# Residual Strength of Reworked Steel Reinforcement Bars

**John Nyiro Mwero[1], Sylvester Ochieng Abuodha[2]**

**[1] Postgraduate Student, Department of Civil & Construction Engineering, University of Nairobi.**
**[2] Senior Lecturer, Department of Civil & Construction Engineering, University of Nairobi.**
**Senior Lecturer, Department of Civil Engineering, Jomo Kenyatta University of Agriculture and Technology**

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Abstract: Reinforced concrete is a major material of construction in Kenya and the world over. A key component of this material is steel reinforcing bars. Sometimes these bars are bent wrongly, straightened and re-bent, resulting in the altering of their original characteristics. Some of such steel has been known to be used whereas some has been condemned as unfit for reinforcing purposes.
This paper reports on an investigation into the residual properties of reworked steel reinforcement bars (R12, Y12, R16 and Y16), including yield strength, ultimate strength, modulus of elasticity and ductility. Comparison of these has been done against those of normal reinforcement bars using tensile tests and the results have shown that even though reworking these bars once reduces the strength and changes the other tensile properties, the extent of change is such that slight modification on the relevant design formulae can render these bars suitable for reinforcing concrete.

Index Terms: Residual Strength, Steel reinforcement bars, carbon, elasticity, ductility.

## 1. INTRODUCTION

Steel is a metal alloy whose major component is iron, with carbon being the primary alloying material. Carbon acts as a hardening agent, preventing iron atoms, which are naturally arranged in a lattice, from sliding past one another. Varying the amount of carbon and its distribution in the alloy controls the qualities of the resulting steel **[1, 2]**. Steel with increased carbon content can be made harder and stronger than iron, but is also more brittle.
Reinforcement steel is used in reinforced concrete structures primarily to carry tensile stresses since concrete is much weaker in tension relative to its strength in compression **[2, 3]**. Reinforcement bars are also employed to carry compressive stresses where the compressive strength of concrete is insufficient, and in some cases to control cracks. For the reinforcement to be effective, it must, in addition to other requirements, be able to generate the necessary strength to resist applied stresses. If this is not ensured then failure of the structure or structural element in question may occur either at the serviceability limit, where cracking and / or large deflections would prevail, or at the ultimate limit, where there would be complete collapse.
Reinforcement bars are usually bent, fixed and cast into concrete by the contractor according to the engineer's specification. In carrying out this, errors do occur in the bending of the reinforcement steel, either due to improper specification on the part of the engineer or improper interpretation of the specifications on the part of the contractor. When this occurs the wrongly bent bars do not fit in with the rest of the detail of the structure.
Two solutions could be offered to this problem:

- Re-straighten and re-bend the bars to comply with the specifications.
- Do away with the bars and use fresh ones that comply with the specifications.

The first option is expensive and wasteful.
When reinforcement bars are bent and re-straightened, their characteristics are altered. Among the most affected of these characteristics are the strength and ductility, which are reduced due to fatigue cracking, strain hardening, etc.
The effect that this strength reduction will have on the steel requirement for sufficient design can be best estimated by looking at the design formulae for reinforced concrete, **[4]** which show that reducing the yield strength $f_y$ of the reinforcement bars, eg by bending and straightening as is the case in this study, would bring about the need to increase the area of steel provided for the design to suffice.
Current practise such as the Ministry of Works specification **[9]** requires that bars once wrongly bent be replaced with properly bent fresh ones. It is felt that these bars could be put into some use since they still have some residual strength that could be harnessed. In fact, some builders have been unofficially known to use bars that have been bent by mistake or, in the wrong way, and re-straightened, and their structures are still in use. The questions one would want to ask would be:

- Just how safe those structures are?
- To what extend could one safely employ such bars?

Clearly, information on the behaviour of re-bars when bent and re-straightened would be of great interest to the engineer, the contractor and even the owner of the project, since this would offer a more economic way of dealing with bending mistakes during steel fixing, which do occur in the construction industry.
Before this is achieved however, there is need to study, quantify, and come up with a data base on the effect of bending and re-straightening of these bars. This paper reports on a study carried out in an attempt to achieve this goal.

### 1.1 Objectives

The main objectives of the study were

1. To collect, test and compare the characteristics of the steel reinforcement bars in the market with those required by the relevant codes, for purposes of checking their compliance with those codes. These characteristics included tensile strength, ultimate strength, percentage elongation and percentage reduction in area.
2. To test some reworked samples of these bars and compare the properties mentioned above to those of normal bars.

