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Original Research Article

Experimental and Theoretical Shear Strength of Simply Supported Reinforced Concrete Beam

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Abstract

The study was conducted to evaluate the experimental and theoretical shear strength of a simply supported reinforced concrete beam with and without shear reinforcement in accordance with Eurocode 2 design criteria. Fifteen (15) reinforced concrete beams of dimension 750mm x 150mm x 150mm reinforced with diameter 12mm size bars were cast at various reinforcement ratios (i.e. 1.0%, 1.5%, 2.0%, 2.5%, and 3.0%), while preliminary and mechanical tests were conducted on the materials (i.e. cement, fine and coarse aggregate, and reinforcement bars) in accordance with relevant codes and standards. The outcome from the findings showed that the cement, fine aggregate and coarse aggregate used to cast the reinforced concrete beam were well graded and satisfies the requirement of code specification. More results showed that the average diameter of the reinforcement bars are 11.67mm, the mean tensile and ultimate strength of the reinforcement bars are 389.73N/mm^2 and 640.80N/mm^2 respectively, while the mean reinforcement steel elongation is 14.23% which mostly met code requirement indicating suitability of the reinforcement bars usage in concrete. Furthermore, the result from the findings showed that the Eurocode 2 (EC2) design criteria of beams without shear reinforcement were lower than the experimental value, while EC2 design criteria for beams with shear reinforcement was close to the experimental value.

Keywords: Shear strength, Reinforcement, Reinforced concrete, Beam, EuroCode.

1.0 INTRODUCTION

A reinforced concrete (RC) beam member is defined as a flexural member which resists loads mainly by bending. Similarly, the resistance or response of a RC beam depends on the physical properties of the materials, and geometrical dimensions of RC beam which are also subjected to statistical variations, and are probabilistic in nature (Taj *et al.*, 2017). The major failure modes in a RC beam that requires focus are the bending moment, deflection, and shear capacity of the beam (John & Adedeji, 2018). The bending and shear failure of a RC beam is a type of failure which can appear in reinforced concrete beams in a support zone and it is caused by bending moment and shear force acting simultaneously in a cross section (Słowik *et al.*, 2017). The safety of a RC beam depends on the resistance 'R', of the beam and action 'S' (load or load effects) on the beam. The action is a function of loads (live load, dead load and super dead.) which are random variables, and the resistance or response of the R.C. beam depends on the physical properties of the materials, and geometrical dimensions of R.C. beam which are also subjected to statistical variations, and are probabilistic in nature (Taj *et al.*, 2017).

Using probabilistic methods, a limit state is verified by direct comparison of the calculated (notional) failure probability with a specified target value given for a reference period adopted for reliability analysis. The flexibility of probabilistic methods makes it possible to reflect structure-specific conditions including requirements on structural performance and local environmental effects. Use of these advanced methods is often justified in cases when very little or very detailed information about structures is available (material properties, geometry, loads) or when expected failure consequences are significant (economic or ecological losses, fatalities and injuries) (Holický, 2013; Steenbergen *et al.*, 2015; Sykora *et al.*, 2017).

The method of designing rectangular reinforced concrete beam is based on limit state design philosophy which makes use of partial safety factors for material strength and load, and since the design variables are random in nature, it becomes much more important to assess the level of safety in the probabilistic design situation (Taj *et al.*, 2017). Also, the lack of knowledge on the potential load applied to a RC structure, as well as the uncertainties related to its features (geometry, mechanical properties) shows that the design of RC structures could be made in a reliability framework in which structural reliability provides the tools necessary to account for these uncertainties and evaluate an appropriate degree of safety (Kassem, 2015).

The failure in reinforced concrete beams is the most often observed in a support zone due to bending moment and shear force acting simultaneously in a cross section and can lead to dangerous, brittle damage (Słowik *et al.*, 2017). Strengthening of reinforced concrete (RC) members in structural engineering is a methodology to address deficiencies from several causes, e.g. design mistakes, changes in the use of a structure, repairing damaged structures or new code requirements, among many others. These deficiencies could lead to bending and shear failures of RC members (a type of failure associated with brittle collapses) which could cause sudden material loss and loss of human lives (Gibert, 2019).

