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Effects of Bending and Re-bending on Mechanical Properties of Locally-Manufactured Steel Rebars

Patrick W Waruhiu [1], Simon I Marandu[2] and Mussa I Mgwatu[2],
[1]*Department of Mechanical and Automotive Engineering, Technical University of Mombasa, P.O. Box 90420-80100, Mombasa, Kenya*
[2]*Department of Mechanical and Industrial Engineering, University of Dar es Salaam, P.O. Box 35131, Dar es Salaam, Tanzania*
Corresponding author: Emails: smarandu@udsm.ac.tz, marandus15@gmail.com
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Abstract

Steel rebars experience deformation when subjected to bending and re-bending operations. Subsequently, their microstructures are impaired thus affecting the mechanical properties and leading to failure. This study establishes the effects of bending and re-bending the steel rebars on the mechanical properties. Experiments were conducted to determine the effects of bending and re-bending of the steel rebars. Testing was conducted on Ten virgin and Thirty specimens which were bent and re-bent at 45º, 90º, and 180º, and followed by tensile tests. Yield strength, ultimate tensile strength, elongation, and ultimate tensile strength to yield strength ratio (R_m/R_e), were recorded. Results showed the yield strength, ultimate tensile strength, elongation, and R_m/R_e of virgin steel rebars varied from 553.62 MPa to 618.49 MPa, 634.39 MPa to 745.68 MPa, 17.6 % to 21.67 %, and 1.14 to 1.19. The yield strength, ultimate tensile strength, elongation, and R_m / R_e of bent and re-bent steel rebars at angles of 45º, 90º, and 180º varied from 603.67 MPa to 677.38 MPa, 692.82 MPa to 751.76 MPa, 6.88 % to 19 % and 1.09 to 1.21. It was established that bending and re-bending increase strength and reduce the ductility of the rebars proportionally.

Keywords: Steel rebars; Bending; Re-bending; Mechanical properties; B500RWR Standard.

Introduction

Buildings are still collapsing leading to loss of lives, injuries, and economic losses, despite technological advancement in the architectural, structural and construction industries (Kioko 2014). Collapsing of buildings across the globe could be associated with many factors such as mechanical failures of reinforced steel bars, a poor mixture of construction, and inadequate strengthened structures (stiffeners). Increasing trends of building failure and collapse in the developing world are reported in various studies (Windapo and Rotimi 2012, Okeke et al. 2020). In Dar es Salaam (Tanzania), a total of about 38 buildings are reported to have collapsed, resulting in 43 known deaths and several unrecorded deaths between 1987 and 2017 (Meena et al. 2018). In the USA, a total of 225 buildings failed and collapsed between 1989 and 2003 (Wardhana and Hadipriono 2003). A recent research results by Okunola (2021) for a study which was conducted in Lagos between 1978 and 2019, revealed about 149 cases of building failure that were associated with inadequate reinforcement. The high rate of building collapsing calls for a critical investigation of all materials involved in buildings. These include cement, sand, gravel, blocks and reinforcement steel bars (steel rebars). The rebar is one of the major building and construction materials for building structures as discussed by Edward and Joseph (2008).

In the construction industry, reinforcing steel bars (steel rebars) are used to strengthen concrete beams, columns, floors, slabs, bridges, skyscrapers, and warehouses because of their desirable mechanical properties (CAKRASTEEL BSI 4449:2005, 2005). Reinforcing concrete structure involves marking out, cutting off, bending to desirable angles, fastening, anchoring in position, and mass concreting to completely cover the steel rebars under concrete mass. The steel rebars carry bending stresses (tensile and compression stresses), thus restraining and preventing structure failure (Düsseldorf 2013). This avoids the sudden collapse of structures.

Usually, steel rebars are manufactured in lengths ranging between 6 m and 12 m. Such longer steel rebars are difficult to transport and store without bending. Bending is also a common fabrication process of the steel rebars for strengthening mass concrete of structures. However, the bending process causes a localised plastic deformation and slip geometry differences across the neighbouring grains of a material (Kaijalainen 2016). This process is usually done under cold working conditions using a desirable fabrication process for making steel rebars. During the bending process, the mechanical properties, and geometrical and internal structures of the steel rebars can be affected. This may be caused by residue stresses which are set up during work-hardening and then locked up within the metal causing strain hardening (Arum 2008).