## 2. SAMPLES

### 2.1 Collection

Samples for tensile tests consisted of cutoffs of R10, Y10, R12, Y12, R16 and Y16, collected from a contractor's yard in Nairobi. A summery of the collected samples was as given in table 1. Shearing was used to cut the bars.

**Table 1: <u>Summery of Collected Samples</u>**

**<u>Samples Batch 1</u>**

| Sample | Bar type & size | Samples reworked | Samples not reworked | Total No. of samples | Angle of bend (deg.) | Radius of bend (mm) | Comments |
|---|---|---|---|---|---|---|---|
| TT1/R10 | R10 | 8 | 2 | 10 | 90 | 33 | Successfully reworked |
| TT1/Y10 | Y10 | 8 | 2 | 10 | 90 | 33 | Successfully reworked |
| TT1/R12 | R12 | 6 | 2 | 8 | 90 | 33 | Successfully reworked |
| TT1/Y12 | Y12 | 8 | 2 | 10 | 90 | 33 | Successfully reworked |
| TT1/R16 | R16 | 8 | 2 | 10 | 90 | 33 | One broke during reworking |
| TT1/Y16 | Y16 | 8 | 2 | 10 | 90 | 33 | One broke during reworking |

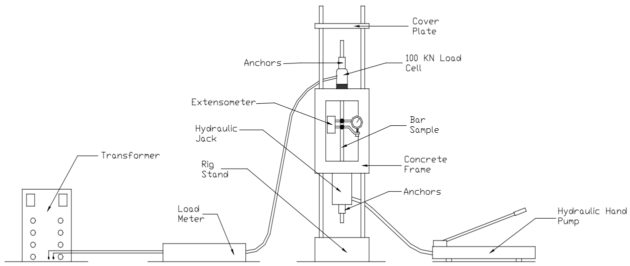
**<u>Samples Batch 2</u>**

| Sample | Bar type & size | Samples reworked | Samples not reworked | Total No. of samples | Angle of bend (deg). | Radius of bend (mm) | Remarks |
|---|---|---|---|---|---|---|---|
| TT1/R12 | R12 | 10 | 2 | 12 | 90 | 20 | Successfully reworked. |
| TT1/Y12 | Y12 | 5 | 1 | 6 | 90 | 33 | Showed some cracks and flaking. |
| TT1/R16 | R16 | 7 | 2 | 9 | 90 | 33 | Successfully reworked. |
| TT1/Y16 | Y16 | 7 | 2 | 9 | 90 | 33 | Showed some cracks. |

### 2.1 <u>Preparation</u>

For all the samples in batch 2, except the R12s strains were taken using Saunders-Roe Foil Electric Strain Gauges. The strain gauges were fixed onto the reworked part of the samples.

**Figure 1:** Testing Rig.




For the R12 samples strains were taken using Batty extensometer (See figure 1). Cutting of all the samples to the required 1 m length was done using a hack saw.

### 2.3 Testing

The tests done at JKUAT were carried out using a Tensile Testing Machine with a capacity of 100 tf.

Before mounting of bars onto the testing machine, their original length and weight were measured and recorded. They were then mounted onto the machine and held in place by the machine's wedge shaped grips before the leads from the strain gauges were attached to a digital data logger. The load was then applied at 0.5 ton intervals at the ends of the samples and for each interval, strain readings taken in the form of print outs from the data logger, at the operation of a button. For most of the bars an extra strain reading was taken at the sample's yield point.

Loading was continued to ultimate failure of the bars after which they were dismounted from the loading machine and tightly refitted together before final length was taken for purposes of calculation of final elongation. Final cross sectional dimensions at the failure point were also taken. Stress strain graphs were then plotted from these results.

The tests done at the University of Nairobi were carried out using a testing rig that consisted of a concrete frame mounted on a stand (fig. 1). Loading was done using a hand operated hydraulic jack. A load cell of 100 KN was used to measure the applied load and a Baty extensometer used to read the extension. The value of load was read via a load meter attached to the load cell. Bar samples were held onto the testing rig using anchors, one above the load cell and another below the jack.

Load was applied at 5 KN intervals, for each a strain reading being taken, until yield was reached. The strain gauge was then removed to avoid its spoiling by excessive straining. Loading was then continued to ultimate failure.