Olawale *et al.*, (2021) compared the Reliability-Based Design (RBD) method with Eurocode 2 (EC2) for a singly reinforced concrete beam. And found that the code provision exceeded the RBD output by 2000 times and 63 times the minimum reinforcement requirement by the code. Similarly, Abejide (2014) assessed reinforced concrete slabs subjected to failure modes in flexure, shear, and deflection with thickness ranging from 100 mm to 250 mm and observed that the design assumptions in EC2 were not safe and dependable as suggested. Hence, review must be made on the code formulations to conform to accepted structural safety set out by the Joint Committee of Structural Safety (JCSS). From the foregoing, due to variation in the adopted code of practices in Nigeria, there is need to compare the experimental and theoretical shear capacity of the beam according to Eurocode 2 design criteria.

2.0 MATERIALS AND METHODS

2.1 Materials

The materials used in this study includes cement, fine and coarse aggregate, water, and steel reinforcement bars.

2.1.1 Cement

Cement was obtained from the open market at Zaria-Kaduna State, Nigeria and used for the experiment.

2.1.2 Fine aggregate

The fine aggregate used was sieved through a BS 4.75mm sieve to remove some of the contained coarse aggregates.

2.1.3 Coarse aggregate

Crushed granite was used in this research. It was obtained from a local dealer within Zaria city, Kaduna State, Nigeria.

2.1.4 Water

Clean and portable drinking water was sourced from Civil Engineering Department of Ahmadu Bello University Zaria Kaduna-state and was used for mixing and curing of the concrete cubes and reinforced concrete Beams.

2.1.5 Steel Reinforcement Bars

Reinforcement steel bar sizes of diameter 12mm, was considered in this study as shear link and main bars, and they were obtained commercially from the open market within Zaria city, Kaduna State, Nigeria.

2.2 Methods

The test methods adopted in the research work are the physical and chemical properties of the cement, properties of the fine and coarse aggregate, mechanical properties of the steel reinforcement bars and shear strength test of the beams. All the tests were conducted in conformity with relevant codes and standard.

2.2.1 Tests on Cement

2.2.1.1 Consistency of Cement

This test was conducted in accordance to BS-EN-196-3 (2016).

2.2.1.2 Setting Time of Cement

The test was conducted as described in BS-EN-196-3 (2016).

2.2.1.3 Soundness of Cement

The test was conducted on cement using the Le Chaterlie's mould as described in BS-EN-196-3 (2016). The specimens were prepared using the water-cement ratio as determined from the consistency test. The expansion of each of the specimen was measured.

2.2.1.4 Specific Gravity of Cement

This test was carried out in accordance with BS-EN-196-3 (2016).

2.2.2 Test on Aggregate

2.2.2.1 Sieve Analysis of Fine and Coarse Aggregates

Sieve analysis was conducted on fine and coarse aggregate in accordance with BS-882:2 (1992).

2.2.2.2 Moisture Content Tests of Aggregates

Three tests was done to ascertain the average natural moisture content for the aggregates in accordance with BS-812:2 (1995).

2.2.2.3 Specific Gravity of Coarse and Fine Aggregate

The specific gravity tests for coarse and fine aggregates were conducted in accordance with BS-812:2 (1995).

2.2.2.5 Bulk Density of Aggregate

The bulk density test was conducted in accordance with BS-812:2 (1995).

2.2.2.6 Aggregate Impact Value Test

The test was conducted in accordance to BS-812-110 (1990).

2.2.2.7 Aggregate Crushing Value

The aggregate crushing value test was carried out in accordance with BS-812-110 (1990).

2.2.3 Test of Steel Bars

The reinforcement steel bars were tested for its mechanical properties i.e. yield strength, ultimate strength, elongation, and diameter in accordance with relevant codes and standards. The reinforcement steel testing was carried out at the concrete laboratory of the Department of Civil Engineering, Ahmadu Bello University Zaria.