In addition, corrosion develops on the surfaces of the steel rebars that are used in construction if not protected and prevented, thus influencing or impairing the strength and durability of reinforced concrete buildings (Rubaratuka 2013). To satisfy the structural design requirements of steel rebars, their chemical properties, mechanical properties, and metallurgical properties should conform with the design requirements. Numerous studies have been conducted to investigate the effects of mechanical properties on performance of the steel rebars in the construction industry. For instance, Apostolopoulos et al (2006) conducted experimental studies assessing corrosion damage subject to cycling fatigue. Their results show that the low cycle fatigue of corroded steel rebars reduces bearing ability, tensile strength and ductility. Other studies attempted to investigate the properties of steel rebars for concrete performance. Chen et al. (2011) investigated the properties of combined steel fibers and steel rebars, and their results demonstrated a significant composite effect on the impact resistance of the concrete structures. Their study established that use of steel rebars improve the impact toughness of the concrete. Fernandez and Berrocal (2019) conducted experimental study of tensile strength on corroded steel rebars, and they found that the strength of the steel rebars was not affected by corrosion. Ikhwan and Dalil (2014) investigated the effects of bending and straightening of 12 mm diameter steel rebars, and found that large curvature bending results in a significant thickness reduction of the bent section and residual stresses remains in cold-worked steel rebars. However, their study was based on one size of the specimens and did not consider re-bending of the steel rebars, which is a common practice in making reinforced concrete structures. Based on literature, there are inadequate studies on building failure pertaining to steel rebars, caused by the change in their mechanical properties. The present study seeks to investigate the effects of bending and re-bending on the mechanical properties under cold working conditions of the locally manufactured steel rebars in Tanzania based on the difference in diameters and bending angles.

Materials and Methods

The reinforced steel bars (steel rebars) of grade B500CWR, which is locally manufactured in Tanzania, were used in this study. The test samples were acquired from a local steel rolling mill (Kamal Steels Limited) in Dar es Salaam, Tanzania. The first step in the preparation of specimens was to determine their chemical compositions and ascertain that were within the specified range according to international standards. The chemical composition of the steel rebars (grade B500CWR) was determined using the product analysis method as stipulated in (ASTM A-751 E-23, 2011) standards. This method measured the average elemental percentage by weight (wt. %) of the samples and data was recorded by the Optical Emission Spectroscopy (OES). The OES is installed with the Q-Matrix and Digital IA Software that calculates values of each constituent element and carbon equivalent (C_{eq}). The carbon equivalent value was calculated using the Equation 1.

$$C_{eq} = C + \frac{Mn}{6} + Cr + M_o + \frac{V}{S} + Ni + \frac{Cu}{15} \tag{1}$$

The obtained chemical compositions in weighted percentages were compared against the British International Standard (BSI) (BSI 4449:2005) as reported in the results and discussion section.

Mechanical testing

Mechanical properties tests were carried out at the Materials Technology and Building Materials laboratories at the University of Dar es Salaam. Two major tests were done, which included the bend test and tensile test. The bend test of the steel rebars was done using procedures stipulated in ASTM E290: 2014, (2014) standard for bending test method. The bending machine used is the automatic rebar bender. (Peddinghaus, Model Bilax 32K). The specimens were obtained from five different nominal diameters, that is

$$D_1 = 10 \text{ mm},\ D_2 = 12 \text{ mm},\ D_3 = 16 \text{ mm},\ D_4 = 20 \text{ mm},\ D_5 = 25 \text{ mm}.$$

For each nominal diameter sample, nine specimens were cut and prepared for bending and tensile tests as indicated in Figure 1. The largest steel rebars were cut at the length of 500 mm for each nominal diameter and were subjected to tensile test (virgin steel rebars). The remaining six specimens were grouped into three pairs, and each pair was bent and plastically deformed at 45°, 90° and 180° respectively as shown in Figure 2.

Figure 1: Rebar specimens arranged according to respective nominal diameter size.

Figure 2: Rebar specimens bent at different angles for different nominal diameter sizes.

All the bending operations were done at room temperature between 28 °C and 35 °C. Later, the bent steel rebars were gradually and constantly straightened using a hydraulic press without shock or impact, and then re-bend to an angle ≤ 20° for determination of their mechanical properties through tensile testing. All tensile tests for both virgin, bent and re-bent steel rebars were performed in accordance with the acceptable standards in ISO 15630-1:2010(E), 2010. Tensile tests were performed using an Automatic Universal testing machine (model: UTM-DMU) with 200 Tonnes of force capacity**.**

Mechanical properties were then evaluated based on elongation, yield strength, and ultimate strength in terms of strain and stress respectively. The obtained results were also compared with Material standards to check if they meet the construction requirements after bending and re-bending operations. Primarily, the tests intended to establish changes of the mechanical properties likely to occur while bending the steel rebars during fabrication, storage and transportation.

