Variability of Mechanical Properties and Weight for Reinforcing Bar Produced in Saudi Arabia

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Abstract: Under the category of material property variations, the variability of the physical and mechanical properties of reinforcing steel affects the performance of reinforced concrete structures. In Saudi Arabia, these properties have minimum requirements, as detailed by ASTM International Standards A 615. In this study, the variability of the weight and mechanical properties of reinforcing steel produced throughout the Saudi Arabia is evaluated experimentally. The results were analyzed to evaluate which manufacturers satisfy the minimum requirements established by ASTM International. 130 ASTM 615 grade 60 samples from different manufacturers were collected and tested to obtain yield strength, tensile strength and elongation. The numbers of samples tested for percent of nominal weight were 96. A statistical analysis of steel rebar’s properties is conducted. EasyFit (5.6) software is utilized to determine the distribution type and to perform the statistical analysis. The analysis showed that yield, tensile, and elongation follows different types of continuous distributions. Finally, control charts are generated for the three tests in order to identify values above and below the 3 sigma. The results show that less than 1.5%, 3% and 7.3 %of the steel failed to meet minimum ASTM standards for yield strength, tensile strength, and weight respectively. All the samples satisfied the ASTM 615-15 condition for elongation.

1. Introduction

Steel is one of the basic building blocks of the modern world. Automobiles, appliances, bridges, oil pipelines, and buildings, all are made with steel. While steel manufacturing has existed for centuries, the process for making steel continues to evolve. Establishments in this industry produce steel by melting iron ore, scrap metal, and other additives in furnaces. Conventional reinforced concrete is a composite material of steel bars embedded in a hardened concrete matrix [1–8]. ASTM standards establish minimum criteria for the mechanical properties of reinforcing steel. With the exception of ASTM A 706, however, they do not set maximum limits nor do they address instances where properties may significantly exceed the standards. This may be of concern because member behavior can differ from the planned response if material properties are significantly higher than those used in the design. For instance, if the reinforcement is too strong in a reinforced concrete flexural member, it is over reinforced. If the member is overloaded, this can result in brittle failure, with the concrete crushing before the steel yields. For members subjected to severe lateral loads, an increase in flexure strength can increase the induced shear forces on the member, also resulting in a brittle failure.
An understanding of the variability of steel properties is also useful in the development of statistically based expressions for member strength, which are used in the development of reliability-based strength-reduction factors in design codes. For these reasons, it is worth examining the actual values of the mechanical properties of the reinforcing steel as compared to those used in design. The mechanical properties of reinforcing steel are controllable in the manufacturing process, but variations between manufacturers and between heats for the same manufacturer do exist. Results may be influenced by several factors including, but not limited to the rate of loading, bar cross-sectional area, and variations in the composition of the steel. All reinforcing steel manufacturers must perform tests on their products to verify that they meet the ASTM standards. These tests measure the yield strength, tensile strength, elongation, and weight per foot (or percent of nominal weight) of the reinforcing steel.