2.2.3.1 Diameter of Steel Bars

The actual diameter of the reinforcement steel bars was determined using the Universal Testing Machine (UTM) in accordance with the recommendations of BS-4449 (1997), and after fracture, the average Yield Strength (YS), average Ultimate Tensile Strength (UTS) and the Percentage Elongation (%E) were obtained using the expressions in equation 1-3:

$$\text{Yield Strength (N/mm}^2) = \frac{\text{Yield Force}}{\textit{Original Cross Sectional Area}} \qquad (1)$$

$$\text{Ultimate Tensile Strength (N/mm}^2) = \frac{\text{Maximum Force the Specimen can withstand}}{\text{Original Cross Sectional Area}} \qquad (2)$$

$$\text{Percentage Elongation (\%)} = \frac{\text{Final Length} - \text{Original Length}}{\text{Original Length}} \qquad (3)$$

The characteristic strength was determined in accordance with ISO-6935-2 (2019) provisions as shown in equation 4;

$$m_{15} - 2.33S_{15} \geq f_y \qquad (4)$$

Where;
m_{15} is the mean value of the tensile strength
S is the standard deviation 2.33 is the value for the acceptability index, *k*, for *n* = 15 for a failure rate of 5%.
f_y is the required characteristic value

2.3 Concrete Mix Design

A trial mix design of the concrete was conducted to obtain a target concrete strength of 35N/mm^2 at 28 days with a w/c ratio of 0.45.

2.4 Tests on Concrete Cubes

2.4.1 Compressive Strength Test

The compressive strength test of the hardened concrete cube was determined after 28 days using the compressive testing machine at the concrete laboratory of Ahmadu Bello University Zaria in accordance with BS-EN-12390-3 (2009).

2.4.2 Beam Shear Strength

Shear test was conducted on the reinforced concrete beam in accordance with EN-1992 (2004). The shear test was a three point bending test simply supported at 150mm away from the edge of the beam from both sides as shown in Figure 1.

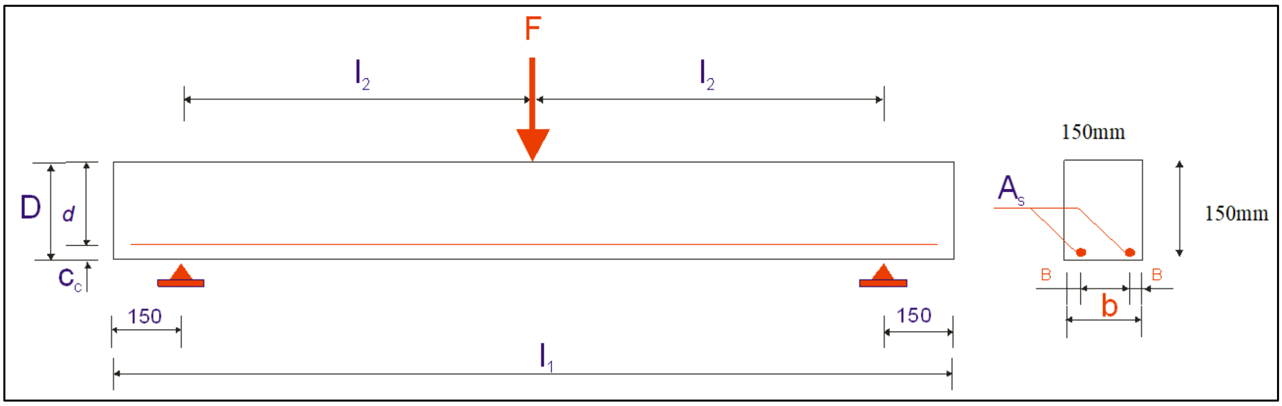

Figure 1: Geometric Properties of Beam Specimen

Figure 1 shows a schematic diagram of the beam. The overall length of the beam was 750mm, the overall depth was 150mm, the effective depth is taken as ‘d’, the breath of the beam was also 150mm, the concrete cover was 20mm, and the beam was simply supported at 150mm from each end as shown in Figure 1. Also, the reinforced concrete beam consists of beams with and without shear reinforcements, and the beams consists of five (5) reinforcements ratios (i.e. 1.0%, 1.5%, 2.0%, 2.5%, and 3.0%) as shown in Table 1.

Table 1: Reinforcement Beam Property Schedule

Sn	Beam Specimen	Breadth (b)	Depth (d)	Length (L)	Diameter	Number of bars	Reinforcement ratio (%)
1	A1	150	150	750	12	2	1.0
2	A2	150	150	750	12	2	1.0
3	A3	150	150	750	12	2	1.0
4	B1	150	150	750	12	3	1.5
5	B2	150	150	750	12	3	1.5
6	B3	150	150	750	12	3	1.5
7	C1	150	150	750	12	4	2.0
8	C2	150	150	750	12	4	2.0
9	C3	150	150	750	12	4	2.0
10	D1	150	150	750	12	5	2.5
11	D2	150	150	750	12	5	2.5
12	D3	150	150	750	12	5	2.5
13	E1	150	150	750	12	6	3.0
14	E2	150	150	750	12	6	3.0
15	E3	150	150	750	12	6	3.0

From Table 1, a total of 15 beams were cast containing reinforcement ratios (1.0 – 3.0%). However, for each reinforcement ratio, the beams were cast in triplicates as shown in the table.

