERC) beam. From Figure 6, a decrease in safety index value with decrease in steel yield strength was observed in accordance with Abejide & Adamu (2013). This indicates a direct proportionality relationship between safety index and characteristic or design strength of steel in line with Abejide & Adamu (2013). At yield strength of 200N/mm^2 and 600N/mm^2, respective safety index values of 1.93 and 3.84 were recorded. This finding indicates that inability to achieve design yield strength of steel in tensile bending could lead to tensile bending failure of the NERC beam. Generally, safety index value increased with increase in reinforcement ratio and constant steel yield strength in accordance with Othman *et al.* (2014) and Wasiu & Adedeji (2018). As such, it could be said that the practice of selecting reinforcement area greater than calculated values in Reinforced Concrete Design (RCD) is good one as it reduces the possibility of failure resulting from non actualization of characteristic or design yield strength of steel at project implementation stage. This practice could be extended to NERC.

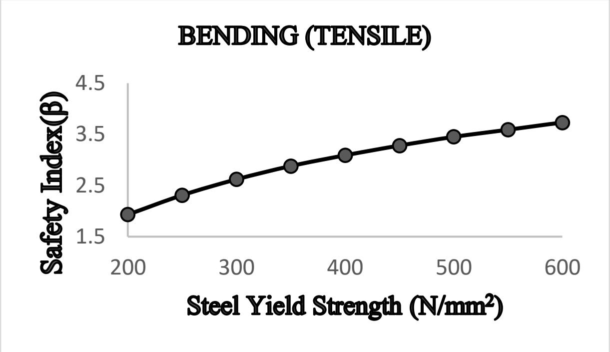

Figure 6: Effect of steel characteristic yield strength on safety of beam in tensile bending

5 CONCLUSIONS

This work presents reliability analysisof Nano Engineered Reinforced Concrete (NERC) beam done according to EN1992-1-1 (2008) and its reference standards. In the study, safety index and failure probabilities were computed at design point for a singly reinforced NERC beam without shear reinforcement designed according to EN1992-1-1 (2008) and its reference standard. Further, some selected NERC beam design variables were varied to determine their effect on the beam's safety and failure probability. The study found that NERC beam behaves in a similar manner to conventional reinforced concrete beam on strength aspect. At design point, the NERC beam has failed to meet the target safety index values provided by EN1990: 2002 (EC0) as a reference standard of EN1992-1-1 (2008) for all the failure modes considered. Therefore, the work suggested that the safety margin provided by EN1992-1-1 (2008) and its reference standards for the design of singly reinforced concrete sections without shear reinforcement be improved. Finally, the study observed the need for incorporation of reliability-based design in Civil Engineering design standards.

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