There has been number of statistical studies dealing specifically with the variability of the mechanical properties of reinforcing steel [9-14]. In these studies, variations in yield and tensile strengths were examined. These variations is believed to be caused by variation in the rolling practices and quality control measures used by different manufacturers, as well as possible variations in cross-sectional area, steel strength, and rate of loading. To develop statistical descriptors for the mechanical properties of reinforcing steel, Mirza and MacGregor [9] studied the results of about 4000 tensile tests. The sample included rebar’s having wide range of diameters (9.5-57.3mm) and two grades of steel (yield strength = 276 MPa or 414 MPa). The means and standard deviations of the mill test yield strengths were found to be 337 MPa and 36.1 MPa for Grade 276 steel, and 490 MPa and 45.6 MPa for Grade 414 steel, respectively. Joshi and Ranganathan [15] analyzed statistical data on yield strength and modulus of elasticity of reinforcing steel bars from rolling mills and building sites. In a study on steel reinforcing bars used in Turkey, Akyz and Uyan [16] agreed with the requirements of Turkish Steel Rebar Specification Standard TS-708. In Saudi Arabia, Arafah [17] used an experimental program to develop probabilistic models for compressive strength of concrete and yield strength of reinforcing steel produced in the country. A total of 955 concrete samples and 434 samples of steel bars were randomly collected from construction sites. Galasso et al. [18] carried out statistical analysis of reinforcing steel properties based on about 200 test data. The data included a wide range of reinforcing steel bars with diameter between 12 and 26 mm made in Italy. Jibrin and Ejeh [19] studied the Chemical composition of reinforcing steel in the Nigerian Construction Industry. A total of 14 companies supplied nineteen samples were tests. Most of the bars showed absence of some element such as Molybdenum, Vanadium, etc. which is a strength and coefficient of weldability determinants BS4449. Also, it is shown that the high percentage of elements such as Silicon and Phosphorus impacted negatively on the strength and deformation characteristics of the bars.

Saudi Arabia’s steel demand has made the country one of the largest consumer in the GCC region. The country also accounts for significant number of construction activities in the Middle-East region. Over the past decade, steel consumption in the Kingdom has increased considerably buoyed by construction boom, growing investment in the real estate sector and rapid infrastructure developments. In addition, the steel industry has witnessed tremendous growth in terms of production, as various players are expanding their production capacities to meet the soaring steel demand [20].

The aim of this work is to study the variability of the mechanical and weights of reinforcing steel produced throughout the Saudi Arabia by experimental work and evaluate manufacturer’s performance in satisfying the minimum requirements established by ASTM International A615. The variability of the mechanical and weight of steel reinforcing bars is evaluated and expressions are developed to represent the probability distribution functions for yield, tensile strength, and elongation. 130 samples from different manufacturers were collected and tested to obtain yield strength, tensile strength and elongation. 96 samples were tested to obtain the percent of nominal weight. A statistical analysis of the rebar properties is conducted for acceptably large numbers of data to identify the variability of the mechanical properties, weight of steel reinforcing bars produced in the KSA under ASTM A 615. Expressions are developed to represent the probability distribution functions for yield, tensile strengths and elongation. The results are very important for the long term financial stability and mechanical viability and structural safety for this sector in KSA.
2. Experimental Method
Samples of steel bars ASTM A615 Grade 60 were collected and labeled from eight local steel manufacturing companies in Saudi Arabia namely Usaimi (US), SABIC (HA), Al Rajhi (RA), Al Ittefaq (IT), Jazira (JA), Watania (WA), Taybah (TA) and Al Yamamah (YA). A total of 130 specimens were randomly selected from the manufacturers stockpiled. All the samples were prepared and tested for the weight and mechanical properties as per ASTM 615-15. These tests were performed at five different laboratories namely Saudi Arabia standard organization, SABIC, Al-Hoty Stanger, Al Ittifaq and Imperial College London. Instron universal testing machine were used to perform the mechanical tests.

3. Results and Discussion
The tests result of mechanical properties and percent of nominal weight of the ASTM 615 grade 60 samples from different manufacturers indicated the followings. The steel bars exhibited variability in yield and tensile strength with minimum and maximum of 403, 620.3MPa and 611.1, 733.2MPa, respectively. The average yield strengths and tensile strength for bars were 535 and 664.7 MPa, respectively. On the other hand, the percentage elongation showed much less variability. The maximum, minimum, and average were 19, 9.7 and 14.7 respectively.