2.5 Eurocode 2 Shear Strength Equation

The shear resistance of the beams was determined by the equation given in European Standard EN-1992 (2004) Eurocode 2 as shown in equation 5 - 8. However, equation 5 was used to calculate reinforced concrete beam without shear reinforcement, while equation 6 – 8 was used to calculate beams with shear resistance.

$V_{Rd,c} = [C_{Rd,c}\, k(100\, \rho_l\, f_{ck})^{1/3} + k_1\, \sigma_{cp}]\, b_w d$ (5)

With a minimum of

$V_{Rd,\,C} = (V_{min} + k_1\sigma_{cp})\, b_w d$

Where;

F_{ck} = characteristic compressive strength of concrete in MPa,

b_w = smallest width of the cross section in the tension area in mm,

d = effective depth of the cross section in mm,

$\rho_l = A_s/bd$ which is the ratio of tensile reinforcement ($\rho_l \leq 0.02$)

$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0$,

$\sigma_{cp} = \frac{N_{Ed}}{A_c} < 0.2\, f_{cd}$ - stress caused by axial force in MPa and is = 0 for non-prestressed members,

$V_{min} = 0.035 k^{3/2} f_{ck}^{1/2}$,

$C_{Rd,c} = 0.18/\gamma_c$

γ_c = safety coefficient for concrete (1.5)

$f_{cd} = \alpha_{cc}\, f_{ck} / \gamma_c$ is value of design compressive strength

α_{cc} = 1 for non prestressed members

For members with vertical shear reinforcement, the shear resistance, V_{Rd} is the smaller value of:

$V_{RD,S} = \frac{A_{sw}}{s}\, Z\, F_{ywd} \cot\theta$ (6) and

$V_{RD,max} = \dfrac{\alpha_{cw}\, b_w\, Z\, v_1\, f_{cd}}{\cot\theta + \tan\theta}$ (7)

Where;

A_{sw} is the cross-sectional area of the shear reinforcement

s is the spacing of the stirrups

f_{ywd} is the design yield strength of the shear reinforcement

v_1 is a strength reduction factor for concrete cracked in shear

α_{cw} is a coefficient taking account of the state of the stress in the compression chord and is = 1 for non prestressed structure

$v = 0.6\, [1 - f_{ck}/250]$

Z = 0.9d

d is the effective depth

Also, θ in equations 6 and 7 can be gotten as;

$\theta = \frac{1}{2} \sin^{-1}\left[\frac{2V_{ed}}{\propto_{cw}\, b_w\, Z\, v_1\, f_{cd}}\right]$

(8)

Where $22^0 \leq \theta \leq 45^0$

3.0 RESULTS AND DISCUSSION

3.1 Preliminary Test Result of Materials

Preliminary tests were conducted on the materials used in this study to determine its conformity to relevant codes, tests were conducted on cement, fine and coarse aggregate, and the results are presented in Table 2.

Table 2: Aggregate Preliminary Tests Result

Description of Test	Results	Standard	Code
Cement			
Consistency (%)	30.0	26-33%	BS-EN-196-3 (2016)
Initial setting time (mins)	133	≥45	BS-EN-196-3 (2016)
Final setting time (mins)	189	≤ 600	BS-EN-196-3 (2016)
Soundness (mm)	2.0	≤ 10mm	BS-EN-196-3 (2016)
Specific gravity	3.14	3.1 – 3.16	BS-EN-196-3 (2016)
Fine Aggregates			
Bulk density (kg/m^3)	1360	<1520	BS-812:2 (1995)
Specific gravity	2.50	2.5 – 2.8	BS-812:2 (1995)
Coarse Aggregate			
Bulk density (kg/m^3)	1405	<1520	BS-812:2 (1995)
Specific gravity	2.60	2.5 – 2.8	BS-812:2 (1995)
Aggregate crushing value (%)	26.02	25 – 30%	BS-812-110 (1990)
Aggregate impact value (%)	25.9	25 – 30%	BS-812-110 (1990)
Water absorption (%)	0.67	< 3%	BS-812:2 (1995)

The results from Table 2 shows that the cement used in this study is adequate for concrete production since the consistency (30%), initial setting time (133 minutes), final setting time (189 minutes), soundness (2mm), and specific gravity (3.14) all met code requirements.

