

Statistical Evaluation of the Geometric Properties Steel Bars for Reinforced Concrete in Botswana

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ABSTRACT

Uncertainties in construction materials, especially steel reinforcing bars, have multiplying adverse impacts on the integrity and reliability of constructed facilities from construction to service life stages. Botswana depends on importation of rebars to meet the ever-increasing demands for buildings and reinforced concrete civil infrastructure. The study assessed the mass and geometric properties of the two most utilized steel reinforcing bars, designated as M1 and M2, in Botswana. With the aid of digital analytical balance and Vernier calipers, measurements of mass per unit length and the relative rib area (RRA), which depends on nominal diameter, rib height, rib spacing, and longitudinal rib or gap thickness were made from 3000 standard bars each of nominal sizes from 8 mm to 25 mm randomly sampled at the suppliers' depots/warehouses and various construction sites in Gaborone and Francistown. The RRA is a measure of the surface geometry for interfacial bonding between steel reinforcing bar and the surrounding concrete. The geometric properties of each steel bar type of the nominal sizes were characterized in terms of the statistical parameters and compared for compliance with standard specifications such as CS2 (2012), ISO 15630, ACI A408. The actual mass and diameter of bars were within the tolerance of $\pm 1\%$ of the respective nominal size which satisfied all the standard requirements. Only the 8 mm diameter M2 bars did not have longitudinal ribs/gaps. ACI specifies a range of 0.10 to 0.14 for RRA, while CS2/ISO 15630 only specifies for the minimum RRA values of 0.040 for 8 to 12 mm bars and 0.056 for 16 to 25 mm bars. M2 bars of 10 mm dia. bars did not satisfy CS2/ISO 15630 requirements. However, M1 (8 mm and 12 mm) and M2 (10, 16 and 25 mm) bar sizes are below the minimum and M2 bars of 20 mm diameter are above the recommended RRA values of ACI A408. These would reduce the load carrying capacity of RC members reinforced with the unsatisfactory bar sizes.

Keywords: Surface geometry, reinforcing bars, relative rib area, interfacial bonding, statistical indices, load carrying capacity.

INTRODUCTION

Steel reinforced concrete has been used for decades as the construction material of choice because it is economical and versatile (Rabi et al., 2022; van Damme, 2018; Otieno, 2008; Jumaat et al., 2006). The embedded steel rebar has a good interfacial bonding with the surrounding concrete and an excellent tensile strength. It can still be bent or shaped for almost any concrete construction application (Sulaiman et al., 2017; Metelli and Plizzari, 2014; Zuo and Darwin, 2000a). The effectiveness of reinforcing bars in concrete is directly connected to the quality of the steel bars and the strength of concrete is good in compression, but weak in tension and flexure. The quality assurance of steel reinforcement in reinforced concrete (RC) infrastructure has not received considerable attention as the compressive strength of concrete at both the design and construction stages. This quality is an aggregation of

the physical, chemical and mechanical properties which are often determined from laboratory experimental and field testing (Bame et al., 2023). The use of sub-standard reinforcing steel bars causes structural defects, failures or ultimate collapse, which could result in loss of lives, properties, infrastructure and economic investments. Therefore, it is imperative to test the properties of steel bars to ensure their compliance with standard specifications, which are necessary to satisfy the ultimate and serviceability limit states (Alexander and Beushausen, 2019).

Efficient and effective transfer of force between reinforcement and concrete is required for optimal design of reinforced concrete structures. Three basic mechanics are required to effectively transfer force or stresses from a deformed reinforcing bar to the surrounding concrete. These are (1) the chemical adhesion between the reinforcing bar and the surrounding concrete; (2) the

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frictional forces arising from the roughness of the interface, forces transverse to the bar surface, and relative slip between the bar and the surrounding concrete; and (3) the mechanical anchorage or bearing of the ribs against the concrete surface (ACI 408R-03, 2012). Although the physical, chemical and mechanical properties of steel bars are critical for these three mechanics, they are most influenced by the cross-sectional and surface geometries.