Figure 1. The influence of Yield Strength (YS) on the ratio (TS)/YS
Fig. 1 shows the influence of yield strength (YS) on the TS/YS ratio, as expected the ratio decreases with increasing the yield strength. This will reduce the ductility of the structure. Note of Caution: There have been many occasions in the past where over strength reinforcing bars (Higher Yield and/or Higher Tensile Strength) are innocently accepted by the Design Engineer or passed on by the supplier as the specified grade in the mistaken belief that stronger is necessarily better. There are number of rebar’s in the list which have high values of yield strength. There could be number of reasons for high strength values, this can be due to the poor chemical composition control manufacturing process. More recently, structures have been designed using plastic design concepts whereby the ability of the structure to yield and redistribute load without catastrophic failure is required. In such cases the post-yield behavior of the steel assumes an increasing importance. In engineering terms, the parameter selected to idealize the ability to withstand plastic loading is the tensile/yield ratio. The unique material strength properties TS & YS are individually important to consider and control as they influence the behavior of structure. Taken together as the Ratio TS/YS (known as the “Strain Hardening Value” in European practice), it indicates the ductility capacity of the structural member or component where it was used. The ASTM A615/A 615/M do not specify or requires any value for this ratio. A large TS/YS ratio means a greater energy absorption capability before failure. In addition, larger deformations are experienced which could serve as visible warning to building occupants prior to total failure or collapse. Less Brittle behavior therefore is experienced. Insufficient value of TS/YS value or the Strain Hardening Value leads to high concentrations of strain and initiates earlier steel fracture at ultimate loads.
- The high ratio of TS/YS helps to impart ductility to structures by:
- Assuring that significant energy absorption and dissipation occur during inelastic deformation.
Preventing the premature failure of reinforcing bars due to brittle behavior.
Guaranteeing that plastic hinging develops at intended locations.
Avoiding premature failure due to strain concentrations.

The statistical analysis including the values of maximum, minimum, average, median and standard deviation for yield strength, tensile strength and elongation are calculated. Tables 1 and 2 depict the summary result of the three tests; yield strength, tensile strength, and elongation. EasyFit (5.6) software was performed in order to obtain required results. The three tests follow different types of distributions as follows:

### Table 1. Descriptive Statistics

| Variable | Value | Percentile | Value |
|----------|-------|------------|-------|
| Sample Size | 130 | Min | 340 |
| Range | 204.91 | 5th | 441.51 |
| Mean | 493.85 | 10th | 555.68 |
| Variance | 297.67 | 25th (Q1) | 355 |
| Std. Deviation | 51.936 | 50th (Q2) | 499.29 |
| Coef. of Variation | 0.3362 | 75th (Q3) | 727.22 |
| Std. Error | 48.553 | 90th | 850.47 |
| Skewness | -0.3237 | 95th | 905.73 |
| Kurtosis | -0.1132 | Max | 920.31 |
| Min | 340 |
| 5th | 441.51 |
| 10th | 493.85 |
| 25th (Q1) | 555.68 |
| 50th (Q2) | 499.29 |
| 75th (Q3) | 727.22 |
| 90th | 850.47 |
| 95th | 905.73 |
| Max | 920.31 |

Yield strength follows “Johnson SB distribution”, it is unimodal distribution and is parameterized by four numbers (γ: shape parameter; μ: location parameter; δ: shape parameter; and σ: scale parameter), as shown in Fig. (2.a). Accordingly; the mean and standard deviation are 540.87Mpa and 51.938Mpa based on Johnson SB distribution, as shown in Table 4. The skewness is to the left; it indicates that the tail on the left side of the probability density function is longer or fatter than the right side as shown in Fig. (2.a). Hence, the mean is less than the median value. However, this result is considered acceptable according to ASTM standards requirements.

Tensile strength follows “Log-Logistic distribution”, which is similar to log-normal distribution but has heavier tails. It has several different parameters such as a scale parameter (α) and shape parameter (β) as shown in Fig. (2.b). The result shows that the mean and standard deviation values of tensile strength are 675.99Mpa and 21.927Mpa, as shown in Table 4, which are considered acceptable according to ASTM standards requirements. The coefficient of variant (CV), which is a function of mean and standard deviation, is 3.2%, which is very low compared to yield strength and elongation. By another word, the tensile strength test has less variation than yield strength and elongation.