Also, from the table, the fine and coarse aggregate used in this study were found to be adequate for concrete production since the specific gravity, bulk density, aggregate crushing value, aggregate impact value, and water absorption value all met code requirements.

3.1.1 Gradation of Fine Aggregate

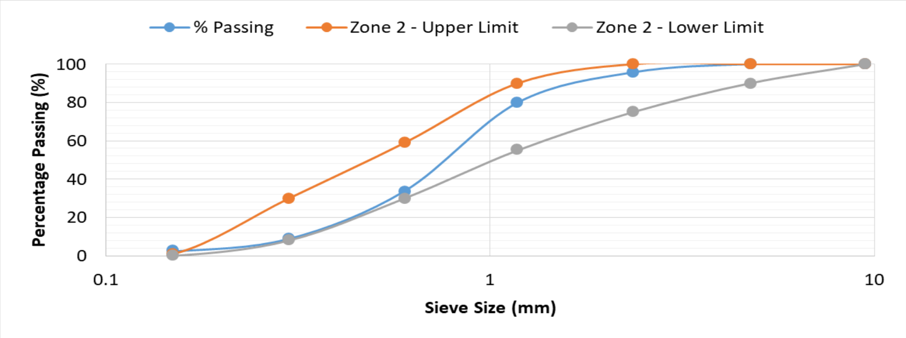

Figure 2: Particle Size Analysis of Fine aggregate

Figure 2 shows the Particle size analysis of the fine aggregate. In grading the fine aggregate, BS 812-1992 was used, which showed that the fine aggregate can be classified as zone 2. This grading zone is a function of the fineness modulus. The fineness modulus is an empirical index of coarseness or fineness of the aggregate obtained by the addition of the cumulative percentages retained on each of the standard sieves. This shows that the fine aggregate is good for the production of mortar.

3.1.2 Gradation of Coarse Aggregate

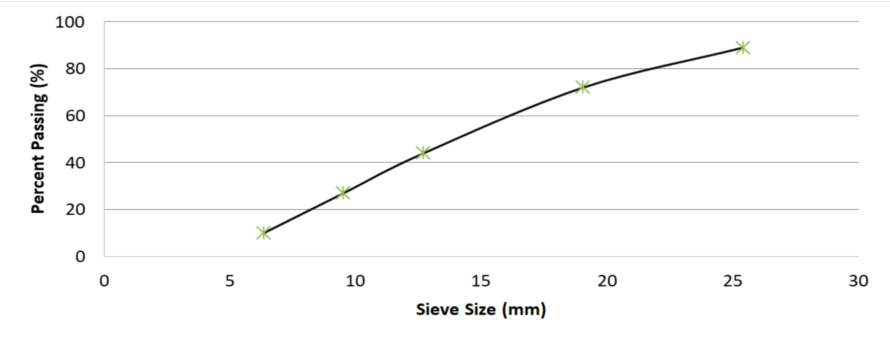

Figure 3: Gradation of Coarse Aggregate

Figure 3 shows the particle size results of the coarse aggregate used in this research and from the graph, the aggregates are uniformly distributed and fell within the limits specified in BS-882:2 (1992). Hence, the coarse aggregate is suitable for concrete production having a nominal size of 25.4mm.

3.2 Mechanical Properties of Reinforcement Steel Bars

This section of the chapter shows the result of the reinforcement steel bars used in this research viz-a-viz its diameter, yield strength, ultimate strength, and elongation.