The bar was then removed and tightly refitted together before final length and cross sectional dimensions were taken. Stress strain graphs were then plotted.

## 3 RESULTS AND DISCUSSION

### 3.1 Results

Results for tensile tests are as summarized on the table 3.

**Table 3: Summary of Tensile Test Results**

| Bar Type | Stress (N / mm$^2$) | | Strain (%) | | Young's Modulus (KN / mm$^2$) | |
|---|---|---|---|---|---|---|
| | **$\sigma_{yield}$** | **$\sigma_{ult}$** | **$\varepsilon_{yield}$** | **$\varepsilon_{failure}$** | **$E_{el}$** | **$E_{pl}$** |
| R12 – N | 345 | 568.75 | 0.175 | 2.672 | 197.22 | 8.681 |
| R12 – RW | 338 ***(97.97 %)*** | 554.74 ***(97.54 %)*** | 0.218 | 1.55 | 157.857 | 14.941 |
| R12 – DRW | 344 ***(99.71 %)*** | 552.08 ***(97.07 %)*** | 0.214 | 1.732 | 165.309 | 18.255 |
| Y12 – N | 470 | 655.4 | 0.5 | 4.108 | 197.214 | 4.216 |
| Y12 – RW | 552 ***(117.44 %)*** | 638.90 ***(97.48 %)*** | 0.55 | 2.520 | 110.89 | 3.162 |
| R16 – N | 326.7 | 531.15 | 0.186 | 1.333 | 176.593 | 15.579 |
| R16 – RW | 267.44 ***(81.86 %)*** | 527.20 ***(99.26 %)*** | 0.217 | 2.650 | 166.104 | 11.367 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Y16 – N | 379.25 | 562.50 | 0.101 | 0.680 | 385.681 | 33.73 |
| Y16 – N | 472.86 ***(124.68 %)*** | 584.10 ***(103.84 %)*** | 0.261 | 0.998 | 317.641 | 11.067 |

### 3.2 Conversion of Final Elongations To Proportional-Gauge-Length Equivalents

The ISO 2566 / 1 – 1973 **[5]** specifies a method of converting percentage elongations after fracture obtained on various proportional and non-proportional gauge lengths (a proportional gauge length is one having a specified relationship to the square root of the cross sectional area ($S_o$) e.g. 5.65 $\sqrt{S_o}$ whereas a non proportional gauge length is one not specifically related to the cross sectional area of the test piece, usually expressed as a given dimension e.g. 50mm **[5 – Sections 3.2 & 3.3]**). The formula on which the conversions are based is considered to be reliable when applied to carbon, carbon manganese, molybdenum and chromium molybdenum steels within the tensile strength range 300 to 700 N / mm$^2$ **[5]**.
The formula can be expressed in a simplified form as below

$$A_r = 2\,A\,\{\sqrt{(S_o)} / L_o\}\ \exp 0.4 \qquad \ldots\ldots \quad \text{(i)}$$

Where $A_r$ is the required elongation on gauge length $L_o$.
A is the elongation on a gauge length of 5.65 $\sqrt{(S_o)}$ **[5 – Section 4]**.

The samples tested in this study were approximately 1 m long. This length was based not on the prescribed relationship for a proportional gauge length but on rather on the machine constraint. The distance between the grips (which is the distance which underwent the elongation during the testing is taken as the gauge length on which the final elongations are calculated. This gauge length is not therefore proportional hence the need for correction of the observed elongations before comparison with the code requirement values for elongation is done. The code **[6, 7]** specifies percentage elongation of 22 % for R12s and R16, and 12 % for Y12s and Y16s. These percentages are the A values in the equation (i).
Using the equation (i) therefore, the prescribed values of minimum elongation that would be required for the test pieces in this study would be as given in table 4.

**Table 4: Converted minimum elongations**

| Bar size & $L_o$ value | Min. % elongation value for $L_o$ = 5.65 $\sqrt{(S_o)}$ | Min. % elongation value for study $L_o$ |
|---|---|---|
| R12s, $L_o$ = 615 mm | 22 | 8.68 |
| Y12s, $L_o$ = 700 mm | 12 | 4.50 |
| R16s, $L_o$ = 700 mm | 22 | 9.25 |
| Y16s, $L_o$ = 700 mm | 12 | 5.04 |

Average percentage elongations and percentage reduction in areas obtained were as summarized on table 5.