Hence, for safety, reliability and durability of RC structures, compliance of the cross-section and surface geometries of steel rebars with relevant standards is fundamental both during construction and in service life. The conformity of the cross-section with the specification is a function of the agreement between the nominal and the actual diameter of bars, which determines the tensile strength of the member (Metelli and Plizzari, 2014; Zuo and Darwin, 2000a). On the other hand, the relative rib area, as a major parameter of the surface geometry, measure the adhesion, frictional forces and the interfacial bonding between steel and the surrounding concrete. This guarantees sufficient concrete-steel shear adhesion to prevent slippage of reinforcement in concrete (Sun et al. 2018; Barsic et al., 2012). The combination of the two is a measure of the load-carrying capacity of RC structural members in tension, compression or flexure. The geometric rib features of bars include the shape, width, height, spacing and inclination with respect to the longitudinal axis of the rods (Leramo et al., 2018). The relative rib area rather than the minimum rib height or the maximum rib spacing controls the bond strength between reinforcing steel and concrete (Metelli and Plizzari, 2014; Zuo and Darwin, 2000a; Zuo and Darwin, 2000b). This was based on a maximum average rib spacing equivalent to 70% of the nominal diameter of the bar and a minimum height of deformations equal to 4% for bars with a nominal diameter.

The purpose of this study was to assess the cross-sectional and surface geometries of steel reinforcing bars used in the import dependent Botswana construction industry. The study highlights the uncertainties that characterize the geometric properties of two most common reinforcing bars sampled from major suppliers and distributors spread over Gaborone and Francistown and the environs using ISO 15630, CS2 and ACI A408R Standards.

Theoretical Background for Relative Rib Area

a) CS2 (2012) and BS 4449:2005+A2:2009

Construction Standard CS2 (2012) is the publication of the Standing Committee on Concrete Technology by

the Government of Hong Kong. It is an extract of Steel for the reinforcement of concrete (BS 4449:2005+A2:2009), a publication of British Standards Institution. CS2 (2012) and BS 4449 (2009) specify the relative rib area, for ribbed steel reinforcing bars using the Simpson’s rule formula as shown in Equation (1):

$$f_R = \frac{(2a_{1/4} + a_m + 2a_{3/4})(\pi d - \sum e_i)}{6\pi d c} \quad [1]$$

where $a_{1/4}$, a_m , $a_{3/4}$ are the height of transverse ribs at the quarter-point, mid-point, and three-quarters point respectively measured as the mean of at least three measurements in this position per row on different transverse ribs. $\sum e_i$ is the part of the circumference without ribs determined as the sum of the average gap (e) between each pair of two adjacent ribs. e is determined from at least three measurements. d is the nominal diameter of the bar and c is the average spacing of the transverse ribs.

A typical surface rib geometry with two rows in transverse ribs is shown in Figure 1. The recommended average rib height, h is 0.03d to 0.15d, the rib spacing c is 0.4d to 1.2d, and the transverse rib inclination angle, β is 35° to 75°. The minimum allowable relative rib area are 0.035, 0.040 and 0.056 for $d \leq 6$, $6 < d \leq 12$ and $d > 12$, respectively.

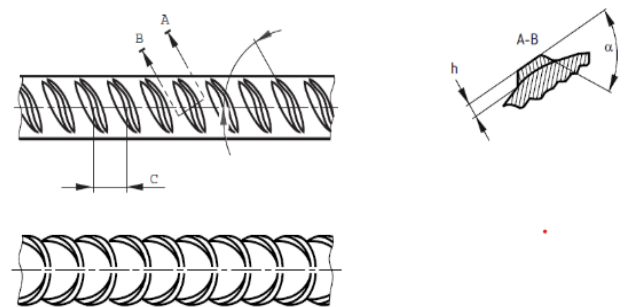


Fig. 1. Surface rib geometry with two rows of transverse ribs

b) ISO 15630-1-2010

The relative rib area specified by ISO 15630-1 (2010) is as expressed in Equation (2)

$$f_R = \frac{1}{\pi d} \sum_{i=1}^n \frac{\frac{1}{m} \sum_{j=1}^m F_{R,i,j} \sin \beta_{i,j}}{C_i} + \frac{1}{p} \sum_{k=1}^q a'_k \quad [2]$$

where n = number of rows of transverse ribs on the circumference, m = number of different transverse rib inclinations per row, q = number of longitudinal ribs for cold-twisted bars, p = pitch for cold-twisted bars determined as the mean of the distances between two consecutive corresponding points of a longitudinal rib on the same longitudinal line, for each longitudinal rib.

where $F_R = \sum_{i=1}^p (a_{s,i} \Delta l)$ is the area of the longitudinal section of one rib (Figure 2), where $a_{s,i}$ is the average height of a portion i of a rib subdivided into p parts of length Δl .

c) ACI 408R (2012)

According to ACI 408R (2012) defines the relative rib area as the ratio of the projected rib area normal to the bar axis to the product of the nominal bar perimeter and the