Results and Discussion

The constituent elements of reinforced steel

Chemical compositions of the steel rebars was evaluated for five nominal diameters of steel grade B500CWR. Based on the British Standards (BS), the key chemical compositions include carbon, sulfur, phosphorus, nitrogen, and copper and their percentage proportions based on cast and product analysis are presented in Table 1.

Table 1: BS maximum chemical compositions by weight percentage (wt. %) of the steel rebar grade.

	Carbon	Sulfur	Phosphorus	Nitrogen	Copper	Carbon equivalent
Cast analysis	0.22	0.05	0.012	0.80	0.50	0.50
Product analysis	0.24	0.055	0.055	0.014	0.85	0.52

As per experiments conducted, the composition elements for the five samples are tabulated in Table 2. Based on the product analysis used in this study, the Carbon content was found to range between 0.151% and 0.229%, the Sulphur (S) from 0.017% to 0.023%, Phosphorus (P) between 0. 026% and 0.030%, Nitrogen (N) was less than

0.02%, and Copper (Cu) varied between 0.123% and 0.183%. The Carbon equivalent (C_{eq}) was found to range between 0.329% and 0.413% as established in Equation (1). All the chemical contents were within the permissible limits according to the standard BSI 4449:2005 (product analysis) as indicated in Table 1. In addition, other elemental compositions were recorded including Manganese (Mn) and Iron (Fe). The Manganese (Mn) content for the steel rebars ranged from 0.700% to 0.812%, and was responsible for the rebar hardenability while the Iron (Fe) content varied from 98.24% to 98.45%. These two elements are important for the evaluation of the tensile strength and ductility of the steel rebars. For instance, the ferrite constituent matrix takes a large share volume in the steel rebars followed by Manganese. This fact cannot be ignored since ductility superiority depends on these two elements.

Table 2: Chemical compositions by weight percentage (wt. %) for five nominal steel rebar diameters.

Element %	**D_1**	**D_2**	**D_3**	**D_4**	**D_5**	**BSI 44499**
C	0.192	0.229	0.221	0.209	0.151	≤0.24
Si	0.191	0.176	0.187	0.246	0.089	-
Mn	0.798	0.776	0.754	0.812	0.700	-
P	0.030	0.030	0.026	0.028	0.027	≤0.055
S	0.019	0.022	0.019	0.023	0.017	≤0.055
Cr	0.133	0.194	0.307	0.190	0.231	-
Cu	0.183	0.158	0.123	0.139	0.128	≤0.85
Ni	0.060	0.066	0.067	0.064	0.162	-
Al	0.011	0.0063	0.0059	0.0085	0.0055	-
N	<0.010	<0.010	<0.010	<0.010	<0.010	≤0.014
Mo	0.0053	0.0060	0.0080	0.0043	0.017	-
Nb	0.0025	0.0028	0.0032	0.0027	0.0021	-
Ti	0.0012	<0.0010	<0.0010	0.0012	<0.0010	-
V	0.0036	0.0039	0.0058	0.0046	0.0042	-
Pb	0.018	0.011	0.0090	0.011	0.0098	-
Sn	0.0010	0.0010	0.0010	0.0010	0.0010	-
B	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	-
CE	**0.365**	**0.407**	**0.413**	**0.391**	**0.329**	**≤0.52**
Fe	**98.34**	**98.31**	**98.25**	**98.24**	**98.45**	**-**

Blue colour illustrates the maximum acceptable limits for the important chemical elements according to BSI 4449. The purpose of the chemical analysis was to confirm acceptable ranges of the various constituent elements if were within allowable limits suitable for heat treatment, and which are acceptable for those particular samples under consideration to produce the desirable phases for reinforcement steel bars. Unbalanced chemical composition as well as the heat treatment process can affect the geometry of the essential constituent regions that lead to the best and optimum desirable mechanical properties of steel rebars.

Mechanical properties

Virgin steel rebars

The mechanical properties of virgin steel rebars were established by performing several tensile tests. Table 3 presents the test results for the five (5) different diameters of virgin steel rebars denoted by D_1, D_2, D_3, D_4, and D_5. The recorded values include Yield strength (Re), Ultimate tensile strength (Rm), Elongation/deformation and Ultimate tensile strength to Yield strength ratio.

Table 3: Tensile testing results for virgin steel rebars.