Table 3: Mechanical Properties of Steel Bars

Beam ID	Steel Diameter (mm)	Number of bars	Steel Ratio (%)	Tensile Strength (f_y)	Ultimate Strength (f_u)	Elongation (%)
A1	11.79	2	1.01	386	621.00	15.73
A2	11.88	2	1.01	386	677.00	14.22
A3	11.47	2	1.01	386	654.00	16.22
B1	11.91	3	1.51	386	612.00	14.11
B2	11.82	3	1.51	386	609.00	13.33
B3	11.65	3	1.51	386	641.00	15.10
C1	11.55	4	2.01	391	621.00	16.20
C2	11.59	4	2.01	391	622.00	14.21
C3	11.60	4	2.01	391	623.00	14.12
D1	11.88	5	2.51	390	643.00	11.23
D2	11.71	5	2.51	390	678.00	13.28
D3	11.52	5	2.51	390	645.00	15.11
E1	11.49	6	3.02	398	678.00	14.03
E2	11.58	6	3.02	398	654.00	12.22
E3	11.66	6	3.02	398	634.00	16.01
Mean	**11.67**			**389.73**	**640.80**	**14.23**

b = 150; d = 150; l = 750

The result from Table 3 shows that the diameter of the reinforcement bars ranges from 11.49 to 11.91mm with an average value of 11.67mm. Also from Table 3, the mean tensile and ultimate strength of the reinforcement steel is 389.73 N/mm^2 and 640.80 N/mm^2 respectively, and the mean reinforcement steel elongation is 14.23%. However, the mechanical properties of the steel bars were compared to standards to confirm its adequacy for use in reinforced concrete.

Table 4: Comparison of Steel Bars with Standard

Standard Diameter	Measured Diameter	Difference in Diameter	Yield Strength	Ultimate Strength	Ultimate/ Yield	% Elongation
12	11.79	1.75	386.00	621	1.61	15.73
12	11.88	1.00	386.00	677	1.75	14.22
12	11.47	4.42	386.00	654	1.69	16.22
12	11.91	0.75	386.00	612	1.59	14.11
12	11.82	1.50	386.00	609	1.58	13.33
12	11.65	2.92	386.00	641	1.66	15.10
12	11.55	3.75	391.00	621	1.59	16.20
12	11.59	3.42	391.00	622	1.59	14.21
12	11.6	3.33	391.00	623	1.59	14.12
12	11.88	1.00	391.00	643	1.64	11.23
12	11.71	2.42	390.00	678	1.74	13.28
12	11.52	4.00	390.00	645	1.65	15.11
12	11.49	4.25	390.00	678	1.74	14.03
12	11.58	3.50	398.00	654	1.64	12.22
12	11.66	2.83	398.00	634	1.59	16.01
Code specification		**± 4.5%**			**>1.15**	**Min 14%**

The result from Table 4 shows that the percentage difference in diameter 12mm steel reinforcement bars ranges from 1.00 – 4.42% which is within the range of ± 4.5% stipulated by BS-4449 (1997), hence its adequacy for use in reinforced concrete structures. Also from the table, although the yield strength of the steel bars are below standard 460N/mm^2 recommended by BS4449, its ultimate tensile strength to yield strength ratios are above 1.15 stipulated by BS4449 which makes it satisfactory for use in reinforced concrete structures. Finally from the table, majority of the steel bars have percentage elongation of 14% and above as stipulated by BS4449 with only four out of the fifteen steel bars (i.e. 26.7%) having values less than code specifications of 14% and above. The outcome of these findings is in accordance with that of Ejeh and Jibrin (2012) who reported that not all reinforcement steel bars used in Nigeria complies with code specification.

Table 5: Experimental Beam Parameters

Beam ID	Width (mm)	Height (mm)	Length (mm)	Compressive Strength (f_{ck})	First Crack Load (kN)	Shear Load (kN)	Failure Load (kN)
A1	150	150	750	31.11	65	66	66
A2	150	150	750	31.11	66	66	70
A3	150	150	750	31.11	64	66	62
Mean					**65**	**66**	**66**
B1	150	150	750	31.78	75	90	90
B2	150	150	750	31.78	78	88	91
B3	150	150	750	31.78	72	92	89
Mean					**75**	**90**	**90**
C1	150	150	750	32.89	79	82	82
C2	150	150	750	32.89	81	83	81
C3	150	150	750	32.89	77	81	83
Mean					**79**	**82**	**82**
D1	150	150	750	36.00	62	102	102
D2	150	150	750	36.00	60	105	100
D3	150	150	750	36.00	64	99	104
Mean					**62**	**102**	**102**
E1	150	150	750	37.78	105	108	108
E2	150	150	750	37.78	100	107	109
E3	150	150	750	37.78	110	109	107
Mean					**105**	**108**	**108**
		Total Mean		**33.91**	**77.2**	**89.6**	**89.6**

The result from Table 5 shows that the mean first crack load of the beam is 77.2kN, with a mean shear load and failure load of 89.6kN each. Also from Table 5, the first crack load increases as the reinforcement ratio and number of the bars in the beam increases, and the shear load is equal to the failure load which is an indication that the failure mode of the beam was brittle in nature.