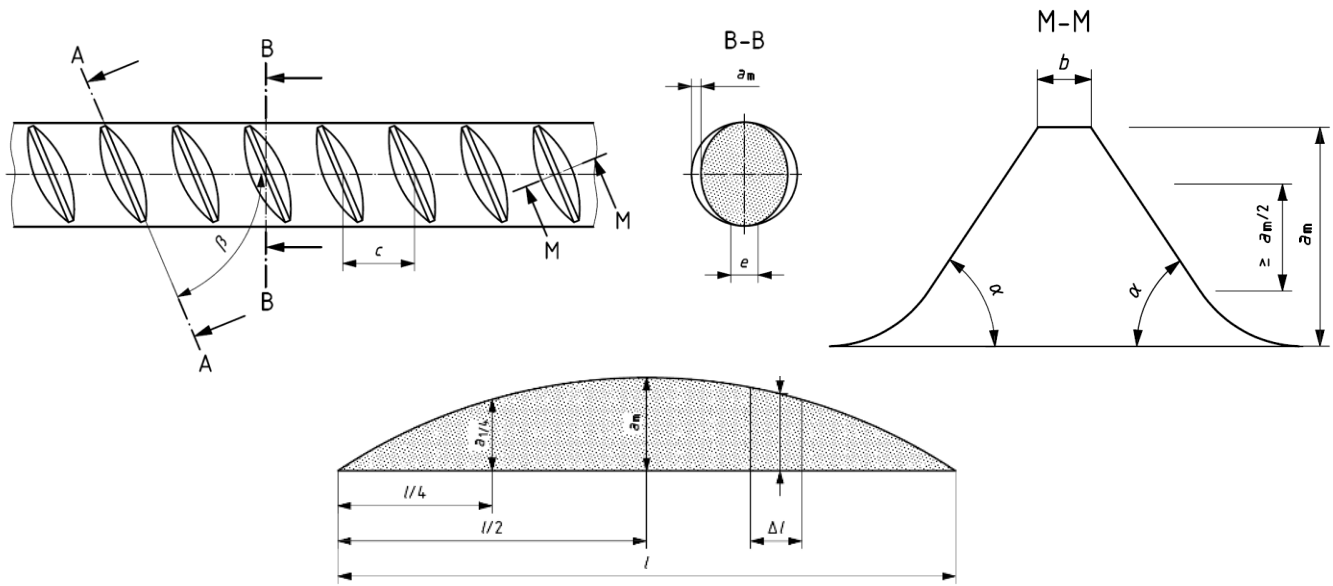
average centre-to-centre rib spacing as expressed in Equation (3).

$$R_r = \frac{h_r}{s_r} \left(1 + \frac{\sum \text{gaps}}{p} \right) \tag{3}$$

where h_r = average rib height, s_r = average rib spacing, $\sum \text{gaps}$ = sum of gaps between ends of transverse deformations, and p = actual perimeter.

For steel reinforcing bars with no gaps or longitudinal ribs, $\sum \text{gaps} = 0$, and R_r becomes

$$R_r = \frac{\text{Bearing area, } \pi d h_r}{\text{Shearing area, } \pi d h_r} = \frac{h_r}{s_r} \tag{4}$$



Section A-A is a flattened representation of a transverse rib.

Fig. 2. Determination of the rib flank inclination (α) and determination of the area of the longitudinal section of one rib (F_R)

MATERIALS AND METHODS

Assessment of reinforcing steel bars used in construction, specifically focusing on samples imported into the country from two major manufacturers designated as M1 and M2 was conducted. The assessment involved testing the physical and geometric properties of these steel bars, which were ribbed or deformed.

All 3000 random samples were sourced from various suppliers' warehouses, distributors' shops and various construction sites in Gaborone and Francistown and the environs. The samples of steel reinforcing bars from nominal diameter 8 mm to 25 mm of standard length 6 m are as shown in Figure 3.



Figure 3. Samples of M1 and M2 steel bars

1. **Random selection of samples:** Reinforcing steel bars were randomly selected from tonnes of imported material from major suppliers, distributors’ storehouses and construction sites in Gaborone and Francistown and the surrounding areas for measurement. 3000 samples of each nominal bar sizes from 8 mm to 25 mm were considered for the study.

2. **Measurement parameters:** The measurements focused on four key geometric properties:

- Actual diameter was measured by placing the outside jaws of the electronic vernier caliper around a point between two transverse ribs, perpendicular to the longitudinal rib.
- Rib height was measured by positioning the knife-edge of the calipers over two adjacent ribs and extending the depth gauge until it contacts the bar.
- Rib spacing was measured by placing the outside jaws of the digital calipers between two adjacent transverse ribs.
- The gap due on the longitudinal rib was measured by placing the outside jaws of the calipers over the outer edge of the longitudinal rib.