Spec Design	Nom Dia (mm)	Area (mm^2)	Meas Dia (mm)	Meas Area (mm^2)	Yield Re (MPa)	Tensile Rm (MPa)	Elongation on 5D %	T/Y Rm/Re
D_1	10	78.5	10	76.44	590.97	745.68	20	1.16
D_2	12	113	11.6	110.02	586.43	669.80	21.67	1.14*
D_3	16	201	15.4	194.92	618.49	718.64	21.25	1.16
D_4	20	314	19.1	308.37	618.86	717.80	21	1.19
D_5	25	491	24.4	489.16	553.62	634.39	17.6	1.14*

The results reveal that Yield strength, Ultimate tensile strength, Elongation and Ultimate tensile strength (Rm)/ Yield strength (Re) ratio vary from 553.62 MPa to 618.49 MPa; 634.39 MPa to 745.68 MPa; 17.6% to 21.67%; and from 1.14 to 1.19 respectively. Comparing the test results to the international standards, Yield strength, Ultimate tensile strength and Elongation values meet the minimum requirements for the B500CWR grade of steel rebars. Steel rebars denoted by D_1, D_3, and D_4 meet the ratio of Ultimate tensile strength (Rm) to Yield strength (Re) which must be within 1.15 and 1.35 for diameters above 8 mm of the B500CWR steel rebars. Steel rebars symbolized by D_2 and D_5 failed to meet the minimum requirements for the ratio of Ultimate tensile strength (Rm) to Yield strength (Re). This is probably due to discrepancies in the production processes such as the inclusion of impurities and abnormal cooling during the drawing process leading to inadequate ductility of the steel rebars. However, the difference of 0.9% from the standard is not significant, as long as the Yield Strength, Ultimate Tensile Strength and Elongation are within the required limits, the steel rebars qualify for construction purposes. Figure 3 provides a graphical representation of the variation of stress against strain with different rebar diameters in virgin conditions. The tensile load is directly proportional to cross-sectional area, hence induced stress in the rebars varies inversely, and strain increases with an increase in nominal diameter.

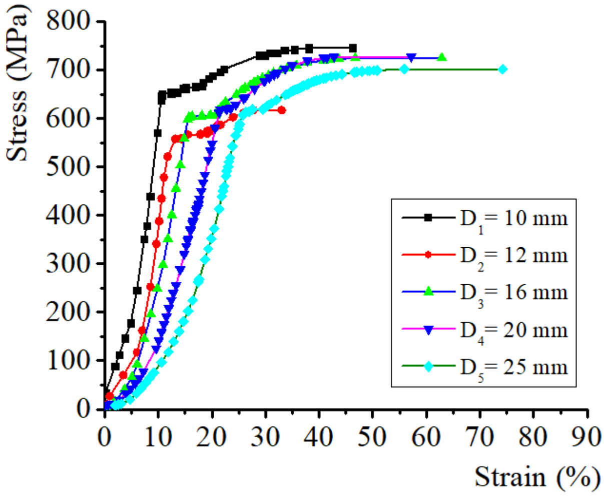

Figure 3: Relationship between Stress and strain of different virgin rebar diameters.

Bend and re-bend of the steel rebars

Bend and re-bend of the steel rebars means that the steel rebars were initially bent to a desired angle, and then straightened, and re-bent to the angle before subjecting them to the tensile tests. Similarly, the mechanical properties of the bend and re-bend steel rebars were determined by testing the specimen's coupons. Table 4 summarizes the test results for the five (5) different diameters of the steel rebars coded as D_1, D_2, D_3, D_4, and D_5. The Yield strength, Ultimate tensile strength, Elongation and Ultimate tensile strength (Rm) to Yield strength (Re) ratio varied from 565.02 MPa to 712.64 MPa, 640.02 MPa to 776.72 MPa, 6.88% to 19% and 1.09 to 1.21, respectively. In the same manner, Yield strength, Ultimate tensile strength and Elongation values met the minimum requirement for the Tanzanian **B500CWR** grade of the steel rebars. As noted in Table 4, some of the test specimens did not meet the minimum requirements for the ultimate Tensile strength to Yield strength ratio. The variation in the ratio ranges from 0.9% to 5.2%. The noted increase in variation of the ratio indicates that the bending and re-bending affected the ductility of the steel rebars. However, all the test results comply with Yield strength, Ultimate tensile strength and Elongation requirements. The discrepancy in the Ultimate tensile strength to Yield strength ratio is not significant, thus deducing that the steel rebars met the minimum required standards. Therefore, the bend and re-bend steel rebars can still meet the requirements of the construction industry except in areas prone to seismic effects.

Table 4: Tensile testing results for bend and re-bend steel rebars.