**Table 5: Average Percentage Elongation and Reduction in Area**

| Bar Type | Average Percentage Elongation | Average Percentage Area Reduction |
|---|---|---|
| R12 / N | 21.06 | 51.98 |
| R12 / RW | 20.36 | 52.73 |
| R12 / DRW | 18.86 | 52.16 |
| Y12 / N | 7.92 | 39.76 |
| Y12 / RW | 20.03 | 39.94 |
| R16 / N | 14.7 | 55.69 |
| R16 / RW | 17.89 | 54.07 |
| Y16 / N | 14.84 | 52.29 |
| Y16 / RW | 6.69 | 47.91 |

### 3.3 Determination of cross sectional areas

The mass per meter length of bar was determined for three samples of each bar type in the study by measuring the weight of a sample and dividing this by its length. Average results for each bar type are as given in table 6.

**Table 6: Average mass per meter of investigated bars**

| Bar Type | Average Mass Per Meter (Kg) | Average Deviation (Kg) | Average Deviation (%) |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Y16 | 1.494 | -0.092 | -5.404 |
| R16 | 1.514 | -0.065 | -4.095 |
| R12 | 1.159 | +0.271 | +30.480 |
| Y12 | 0.863 | -0.040 | -2.816 |
| R10 | 0.873 | +0.257 | +41.721 |
| Y10 | 0.599 | -0.017 | -2.814 |

The method adopted for the determination of the cross sectional areas of steel used in this study for purposes of checking its compliance to the requirement of the codes of practice was the one described in the relevant codes **[6 – Clause 8, 32 – Clause 12.1, 7 - Clause 4.4.1]** as outlined below.
For bars whose pattern of deformation is such that, by visual inspection, the cross sectional area is substantially uniform along the length of the bar, the effective cross sectional area can be taken as the cross sectional area determined by weighing and measuring to a precision of ± 0.5 per cent of length and not less than 0.5 m when;

Gross cross sectional area (in $mm^2$) = Effective cross sectional area

$$= W / (0.00785\ L). \qquad \ldots\ldots \qquad (ii)$$

Where W = Mass (in Kg),
L = Length (in m).

This formula is based on the value of the nominal density of steel taken to be 0.00785 Kg / $mm^2$ per meter run **[6 – Clause 10.2, 7 – Clause 3.4]**. Average values of cross sectional area for each size of bar investigated were found to be as given on table 7.

**Table 7: Average cross sectional areas**

| Bar Type | Average Cross Sec. Area ($mm^2$) | Average Diameter (mm) | Deviation (mm) | Deviation (%) |
|---|---|---|---|---|
| Y16 | 190.3 | 15.6 | -0.43 | -2.73 |
| R16 | 192.9 | 15.7 | -0.30 | -1.90 |
| R12 | 147.6 | 13.7 | +1.67 | +13.9 |
| Y12 | 109.9 | 11.8 | -0.17 | -1.40 |
| R10 | 111.2 | 11.9 | +1.90 | +19.0 |
| Y10 | 76.3 | 9.8 | -0.17 | -1.67 |

## 3.4 Discussion
### 3.4.1 Introduction
Tensile tests were carried out on Y16, Y12, R16 and R12 bar samples. Of notable interest is that as opposed to prior expectations that the reworked bars would break on the region of the rework, most of the bars were breaking away from reworked regions. This could have been caused by a number of reasons, some of which have been discussed below together with other observed issues of interest.

### 3.4.2: Cracking
During reworking of some of the reinforcement bar samples, two bars (one R16 and one Y16) broke as they were being straightened. In addition to this, most of the bigger reworked bars tested (especially Y16) were found to be cracking during straightening.
This is suspected to have been the main cause of failure on the reworked regions of these bars. Two main problems of cracking may have led to this kind of failure:

a) Cracking reduces effective cross sectional area at that particular point on the bar, providing a point of weakness and,
b) Cracks are regions of stress concentration that could lead to failure before the ultimate strength of the steel is reached. When cracked steel is subjected to tensile stresses in a direction perpendicular to the direction of the crack, stresses at the crack front are significantly increased approaching a theoretical infinite value for sharp crack fronts.

### 3.4.3: Strain Hardening
The square twisted bars are usually brought to their strength by the strain hardening process, having been manufactured as mild steel square bars and then twisted through an optimum angle to achieve the higher strength. It is known that strain hardening serves to increase the strength of mild steel only to a certain degree beyond which further straining will cause loss of strength as is evident on the stress strain curve for mild steel. It is possible that the process of reworking the square twisted bars in this case could have taken

the bars beyond the optimal level of strain hardening thus causing weakening on the regions of rework. This could have been a cause for failure on these regions for these bars.