This process ensures accurate measurement of the geometric properties of the reinforcing bars, which is crucial for quality control and compliance with standards as stated in ASTM A615 are shown in Fig. 4.

The following equations were used for statistical analysis of the results obtained for.

$$\text{Mean: } \bar{x} = \frac{\sum_{i=1}^n x_i}{n} \quad [5]$$

$$\text{Standard deviation: } s = \frac{\sum \sqrt{|x_i - \bar{x}|^2}}{n-1} \quad [6]$$

$$\text{Coefficient of variation, } CoV = \frac{s}{\bar{x}} \quad [7]$$

$$\text{Skewness, } s_k = \frac{n}{(n-1)(n-2)} \frac{\sum_{i=1}^n (x_i - \bar{x})^3}{s^3} \quad [8]$$

Kurtosis,

$$k_{ts} = \frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum_{i=1}^n \left(\frac{(x_i - \bar{x})^4}{s^4} \frac{3(n-1)^2}{(n-2)(n-3)} \right) \quad [9]$$

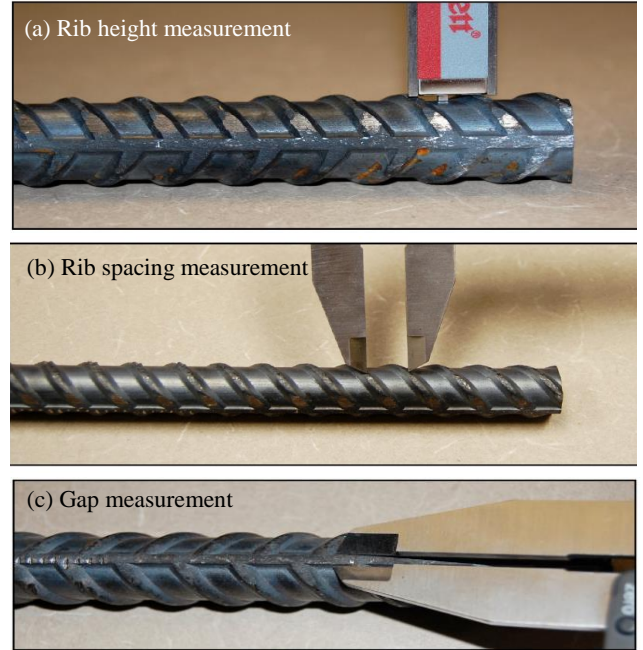


Figure 4. Measurement parameters for relative rib

RESULTS AND DISCUSSION

The average measurement data for the geometric properties of sampled 8 mm, 10 mm, 12 mm, 16 mm, 20 mm and 25 mm diameter steel reinforcing bars is summarized in Table 1 to provide a comprehensive overview of the experimental results and statistical analysis of the geometric properties of the sampled steel reinforcing bars. They are crucial for understanding the variability and quality of the bars tested, which is essential for ensuring compliance with standards and quality control in construction and engineering applications.

Actual mass per meter of steel reinforcing bars

The average mass per unit length (in kg/m) of 3000 samples for each nominal size of M1 and M2 were measured as shown on Table 1. The results showed that the measured samples from M1 and M2 are agreeable to as specified by mass per meter in BS 4449 (2005) for all diameter sizes. The standard deviations were all agreeable to the given tolerance. It has been noted that diameter 20 mm of M1 has the least uncertainties as it has the lowest coefficient of variation (CoV). The results shows that most of samples of 8 mm diameter were closer to the mean value as compared to other diameters.

Table 1. Average mass of steel reinforcing bars

Type	Statistical Analysis	Nominal bar diameter					
		8 mm	10 mm	12 mm	16 mm	20 mm	25 mm
M1	Average (kg/m)	0.397	0.618	0.885	1.577	2.469	3.857
	Standard deviation	0.020	0.026	0.037	0.064	0.095	0.155
	COV (%)	5.098	4.153	4.134	4.063	3.861	4.010
M2	Average (kg/m)	0.395	0.617	0.887	1.578	2.465	3.835
	Standard deviation	0.023	0.027	0.041	0.078	0.114	0.174
	COV (%)	5.745	4.343	4.615	4.941	4.638	4.543