Spec. Design code	**Nom Dia (mm)**	**Angle Bend Degree**	**Yield Re (MPa)**	**Tensile Rm (MPa)**	**Elong on 5D%**	**TS/YS Rm/Re Ratio**
		45°	656.25	712.87	19	1.09
D_1	10	90°	712.64	776.72	17.6	1.09
		180°	663.25	765.69	17.6	1.15
		45°	652.17	721.67	15.2	1.11
D_2	12	90°	659.58	716.77	14.67	1.09
		180°	565.02	640.02	13.3	1.13

		45°	680.49	797.35	6.88	1.17
D_3	16	90°	626.09	707.31	14.63	1.13
		180°	601.92	687.73	15	1.14
		45°	645.31	751.46	11.7	1.16
D_4	20	90°	576.52	666.40	10.5	1.16
		180°	603.83	692.53	7	1.15
		45°	607.79	696.47	10.4	1.15
D_5	25	90°	589.84	711.37	16.16	1.21
		180°	613.38	736.69	9.6	1.20

Figure 4 presents the results graphically showing the relationship between stress and strain for the bend and re-bend steel rebars of a given nominal diameter. Generally, the results indicate that bending and re-bending influence the strength behaviour. Though the tensile strength varies directly depending on the cross-sectional area of the bar, the strength behaviour is significant for the bend of 45 degrees, followed by the 90 degrees and lastly the 180 degrees curve. This could be due to the hardening of the material and the dislocation of the grains as a result of deformation. A microstructure observation could validate the aforementioned probability reason as to why the behaviour of tensile stress versus strain showed significant variation between the 45-degree bends and 90-degree bends followed up by the 180-degree bends.

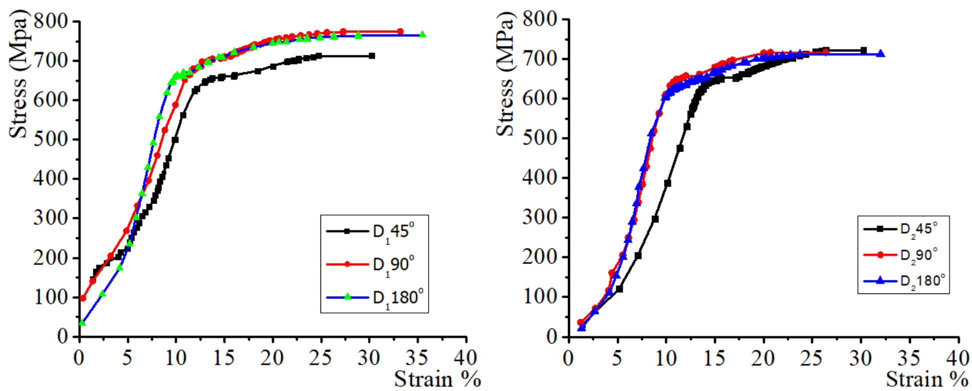

Figure 4a: Relationship between Stress and Strain for D_1 and D_2 steel rebars; bend and re-bend angle of 45°, 90° and 180°

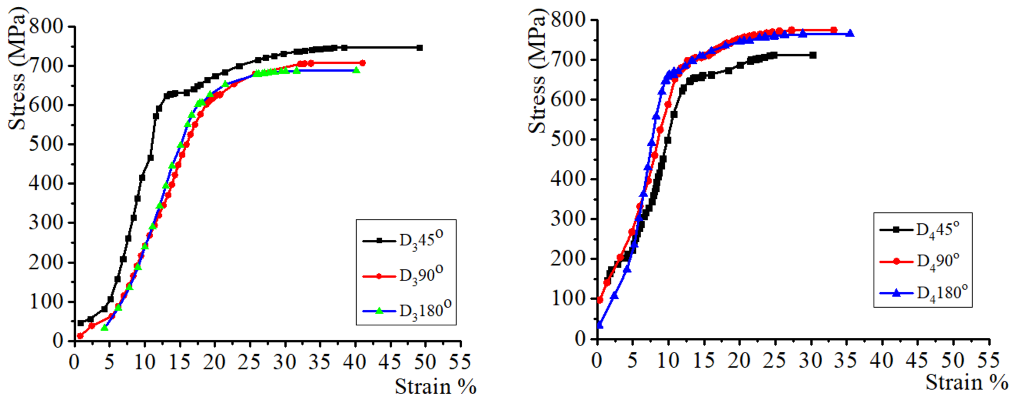

Figure 4b: Relationship between Stress and Strain for D_3 and D_4 steel rebars; with the bend and re-bend angle of 45°, 90° and 180°

