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Research Article

Experimental Investigation of the Ratio Between the Tensile Strength and Yield Stress of Reinforcing Bar

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Abstract

Steel is an iron alloy with additional carbon to improve its strength and fracture resistance. Reinforcing steel, also known as rebar, is a steel bar that's added to concrete to strengthen it. This study provides a comprehensive analysis of the tensile strength-to-yield stress (TS/YS) ratio and its implications for the ductility and performance of steel in structural applications, with a particular focus on earthquake-resistant design. Ductility is essential for preventing structural collapse during extreme events. The (TS/YS) ratio is crucial for structural systems expected to endure strain-hardening range stresses. The relevance of this ratio in the design of buildings and bridges is emphasized, especially regarding ductile elements and stress concentrations. Building codes, including the Bangladesh National Building Code (BNBC 2020) and the American Concrete Institute (ACI) 318M-14, mandate that the (TS/YS) ratio exceed 1.25, and guarantee adequate inelastic rotation capacity in structural members. This experimental investigation broadly evaluates Grades 40, 60, and 72.5 rebars with different diameters of 12 mm, 16 mm, and 20 mm, providing insights into the variation of TS/YS ratios across a broad strength spectrum to ensure structural reliability and optimize material selection. The results show that despite of higher yield stress of 72.5 grade bar (86 ksi), 60 grade bar shows better TS/YS ratio of 1.55. Elongation rates remained within acceptable limits for both 60 and 40 grade bar which is 21%, although the 72.5-grade rebar exhibited slightly lower elongation. Displacement-controlled tensile tests captured full stress-strain curves, indicating that the 60-grade rebar outperformed the others, particularly at the 16 mm diameter. Necking and complete cup-cone failure is found for 12 mm rebars. Overall, this experiment supports the feasibility of utilizing higher-grade rebars, especially Grade 60, in special structural systems to enhance ductility and performance during seismic events.

Keywords: Rebar, Tensile Strength, TS/YS Ratio, Universal Testing Machine, Yield Stress

Introduction

Designing structures to withstand natural forces like earthquakes, hurricanes, tornadoes, and snowstorms involves substantial challenges and has occasionally led to structural failures. A successful design requires not only an understanding of the characteristics and impacts of these hazards but also consideration of the structure's purpose and occupancy. Fundamentally, structures must ensure both safety and functionality during regular service while also resisting collapse under extreme events like earthquakes [1]. Safety is achieved by ensuring that structural components are built with enough strength and stability so that their factored resistance meets or exceeds the impact of the most critical load combinations. Furthermore, robust structural configurations and connections are needed to prevent progressive collapse following localized failures, thereby maintaining overall integrity [2].

Alongside safety, serviceability is a vital design criterion, which is addressed by controlling deflections, vibrations, and other service-related effects within acceptable limits. For economically feasible designs, ductility becomes especially important since it prevents sudden collapse during extreme conditions. Ductility refers to the ability of structures, their components, and materials to undergo inelastic deformations while retaining their strength [3]. This property enables energy absorption during seismic or other high-stress events, thereby improving structural resilience.

A critical material for ensuring ductility and strength in construction is reinforcing steel, or rebar. Rebar compensates for concrete's low tensile strength by providing the necessary resistance to tension, thus complementing concrete's high compressive capacity [4]. Its ribbed or indented surface enhances bonding with concrete and reduces slippage, which increases structural performance [5]. Numerous studies have employed universal testing machines (UTM) to determine the tensile strength (TS) and yield stress (YS) of rebar and structural steels.

Dong, et.al [6] conducted a detailed study on SS41 and SM50A steel grades in Japan, while Brockenbrough [7] expanded the focus to include various ASTM steel grades widely applied in construction. Similarly, Bartlett, et.al [8] examined ASTM A992 properties based on 207 tests and compared their findings with earlier works. Furthermore, Padilla-Llano and Ocel [9] introduced a high-strength steel bar with a yield strength exceeding 520 MPa, which marked a significant leap in rebar technology. Hadi [10] investigated 500 MPa reinforcing bars in concrete beams and reported superior strength properties, though sudden failures were observed in larger-diameter specimens. Rebar enhances the tensile capacity of concrete members, mitigates thermal expansion effects, and improves structural integrity [11,12]. High-strength steel bars, in particular, bring additional advantages such as reduced reinforcement ratios, lower installation costs, improved workability of concrete due to less congestion, and extended service life through better corrosion resistance [13]. Despite the benefits, reinforced concrete (RC) beams must achieve sufficient ductility at ultimate loads, as increased steel stresses under service conditions can still result in undesirable cracking [14].