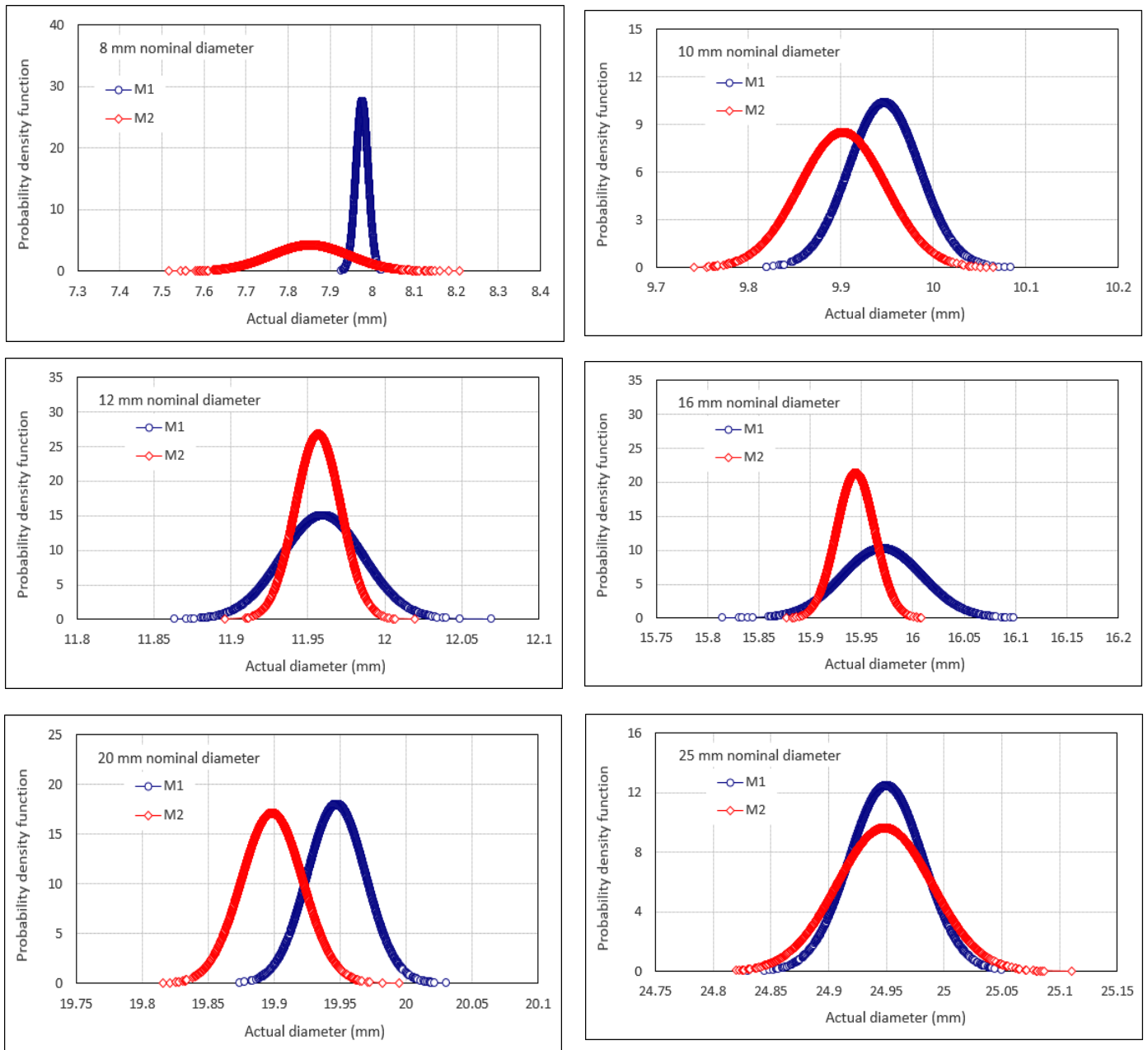


Figure 5. Probability density function curves of 8 mm to 25 mm nominal bar

Actual diameter of steel reinforcing bars

The statistical analysis and probability density function curves of actual diameters in Fig. 5 shows that the average actual diameters of M1 samples were slightly greater than average actual diameters of M2 with an exception to the actual diameters of 12 mm and 25 mm sizes which were the same for both M1 and M2. The median values of the measured samples shows that most of the samples from both M1 and M2 were close to the average diameter sizes from 8 mm to 25 mm.

Figure 6 presents the statistical parameters of the analysis of the 3000 random samples such as the standard deviation, CoV, skewness and kurtosis of all actual diameters bar sizes for the cross-sectional geometry. The standard deviation of M2 samples for diameter sizes 8 mm, 10 mm and 25 mm, high which brings about high CoV of those samples. The higher the CoV, the higher the variability of results obtained. For M1 samples, diameter

size of 16 mm showed a higher dispersion of results from the average value followed by 10 mm and 25 mm sizes in terms of standard deviation.