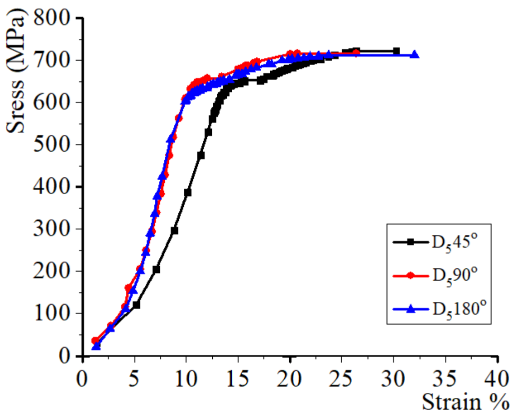

Figure 4c: Relationship between Stress and Strain for D_5 rebar; with the bend and re-bend angles of 45°, 90° and 180°

Comparison of mechanical properties of virgin steel rebars with the bend and re-bend steel rebars

The study compared the mechanical properties of the virgin steel rebars with those of bend and re-bend steel rebars. Figures 5 to 8 show a comparison of Yield strength, Ultimate tensile strength, Elongation and Ultimate tensile strength (Rm) to Yield strength (Re) ratio respectively. The comparison reveals that the Yield strengths of the virgin steel rebars are lower than those for the bend and re-bend steel rebars for the respective diameters. The reason for the increase in Yield strength for the bend and re-bend steel rebars may be due to work and strain hardening effects as a result of plastic deformation. This fact corresponds to a review by Scott et al (2014). Similarly, the elongations for most of the re-bend steel rebars decreased as compared to virgin steel rebars, which might be the result of an increase in hardness upon bending. In addition, nearly all the Ultimate tensile strength to Yield strength ratios decreased for the re-bend steel rebars, indicating strain hardening and loss of ductility due to bending and re-bending effects.

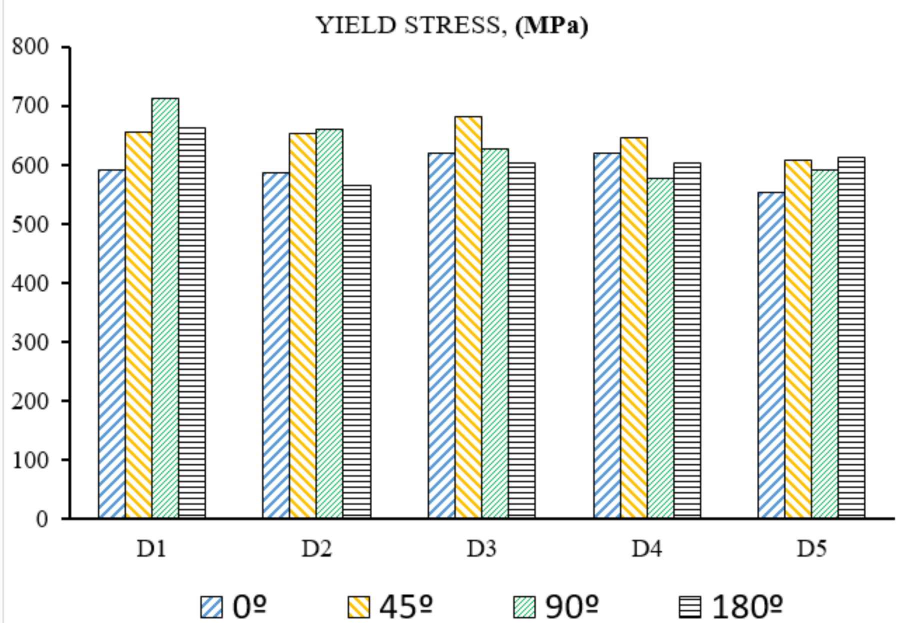

Figure 5: Comparison of Yield strength for the different diameters of the rebar at different angles.