To address these concerns, a particularly important aspect of such assessments is the tensile strength to yield strength ratio (TS/YS). This ratio is widely recognized as an indicator of a material's ability to withstand plastic deformation beyond its yield point [15]. Tavio, et.al [16] conducted an

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investigation on steel grades 420 and HSS bars of 550, 650, and 700 MPa to assess the effect of variations in the TS/YS ratio when it falls below or exceeds the prescribed limit. According to his findings, high-strength steel (HSS) did not satisfy the ductility requirement, as the TS/YS ratio was below 1.25. Dexter, et.al [17] performed a statistical analysis of experimental Y/T ratios and concluded that, adequate ductility can be achieved in steel grades with Fy < 345 MPa (50 Grade). Against this background, the present study examines the tensile and yield strength properties of different rebar grades available in Bangladesh (40, 60, and 72.5) with diameters of 12 mm, 16 mm, and 20 mm. The findings will assist practicing engineers in understanding the influence of the TS/YS ratio on structural design, while also providing insights into the characteristics of various rebar grades and their properties. The main objectives of this study are:

- To investigate the tensile strength and yield strength ratios of rebar grades 40, 60, and 72.5 across diameters of 12 mm, 16 mm, and 20 mm.
- To investigate the relationship between tensile strength and yield stress in reinforcing bars, with particular emphasis on the influence of rebar diameter. The study also considers additional parameters such as elongation, modulus of elasticity, and failure patterns to provide a comprehensive understanding of material behavior.

Methodology

Materials and Equipment

The test plan involved collecting rebar samples from specific sources (Figure 1) and assessing their general characteristics. This study employs JSRM, SS, RRM, and EIS branded rebar specimens of 40, 60, and 72.5 grades, with different diameters of 12 mm, 16 mm, and 20 mm.

The choice of rebar diameter in structural design is influenced by several factors, including load capacity, ductility, ease of construction, cost efficiency, and compliance with building codes. Larger bars, such as 20 mm, 25 mm, or 32 mm, are commonly used in high-load structural components like beams, columns, and foundations because they provide higher strength and stiffness [18]. In contrast, smaller bars, such as 10 mm, 12 mm, or 16 mm, are better suited for slabs, stairs, walls, and lighter elements where distributing reinforcement is more important than carrying heavy loads [19]. Closely spaced smaller bars improve ductility and help control cracking caused by shrinkage and temperature changes, while larger bars placed farther apart may achieve the same strength but are less effective in crack management [20]. Additionally, structural codes such as ACI, Eurocode, and BNBC provide limits on bar diameters to ensure safety, serviceability, and ductility.

A Universal Testing Machine (UTM) with a capacity of 1000 kN (Figure 2) is used to evaluate the mechanical properties of materials, including tensile strength, yield strength, elongation, and compressive strength. The UTM machine is calibrated against ASTM E4.

It is capable of applying tension, compression, and bending forces. UTMs are available in hydraulic and electromechanical configurations, providing exact control over force, speed, and displacement, ensuring accurate testing and analysis of varied material specimens. The experiments were conducted at the Engineering Material Laboratory of Ahsanullah University of Science and Technology (AUST) to analyze the properties of the rebar.

Figure 1. Sample of reinforcing bar

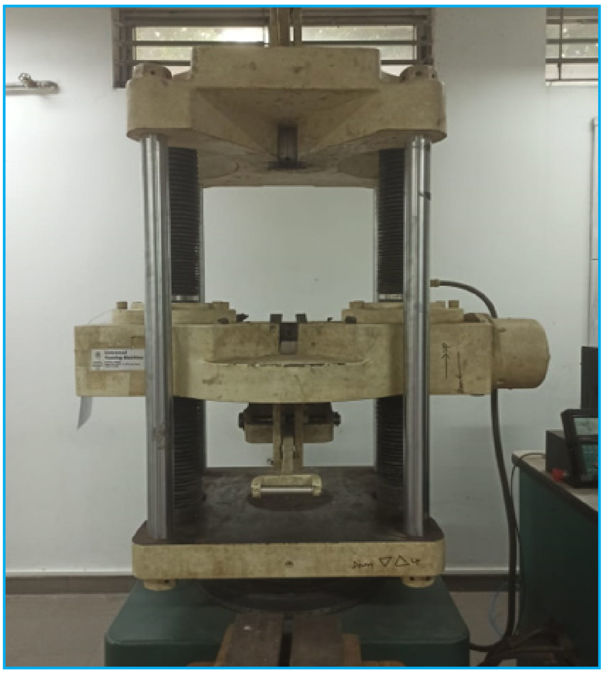

Figure 2. Universal Testing Machine (UTM)