Skewness of the normal distribution curves were assessed to verify how symmetrical the curves were to the mean value while kurtosis was calculated to measure the risk or uncertainty of data obtained by classifying curves as peaked or flat. The criteria used was between -0.5 and 0.5, the data are fairly symmetrical, between -1 and -0.5 or between 0.5 and 1, the data are moderately skewed and lastly skewness less than -1 or greater than 1, the data are highly skewed. For kurtosis, the general guideline is that if the number is greater than +1, the distribution is too peaked while a kurtosis of less than -1 indicates a distribution that is too flat. The results shows that all diameters from M1 and M2 were fairly skewed and very low risk/uncertainty in terms of graphs being peaked or flat.

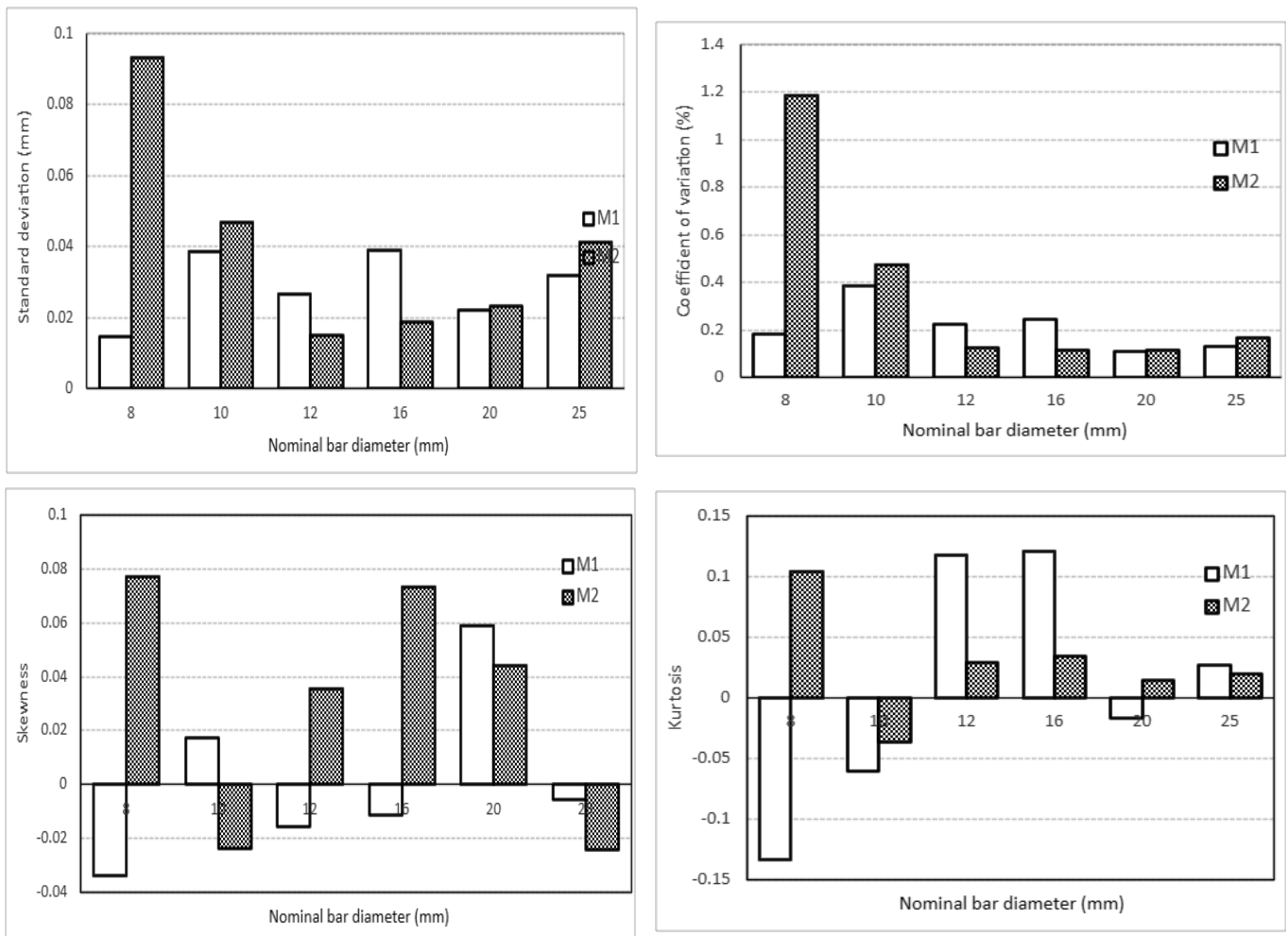


Figure 6. Statistical parameters of cross-sectional variability in bar sizes

Relative rib area

Average relative rib areas for all nominal bar size samples of both M1 and M2 are compared by bar graphs in Fig. 7. The results show that ISO 15630 (2010) produced the highest RRA values and was closely followed by ACI 408R (2012) and lastly CS2 (2012) which was comparative to BS 4449 (2005). With ISO 15630, RRA for M1 was very high for bar sizes 16 mm, 20 mm and 25 mm whereas for M2 is high in 12 mm, 20 mm and 25 mm bar sizes. The bars for M1 and M2 met requirements for RRA when using all standards except for few cases with ACI 408. M1 (8 mm and 12 mm) and M2 (10, 16 and 25 mm) bar sizes were below the minimum and M2 bars of 20 mm diameter were above the recommended RRA threshold values of ACI A408. Bond strength is strongly dependent on the relative rib area because an increase in relative rib area from 0.04 to 0.10 leads to an increase of bond strength of up to 40% (Metelli & Plizzari, 2014).