Elongation follows “Pearson 6 distribution” as shown in Fig. (2c), it is one member of Pearson family. This type of distribution is used in risk analysis. It has four parameters; shape parameters (α1, α2), scale parameter (β), and location parameter (γ). Table 4 shows that the range of elongation value is between “9.5%” to “19%”. The coefficient of variation (CV) is equal to 14.4%, which is very high compared to yield and tensile strength. Hence, chemical tests are required to identify the elongation results and to get thoroughly about steel behaviors regarding elongation.
Figure 3. Control Charts (a) Yield Strength; (b) Tensile Strength; (c) Elongation

Fig. 3 depicts control charts of the three tests; yield strength, tensile strength, and elongation respectively. The control chart is utilized to identify values above and below 3 $\sigma$ of mean value. However, the results show that there is no any value above or under the three limits of 3 $\sigma$. For yield strength test; the under, mean, and upper are 385.06 Mpa, 540.87 Mpa, and 696.86 Mpa respectively. For tensile strength test; the under, mean, and upper are 610.21, 675.99, and 741.78 respectively. Finally, for elongation test; the under, average, and upper are 8.33%, 14.4%, and 21.02% respectively. In comparing the data with the minimum standards set forth by ASTM, the following are observed. The value of yield strength recorded for all samples were analyzed. Of those, 3 (1.5%) did not meet the minimum ASTM standard for grade 60. The same analysis for tensile strength on 130 samples showed that only 6 (3.0%) did not meet the minimum ASTM standard for grade 60. Finally, the elongation recorded for 130 samples showed that, all have met the minimum ASTM standard for grade 60. However, the analyses on 96 rebar’s samples show that approximately 7 (7.3 %) failed to meet minimum ASTM standards weight.

Table 2. Statistical analysis of mechanical properties of A 615 Grade 60 steel rebar’s

| Function       | Yield Strength (MPa) | Tensile Strength (MPa) | Elongation % |
|----------------|----------------------|------------------------|--------------|
| Distribution Type | Johnson SB           | Log-Logistic (3P)      | Pearson 6    |
| Skewness       | Left                 | Left                   | Left         |
| Maximum        | 620.31               | 733.19                 | 19           |
| Minimum        | 420                  | 611.15                 | 9.5          |
| Mean           | 540.87               | 675.99                 | 14.096       |
| Standard Deviation | 51.938            | 21.927                 | 2.115        |
| Coefficient of Variation - CV | 9.6 (%)          | 3.2 (%)                | 14.4 (%)     |
| Validation of Control Chart | 100 %           | 100 %                  | 100 %        |

4. Conclusion and recommendations

Mechanical tests conducted on 130 samples of locally manufactured steel reinforcing rebar’s in Saudi Arabia. The results of the tests have shown that less than 1.5 and 3% of the steel failed to meet minimum ASTM standards for yield strength and tensile strength, respectively. All the samples satisfied the ASTM 615-15 condition for elongation. More ever, the analyses on 96 rebar’s samples tested for weight showed that approximately 7 (7.3 %) failed to meet minimum ASTM standards requirements. It is also evident that, for most bars sizes of A 615 Grades 60, the mean for the mechanical properties are not situated at the midpoint of the data range, indicating non-normal distributions, therefore, the characteristic mechanical properties of locally produced steel bars is not consistent. The following recommendation and benefits can be deduced from this study.

1. The results are very important for the long term financial stability and mechanical viability and structural safety for this sector in KSA
2. Saudi Arabia Standard organization should make studies on mechanical characteristics of the rebar at least every 5 years to collect a large set of data from the manufacturers as to observe the consistency in the production process.
3. Saudi Arabia Standard Organization board should make sure, all the local producers follow the standard.
4. The expected immediate and long term benefits from this study include:
Assessment of current production of rebar’s in Kingdom;  
Identification of potential improvements to existing standard, for reduced risks of accepting lower quality materials;  
Using variability analysis procedures for assessing product variability based on production data

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