3.3 Experimental and Theoretical Beam Parameters

The theoretical shear parameters were calculated using equation 5 to 8 while the experimental parameters were obtained from laboratory work after 28 days crushing as shown in Table 5. However, Figure 4 shows the values of the experimental and theoretical shear strength of beam at various reinforcement ratios.

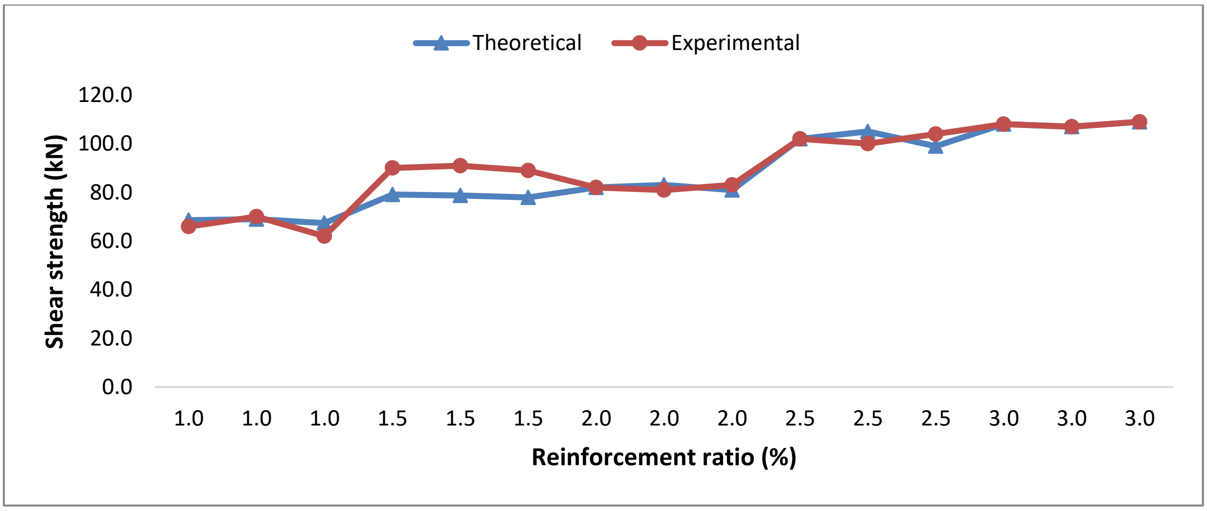

Figure 4: Theoretical and Experimental Shear strength

The result from Figure 4 shows that for 1.0 and 1.5% reinforcement ratios (beams without shear reinforcement), the experimental shear strength was a bit higher than the theoretical shear strength, while for 2.0, 2.5, and 3.0% reinforcement ratios (beams with shear reinforcement), the experimental and theoretical shear strength values are in close agreement. This implies that the theoretical equation for shear strength calculation of beams with shear reinforcement (equation 6 – 8) performs better compared to theoretical equation of for shear strength calculation of beams without shear reinforcement (equation 5). This is in accordance with findings of Olawale et al. (2021); and Abejide (2014) who reported that EC2 code provision exceeded the experimental design output and hence review must be made on the code formulations to conform to accepted structural safety (Abejide, 2014).

4.0 CONCLUSION

The properties of cement, fine aggregate, and coarse aggregate (NA) all met code requirement and is suitable for concrete production, while the reinforcement steel bars diameter, ultimate to yield strength ratio were in accordance to code specification with only 26.7% of the steel bars elongation not conforming to code requirement. More result from the findings showed that the Eurocode 2 design criteria of beams without shear reinforcement predicts beam shear capacity lower than the experimental value, while EC2 design criteria for beams with shear reinforcement is in close agreement with the experimental value for design of shear resistance of beams.

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