The fib Model Code (2010) which requires $RRA \geq 0.05$ reveals that the RRA values above 0.14 may develop higher bond stresses. Lower relative rib area and higher coefficient of variation increases uncertainties. The standard deviation of samples was low, but 10 mm diameter bars of M2 steel bars recorded high CoV values. Uncertainties are most likely where CoV was as high as evident with the actual diameter of 8 mm and 10 mm of M2. Diameter 8 mm of M2 had the highest values for skewness and kurtosis showing that it is highly skewed to the left and a highly peaked. A high positive kurtosis is considered as a risk because it is a leptokurtic distribution showing heavy tails on either side. They have large outliers as compared to all other diameter sizes. This concludes that M1 samples were preferred to M2 which are characterized by some relative rib area. The statistical summary of the measured diameters of bars for M1 and M2 reinforcing bars are summarized in Table 2, while

Table 3 to Table 6 present the statistical summary of the relative rib areas computed by different international and national models.

Studies have shown that relative rib area rather than the minimum rib height or the maximum rib spacing influences the bond stress between reinforcing steel and the surrounding concrete. In addition, high relative rib area of steel bars may enhance bond strength (Barbosa et al. 2008, Metelli & Plizzari, 2014).

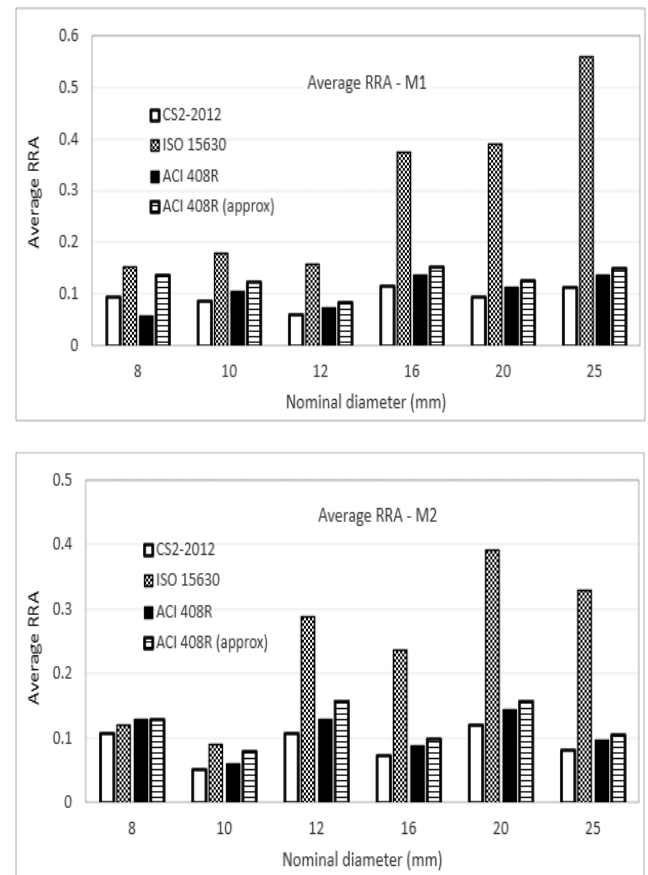


Figure 7. Relative rib areas of all nominal bar sizes for different standards

Table 2. Statistical summary of actual diameter of reinforcing bars

Bar size (mm)	8		10		12		16		20		25	
	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2
Average	7.98	7.85	9.95	9.90	11.96	11.96	15.97	15.94	19.95	19.90	24.95	24.95
COV (%)	0.18	1.19	0.39	0.47	0.22	0.12	0.24	0.12	0.11	0.12	0.13	0.17
Skewness	-0.03	0.08	0.02	-0.02	-0.02	0.04	-0.01	0.07	0.06	0.04	-0.01	-0.02
Kurtosis	-0.13	0.10	-0.06	-0.04	0.12	0.03	0.12	0.03	-0.02	0.02	0.03	0.02