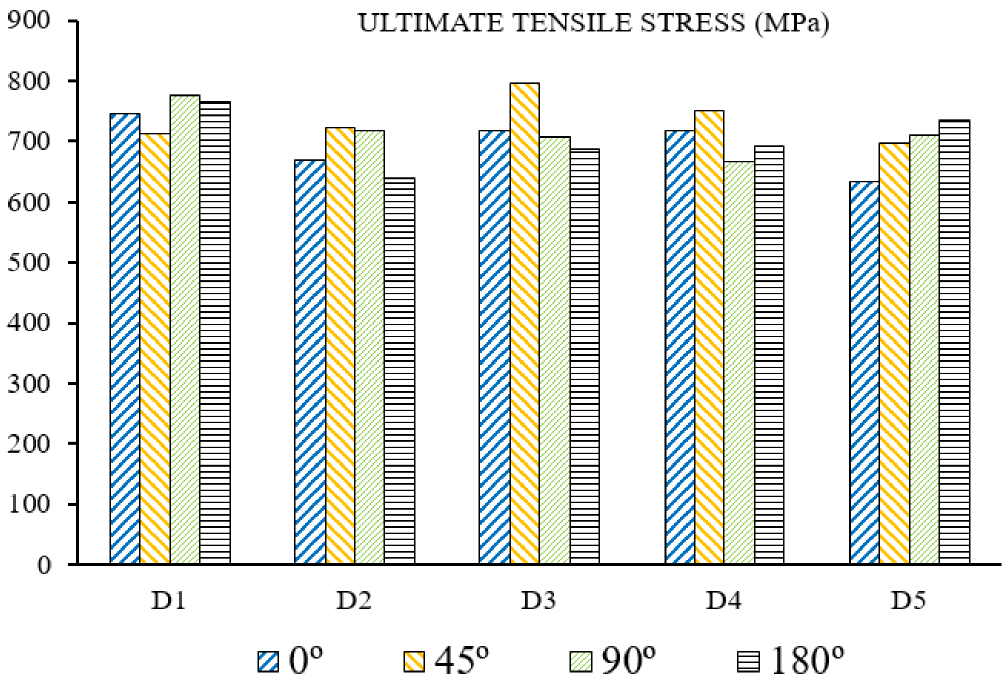

Figure 6: Comparison of Ultimate tensile strength for the different diameters of the steel rebars bent at different angles.

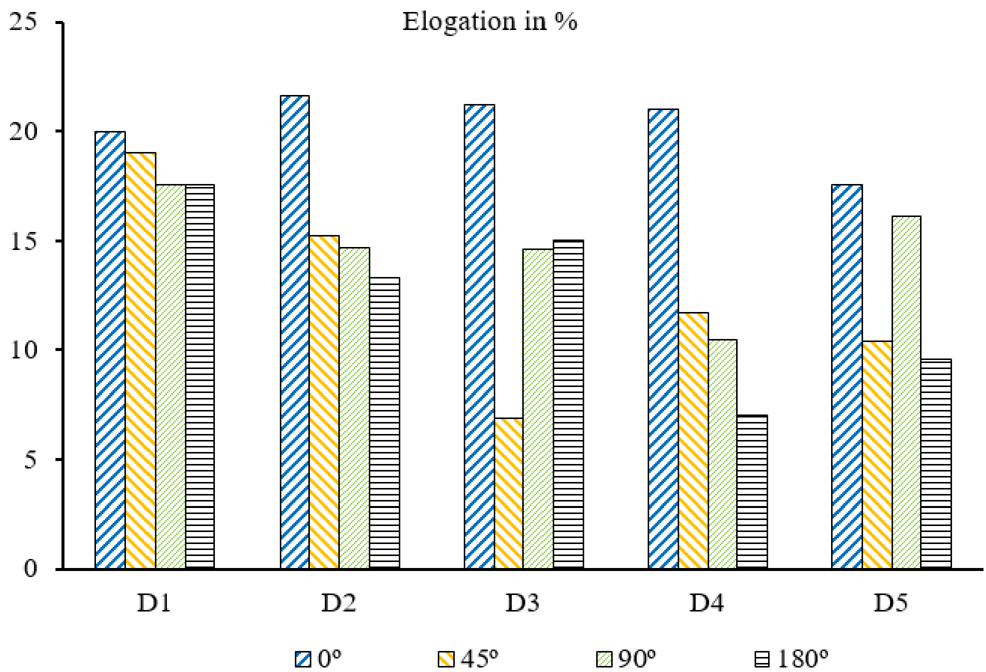

Figure 7: Comparison of Elongation for different diameters of the steel rebars bent at different angles.