Strain hardening might also have caused the increase in the yield strength of most of the Y12 samples. If it's assumed that the twisting done during manufacturing did not reach the optimum level of strain hardening, it is possible to argue that the reworking had hardened the bars further on the regions of rework (since these were the regions where the strain gauges were fixed) causing yield to seem to occur at higher stresses as figure 2 suggests.

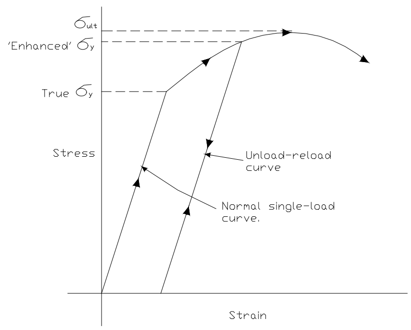



**Figure 2:** 'Enhanced' yield stress on the load – reload curve.

This kind of scenario has the problem that the difference between the 'enhanced' yield and the ultimate failure load is greatly reduced. Now, the codes [31,18] require that the ultimate tensile strength of the bars be at least 15 % greater than the yield strength for mild steel, and 10 % for high yield steel. When the yield strength is 'enhanced' the percentage difference between the yield and the ultimate stress is significantly reduced and could cause this particular condition not to be met.

Another issue that would arise if this assumption is true is the reduction of the plastic region of the stress strain curve. This could cause restraint on plastic design since ductility is significantly reduced especially in smaller bars **[8]**.

### 3.4.4: Kinks

When the bar samples were bent and straightened there were kinks that were left at the points of bending and these also were found to have a significant effect on the behavior of these bars under tension.

Strain gauges were used on the samples tested in JKUAT. These gauges were fixed on the reworked regions since it's the behavior of the steel on these regions that was of interest. In some of the bars where the kinks were more pronounced there occurred a significant amount of compression (up to -4500 x $10^{-6}$ at 68 KN tensile load for one Y16 sample).

From the stress strain relationship;

$$E = \sigma / \varepsilon$$

Taking E = 205 KN / $mm^2$. Stress on the compression side of this bar's cross section can be calculated as

$$\sigma = 205000 \text{ N / mm}^2 \times 0.0045$$

$$= 922.5 \text{ N / mm}^2$$

Adding this value algebraically to the direct tensile stress at the point when this strain was observed. Total stress on the outer face of the bar

$$\sigma_t = 350 - 922.5$$

$$= -572.5 \text{ N / mm}^2$$

This value is way above the known yield stress of the bar and thus this can be taken to suggest that the yield point was long exceeded at this point. Now, if it is assumed that the stress on the outer surface of the bar (where the strain gauge was placed) is at yield (≃ 460 N / $mm^2$), it is a requirement of static equilibrium that some other part of the section be stressed by an equal amount in the opposite direction so as to achieve a balance of forces. Due to this, it can be argued that the inner face of the kink is likely to yield much earlier since it's subjected to both bending and direct tensile stresses, leading to the weakening of the whole bar in tension.

One could also look at this problem as below;

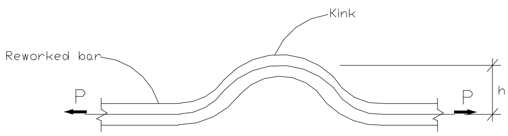



**Figure 3:** Kink on Bar.

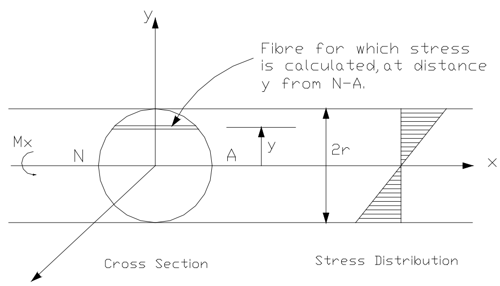



**Figure 4:** Bar Cross Section and Bending Stress Distribution.

From figure 3 the bar subjected to a tensile force P and having a kink of height h as shown in the figure will have a moment, say Mx, due to the eccentricity of the applied force.
From the equation for flexure:

$$M / I_{xx} = \sigma / y$$

Where M = Applied moment
$I_{xx}$ = Second moment of inertia of the section
$\sigma$ = Resulting axial stress
y = distance of the fiber for which stress in sought, from the neutral axis.