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Test Procedure

All the tests were done according to the code ASTM E8M-13a: Standard Test Methods for Tension Testing of Metallic Materials [21]. The tensile test procedure began by using slide calipers to measure the specimen's diameter which is shown in Figure 3(a), as per the weight method specified in the standard testing procedure. The gage length and extensometer constant were recorded prior to testing. The specimen was then positioned and securely fixed in the center of the machine's grips to ensure proper alignment which is shown in Figure 3(b). Once the specimen was attached to the extensometer, the machine was turned on, and the testing conditions were set according to the specifications, including the speed of the test. The load was gradually increased until the specimen fractured under tensile stress which is shown in Figure 3(c, d, e). Upon completion of the test, the yield stress, tensile strength, elongation, and other mechanical properties were calculated based on the data recorded during the test. The TS/YS ratio, Modulus of Elasticity and %Elongation of length were calculated using Equations 1-3. Where l_f is final length rebar after testing and l_i is initial length rebar before testing.

$$Ratio\ \frac{TS}{YS} = \frac{Tensile\ srength}{Yield\ stress} \tag{1}$$

$$E = \frac{\Delta Stress}{\Delta Strain} \tag{2}$$

$$\%\ Elongation\ of\ length = \frac{l_f - l_i}{li} \times 100\% \tag{3}$$

This method allowed for precise measurement of the material's stress-strain behavior, which is critical in determining its suitability for structural applications. To investigate the properties of the rebar, tensile strength tests were carried out in accordance with standard specifications.

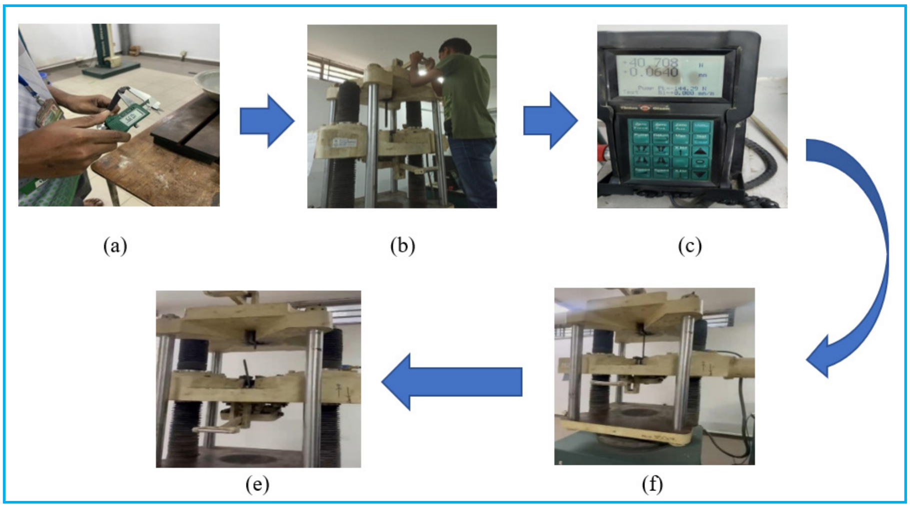

Figure 3. (a) Measurement of specimen diameter by slide callipers, (b) Setup UTM for the experiment, (c) Display of UTM, (d) UTM with sample rebar during the tension test, (e) Rupture of Specimen

Result and Discussion

This study incorporated three grades of reinforcing steel bars: 72.5, 60, and 40. Each grade included bar diameters of 12 mm, 16 mm, and 20 mm. The selection of this specific grade and diameter was deliberate, addressing the study's focus on specific performance metrics rather than overall strength.

For most bar diameters, three samples were tested to ensure reliability and consistency in the results. By testing a range of grades and diameters, this research aimed to assess the mechanical behavior of rebars under diverse conditions. The inclusion of three bar diameters across each grade allowed for a comprehensive evaluation of how these factors influence the TS/YS ratio. The decision to prioritize certain combinations over others was guided by the study's objectives, ensuring that relevant structural characteristics were thoroughly examined. This approach highlights the careful consideration given to the material selection and testing methodology, contributing valuable insights into the performance of reinforcing steel bars under varying conditions. The results were compared according to the code ASTM A615/A615M: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement [22].

Rebar (72.5 Grade)

Figure 4 displays the combined stress-strain curves for 72.5-grade rebars with diameters of 12 mm, 16 mm, and 20 mm. The stress is measured in Ksi, and the strain is plotted along the x-axis. The 12 mm rebar exhibits the lowest peak stress, around 95 Ksi, indicating a lower tensile strength compared to the larger diameters. The 16 mm rebar demonstrates a higher peak stress, approximately 105 Ksi, while the 20 mm rebar reaches the highest peak stress, exceeding 110 Ksi.