Table 3. Statistical summary of relative rib areas computed by CS2 (2012)

Bar size (mm)	8		10		12		16		20		25	
Statistical Parameters	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2
Average	0.094	0.107	0.087	0.051	0.061	0.107	0.115	0.074	0.094	0.121	0.114	0.081
COV (%)	2.66	2.66	2.81	12.23	2.07	0.78	1.36	0.96	1.25	4.20	1.49	3.15
Skewness	0.008	0.123	-0.001	0.105	0.011	-0.004	0.048	-0.045	0.025	0.131	0.024	0.006
Kurtosis	0.014	-0.047	0.021	0.004	0.064	0.023	-0.087	-0.038	-0.083	-0.014	-0.007	0.118

Table 4. Statistical summary of relative rib areas estimated by ISO 15630

Bar size (mm)	8		10		12		16		20		25	
Statistical Parameters	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2
Average	0.154	0.121	0.179	0.091	0.157	0.289	0.376	0.238	0.392	0.392	0.561	0.329
COV (%)	5.25	7.27	6.14	19.83	3.55	1.27	2.24	2.11	2.28	11.07	7.97	10.83
Skewness	0.006	-0.117	-0.050	0.151	0.034	0.033	-0.201	-0.057	-0.007	-0.149	-1.356	-0.212
Kurtosis	-0.006	0.114	0.019	-0.010	-0.058	-0.024	0.146	-0.035	0.102	0.022	2.295	0.038

Table 5. Statistical summary of relative rib areas computed by ACI 408R-03

Bar size (mm)	8		10		12		16		20		25	
Statistical Parameters	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2
Average	0.059	0.129	0.104	0.061	0.073	0.129	0.138	0.089	0.113	0.145	0.137	0.097
COV (%)	4.18	3.65	4.55	19.35	3.31	1.11	1.62	1.61	2.05	5.94	2.43	5.25
Skewness	0.070	0.077	0.060	0.094	0.030	0.027	0.071	-0.039	0.068	0.027	0.078	-0.012
Kurtosis	-0.119	-0.071	-0.025	-0.029	-0.062	-0.041	0.015	-0.006	-0.007	-0.039	-0.015	-0.154

Table 6. Statistical summary of relative rib areas estimated ACI 408R-03 (approx)

Bar size (mm)	8		10		12		16		20		25	
Statistical Parameters	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2	M1	M2
Average	0.138	0.129	0.124	0.079	0.085	0.158	0.153	0.100	0.126	0.158	0.151	0.106
COV (%)	4.08	3.65	4.55	19.30	3.31	1.10	1.62	1.61	2.05	5.94	2.43	5.25
Skewness	0.055	0.077	0.063	0.088	0.031	0.024	0.073	-0.031	0.068	0.028	0.081	-0.014
Kurtosis	-0.158	-0.071	-0.026	-0.036	-0.053	-0.060	0.009	-0.001	-0.003	-0.036	-0.011	-0.154

CONCLUSIONS

The following salient conclusions can be drawn from the study. The average mass of steel reinforcing bar samples of M1 and M2 were almost the same for all diameters and met all standard requirements. However, the standard deviation and the CoV of nominal bar size 8 mm for M2 were evidently conspicuously high at 0.09 and 1.19% respectively, but still fell within the acceptable limit. The average actual diameters of M1 and M2 were slightly lower than all nominal diameters though fulfilled the requirement with their tolerance. M1 (8 mm and 12 mm) and M2 (10, 16 and 25 mm) bar sizes are below the minimum and M2 bars of 20 mm diameter are above the recommended RRA values of ACI A408. Relative rib area calculated using ISO 15630 and CS2 met the requirements. In conclusion, M1 have better properties as no risks were detected on actual diameters and relative rib areas, and as such enhances the interfacial bonding, tension and flexural capacity of RC structures.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Authors' contribution

AP Adewuyi initiated the research idea, identified the research gaps in the existing literature, designed the experimental process, verified the analyzed data obtained and partly wrote and revised the manuscript. GB Eric developed the proposal, conducted the field study designed, implemented the experimental plan, analyzed

the data and wrote the manuscript. Both authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests in this research and publication.

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