$$\sigma = M\, y / I_{xx}$$

Substituting for $I_{xx} = \pi r^4 / 4$

$$\sigma = (4\, M\, y) / \pi_4$$

From figure 3, as the tensile force P increased, the kink height h was found to be decreasing until the bar was completely straight (this was found to occur at approximately the yield point). At zero force, moment ($P^I$ x $h^I$) is zero ($P^I = 0$) and at yield the moment is also zero ($h^I = 0$). If a linear inverse proportional relationship is assumed between P and h (since this variation occurs in the elastic portion of the stress strain curve), the maximum moment will occur at an optimum value of the product of $P^I$ and $h^I$ which will be at approximately when $P^I = P_y / 2$ and $h^I = h / 2$.
Ie; $M = (P_y / 2) \times (h / 2)$

$$= P_y h / 4$$

Substituting for M in stress equation;

$$\sigma = 4y \,.\, P_y h / 4\pi r^4$$

$$= P_{y.}h.y / \pi r^4$$

This expression shows that bending stress in a circular cross section varies linearly since the only variable, y, varies linearly from zero to r. Maximum stress is felt on the outermost fiber i.e. at y = r. Substituting for y = r in the stress equation gives:

$$\sigma_{max} = P_y.h / \pi r^3$$

The most critical value of h was found to be about 25mm for the bigger bars. Taking this value and assuming the yield to have occurred at 460 N / mm$^2$, substitution into the stress equation above gives for a 16 mm diameter bar:

$$\sigma_{max} = (92.49 \times 10^3 \times 25) / (3.142 \times 8^3)$$

$$= 1438.3 \text{ N / mm}^2$$

This figure again is found to exceed the yield stress by far and can be taken to imply that by the time the bar is seemingly reaching yield, part of it has yielded long before. This, in addition to lowering the overall tensile strength of the bar, would also affect the ductility of the bar as there would be differential plastic deformation with a small part being yielded while most of the rest of the bar is still in the elastic region.

### 3.4.5: Position of breaking

The position of failure for the bars tested was recorded and is summarized in the table 8.

**Table 8: Frequency of bars breaking at rework**

| Bar | Broke at rework | | Broke away from rework | |
|---|---|---|---|---|
| | Number | Percentage | Number | Percentage |
| R12 | 4 | 44.4 | 5 | 55.6 |
| Y12 | 0 | 0 | 5 | 100 |
| R16 | 0 | 0 | 7 | 100 |
| Y16 | 3 | 42.9 | 4 | 57.1 |

As is evident on table 8, most of the tested bars had a tendency of breaking away from the reworked area. For these bars it was observed that they did not have a specific position or region where they broke and were breaking at any point between the rework and the grips.

It is suspected that this could have been caused by work hardening during reworking. From figure 2, it is possible that the bars were taken to a point beyond the yield say the one marked 'Enhanced' $\sigma_y$ during reworking and thus making the reworked region effectively harder than the rest of the beam. At the time of testing, this region of rework could have been taken through further rework, causing the breakage to occur on the other regions from the rework. If this is true then the criteria for the breaking changed from the expected one of the 'weakened reworked area' to one of the point with minimum cross sectional area i.e. the bars broke at the points with minimum cross sectional area. Such a point would occur randomly along the bar thus the random failure points observed in these bars.

There are some bars that were however significantly affected by the reworking as is evident on table 8. Close to one half of both the R12 and Y16 bars tested broke on the region of the rework. It is possible that these bars were affected by one or both of the scenarios discussed in 3.4.2 & 3.4.4 above.

### 3.4.6: Ductility

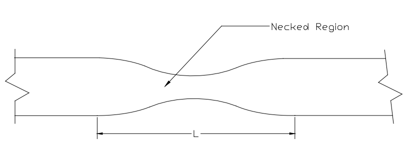
Ductility is usually measured using either or both of the quantities;

- Percentage elongation
- Percentage reduction in area

For percentage elongation, it is usually required that the gauge length used in the tests be given together with the results. This is because the extent by which the bar yields at the point where it necks is a function of, among other factors, the cross sectional area and the ductility of the particular bar. The length of the bar however, if longer than the extent over which the necking occurs, has no effect on the length of the necked region L, (figure 5). Due to this therefore, the longer the gauge length, the lower the minimum percentage elongation required and thus the need for converting the prescribed minimum percentage to conform to the gauge length of study.