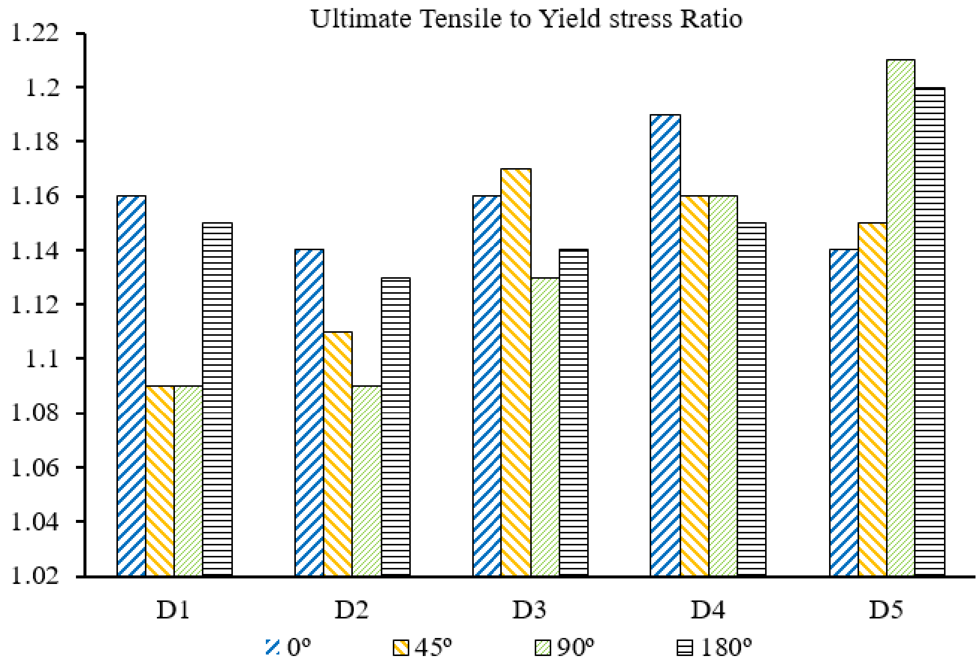

Figure 8: Comparison of Ultimate tensile strength (Rm) to Yield strength (Re) ratio for different diameters of the rebars bent at different angles.

Table 5 summarizes obtained values of Yield strength, Ultimate tensile strength, Elongation and Ultimate tensile strength (Rm) to Yield strength (Re) ratio for different diameters of the rebars that were bent at different angles as compared with virgin steel rebars. In Table 5, the value of virgin steel rebars are indicated in red colour.

Table 5: Comparison of Yield strength, Ultimate tensile strength, Elongation and Ultimate tensile strength (Rm) to Yield strength (Re) ratio.

Specification Designation	Nominal Diamond	Angle Bend	Yield	Tensile Rm (MPa)	Elongation on 5D %	TS/YS
code	(mm)	Degree	Re (MPa)			Rm/Re Ratio
D_1	10	0º	590.97	745.68	20	1.16
		45º	656.25	712.87	19	1.09
		90º	712.64	776.72	17.6	1.09
		180º	663.25	765.69	17.6	1.15
D_2	12	0º	586.43	669.8	21.67	1.14
		45º	652.17	721.67	15.2	1.11
		90º	659.58	716.77	14.67	1.09
		180º	565.02	640.02	13.3	1.13
D_3	16	0º	618	718.64	21.25	1.16
		45º	680.49	797.35	6.88	1.17
		90º	626.09	707.31	14.63	1.13
		180º	601.92	687.73	15	1.14
D_4	20	0º	618.86	717.8	21	1.19
		45º	645.31	751.46	11.7	1.16
		90º	576.52	666.4	10.5	1.16
		180º	603.83	692.53	7	1.15
D_5	25	0º	553.62	634.39	17.6	1.14
		45º	607.79	696.47	10.4	1.15
		90º	589.84	711.37	16.16	1.21
		180º	613.38	736.69	9.6	1.2

Note that the Red colour indicates Virgin steel rebars

Conclusions and Recommendations

The study determined the effects of bending and re-bending on the mechanical properties of Tanzanian locally manufactured steel rebars. The specimens were prepared and experimentally tested to determine the effect on mechanical properties between the virgin steel rebars and those bent and re-bent at different angles for different nominal diameters. The experimental results showed that virgin and bend and re-bend steel rebars comply with standard requirements. The results on the Yield strength, Ultimate tensile strength, Elongation and Ultimate tensile strength (Rm) to Yield strength (Re) ratio were within the recommended standard limits. Comparatively, nearly all the Yield strength, Ultimate tensile strength, Elongation and Ultimate tensile strength (Rm) to Yield strength (Re) ratio increased for the bending and re-bending steel rebars due to cold work and strain hardening effects. The results further revealed that there is a reduction in ductility for the bend and re-bend steel rebars. The findings confirmed that Tanzanian locally manufactured steel rebars conform to the standard requirements, but this does not relieve the mandatory requirement of testing the steel rebars before using them to reinforce structural members.

Declaration

We have no conflicts of interest to disclose.

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