**Figure 5:** Necked region of tensile test sample

The length of the necked region, L, in the samples in this study was found to range approximately from 30 mm to about 60 mm with



the more ductile bars having the higher values. This compared to the distance between the grips (say 650 mm as in the R12 samples) is fairly significant. However, from the equation (iii) used in the conversions, a slightly longer bar would have a very small value of the required minimum elongation. Bars specified for reinforcing concrete have lengths of up to of 12 m (nominal length of manufacture). An R12 bar of such length (12 m) would be required to have the following minimum elongation requirement:

$$A_r = 2\,A\,\{\sqrt{(S_o)} / L_o\}\ \text{Exp}\ 0.4 \qquad \ldots.. \qquad \text{(iii)}$$

$$= 2 \times 22 \times \{\sqrt{(113.1)} / 12000\}^{0.4}$$

$$= 2.65\ \%.$$

Considering the kind of percentage elongations that the R12 samples were giving, a value of 2.65 % such as calculated above would be easily achievable. This might mean that the effect of reworking which would be expected to reduce ductility is most likely to be critical in shorter bars than in longer ones.
Converting the values of minimum elongation given by the codes **[6, 7]** and comparing them with the elongations from the tensile tests table 5, gives the summary table 9.

**Table 9:** **Summary of average percentage elongations and converted minimum percentage elongation requirements**

| Bar type and size | Average percentage elongation | | | |
|---|---|---|---|---|
| | Converted | Normal bar | Reworked bar | Double reworked bar |
| R12s | 8.68 | 21.06 | 20.36 | 18.86 |
| Y12s | 4.50 | 7.92 | 20.03 | - |
| R16s | 9.25 | 14.7 | 17.89 | - |
| Y16s | 5.04 | 14.84 | 6.69 | - |

Generally all the bars were found to be within the code limits for minimum percentage elongation. An interesting observation however was in the R12 samples that showed a small but clear decline in percentage elongation with reworking the bar twice as opposed to reworking once as in the other bars. This is probably the result of a larger degree of strain hardening, due to more reworking. Again, as expected, the bigger bars were found to be less ductile than the smaller ones, even after reworking. Reworking did not reduce the percentage elongation enough to disqualify such bars by this requirement.

### 3.4.7: Yield and Ultimate Stresses

From table 3 clear decline of ultimate strength is observed for R12 samples from normal, to reworked, to double reworked bars. For the Y12 bars, the yield stress was generally 'enhanced' in the reworked bars as discussed in section 4.1.5.2 (≈ 117 % of the normal bar'). However, the ultimate strength of the reworked bars was found to have been reduced (≈ 97 % of the normal bar'). R16 samples showed a slight reduction in both yield (82 % of the normal) and ultimate (99 % of the normal) strengths. This could probably be as a result of reduction of area since some of these bars were found to be cracking transversely to the longitudinal axes of the bars. Both yield and ultimate strengths of Y16 bars were found to be higher in the reworked bars than in the normal bars (≈ 124 & 103 % of the normal respectively). This could be a result of further strain hardening caused by the reworking. It is interesting to note here that the average yield strength for the Y16 Normal Bars (≈ 380 N / $mm^2$) is less than that specified in the code **[7]**, this could probably be due to insufficient amount of twist during manufacturing. Generally, in all the bars except the Y16s, reworking seemed to be reducing the ultimate strengths of the bars even though only to a small extent.
It is a requirement of the codes for steel reinforcement bars [**7, 6**] that the ultimate strength of mild steel bars be at least 15 % that of their yield strength while for high yield bars this margin be at least 10 %. From table 3, the bars tested were found to comply with this requirement. Reworking was found to be reducing this percentage margin in all bars except R16s. This reduction was expected as is discussed in preceding sections. It should however be noted that the reducing effect was so small that the reworked bars were found to be able to meet the code requirement, on the average. However, some individual Y12 bars were observed to fall short of the minimum 10 % requirement.

### 3.4.8: Mass per meter run and cross sectional areas

From table 6, it is observed that all of the high yield test samples do not meet the requirement for tolerance of mass per meter run [**7, 6**]. This is as opposed to the round bars, which show a better compliance to this requirement. It was also observed that some of the bars complied with the code requirement for deviation, ie ± 4.0 per cent **[6]**. The other round bars seem to be more conservative in that they showed large positive values of deviation from this requirement. However, since this tolerance is subject to the one on mass per meter **[7, 6]**, to which the bars were found not to comply, they were found not to comply with the standards requirement.

**Young's Modulus of Elasticity**

The average $E_{el}$ Values for reworked samples were expressed as a percentage of the $E_{el}$ values for the normal bars and are given in table 10.

**Table 10: Reworked Bar $E_{el}$ Values as a Percentage of the Normal Bar $E_{el}$ Values**

| Bar Type & Size | Average $E_{el}$ Value (KN / mm$^2$) | Average $E_{el}$ Value (% of Normal) |
|---|---|---|
| R12 / N | 197.22 | 100.00 |
| R12 / RW | 157.59 | 80.04 |
| R12 / DRW | 165.31 | 83.81 |
| Y12 / N | 197.21 | 100.00 |
| Y12 / RW | 110.89 | 56.23 |
| R16 / N | 176.59 | 100.00 |
| R16 / RW | 166.10 | 94.06 |
| Y16 / N | 385.68 | 100.00 |
| Y16 / N | 317.64 | 82.36 |

As can be seen in table 10, the normal samples seemed to have, on the average, higher values of $E_{el}$. This seems to suggest that reworking might have reduced the stiffness of these bars. An average percentage of the $E_{el}$ value for the R12 reworked bars was found to be 80.04 %. This indicates an average reduction of the $E_{el}$ value from the normal of close to 20 %, which is considerably significant. This trend is repeated in the averages for Y12s, Y16s and, to a small extent, for R16.
From these plots it’s clear that the reworking had a significant effect on $E_{el}$ values. Looking at the stress strain relationship,

$$E = \sigma / \varepsilon$$

A decrease in the value of E would be a result of a bigger increase in the value of $\varepsilon$ without a corresponding proportional increase in the value of $\sigma$. This scenario is usually observed in the plastic zone where there is a large increase in strain without a corresponding proportional increase in the value of stress. It is possible therefore that the reworked bars in this study had reached yield point on the reworked regions during reworking, giving the reduced $E_{el}$ values.
The stresses used in this calculation were based on observed areas derived from the weights and the lengths of the bars. During reworking cracking of the bars was observed. It is possible that this cracking could have caused a reduction in the effective cross sectional area of the test bars resulting in higher actual stresses for a particular load than those calculated. If such a scenario occurred, even if the bar was still within the plastic range, the values of $E_{el}$ could be seen to be lower since they would be based on lower stress values than those actually experienced within the bars. This also could also have contributed to the ‘reduction’ in the values of $E_{el}$.

**Conclusions**
Results obtained from the study led to the following conclusions

i. Reworking of reinforcement bars reduces the elongation of the bars before ultimate failure, even though for almost all practical purposes the reduction is insignificant.
ii. Reworking causes cracking especially in bigger bars. It was also observed that bars that didn’t completely break during the rework, were capable of achieving a significant amount of the original yield and ultimate strengths.
iii. Yield and ultimate strength showed a decrease due to reworking for most of the bars tested (2.5 % for R12 and Y12, 0.7 % for R16). R16 showed a slight increase (3.8 %). Minimum percentage difference between yield and ultimate strengths was found to follow this trend as well even though the values observed on the reworked bars were well within the minimum requirements given by the relevant codes.
iv. Reworked bars were found to have some residual kinks which could cause ‘early yielding’ in some portions of the bar section causing reduction in yield strength of the bars.
v. Reworked bars were found to be more likely to break away from than on the reworked region.
vi. The modulus of elasticity is significantly reduced by reworking. In some bars (eg. R12s) the reduction was found to be by as much as 44 %.

**Recommendations**
The following recommendations can be made for further work:

1. A number of tensile tests large enough to satisfy statistical requirements be carried out so as to be able to get results that are a true representative of the steel in the market.
2. Vary the number and amount of rework to determine the relationship between property change and number / amount of rework.
3. Using the results obtained in (i) above try and modify the available design formulae to enable the use of reworked steel, and the evaluation of structures built using such steel.

4. Study the relationship between the constituents of steel and its residual tensile characteristics to determine optimum ranges of particular constituents within which steel can be reused as reworked steel.
5. Look into methods of reforming steel reinforcement bars into desired shapes to determine the most efficient method in terms of preserving the original properties.

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