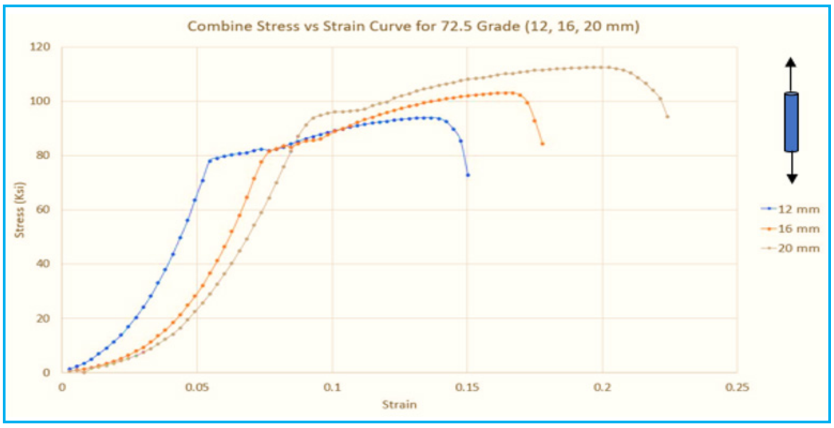

Figure 4. Combined Stress vs Strain Curve for 72.5 Grade (12mm, 16mm, 20mm)

All three curves follow a similar progression: an initial linear elastic phase, followed by yielding, and then strain hardening before a decline in stress beyond the ultimate tensile strength. The 20 mm rebar exhibits superior stress capacity, indicating better performance under tensile loading. This variation highlights the influence of diameter on tensile behavior, with larger diameters generally capable of withstanding higher stress levels while maintaining similar strain characteristics. The figures of necking and failure pattern of 12 mm, 16 mm, and 20 mm dia of 72.5 grade rebar are given in Figure 5 and 6.

(a) 12 mm (b) 16 mm (c) 20 mm

Figure 5. Necking of (a) 12 mm, (b) 16 mm, (c) 20 mm of 72.5 grade rebar

(a) 12 mm (b) 16 mm (c) 20 mm

Figure 6. Failure of (a) 12 mm, (b) 16 mm, (c) 20 mm of 72.5 grade rebar

Figure 5 and 6 showcase the failure patterns of 72.5 grade bars with diameters of 12 mm, 16 mm, and 20 mm under tensile testing. Figures 5(a) and 6(a) display the fracture surface and rupture point of the 12 mm bar, revealing ductile failure characterized by significant necking and a "cup-and-cone" fracture pattern, indicating notable plastic deformation. According to ASTM A615/A615M, ductile failure is characterized by significant plastic deformation and necking, which involves a reduction in the cross-sectional area. The incomplete cup-and-cone formation implies that these bars reached their ultimate strength with limited strain hardening, leading to a more abrupt failure. In contrast, the smaller-diameter rebars and lower-grade steels, which displayed full cup-and-cone fractures, benefited from higher elongation and better strain distribution, contributing to superior ductility (Table 1).

For the 16 mm bar, shown in Figures 5(b) and 6(b), tensile strengths exceeded 100 Ksi, reaching up to 104.68 Ksi, with a tensile-to-yield ratio greater than 1.2 and elongation below 7%, emphasizing strong mechanical properties. Figures 5(c) and 6(c) highlight the failure behavior of the 20 mm bar, which achieved tensile strengths near 100 Ksi, with tensile-to-yield ratios between 1.2 and 1.8 and elongation ranging from 9% to 12%. As necking is found, the observed failure patterns underline the ductile nature and varying plastic deformation characteristics of the reinforcement bars.

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Table 1. Average properties of different samples of 72.5 grade Rebar

Properties	Sample Diameter		
	(12 mm)	(16 mm)	(20 mm)
Modulus of Elasticity, E (Ksi)	2690	2223.33	1746.66
Yield Stress, YS (Ksi)	80.768	81.986	88.086
Tensile Strength, TS (Ksi)	95	103.668	104.103
TS/YS	1.177	1.266	1.183
Elongation (%)	6.94	6.53	10.556
Failure pattern	Cup-cone fracture (necking found, i.e. Ductile)	Incomplete Cup-cone fracture (necking found, i.e. Ductile)	Incomplete Cup-cone fracture (necking slightly found, i.e. Ductile)

Rebar (60 Grade)

Figure 7 illustrates the combined stress-strain curves for 60-grade rebars with diameters of 12 mm, 16 mm, and 20 mm. Each curve shows the stress (in Ksi) versus strain relationship during tensile testing. The 12 mm rebar exhibits the lowest stress levels throughout, reaching a peak stress of approximately 95 Ksi. The 16 mm rebar follows a similar trend but achieves a slightly higher peak stress, around 100 Ksi. The 20 mm rebar displays the highest stress levels, with a peak stress close to 110 Ksi, indicating superior tensile strength compared to the other diameters.

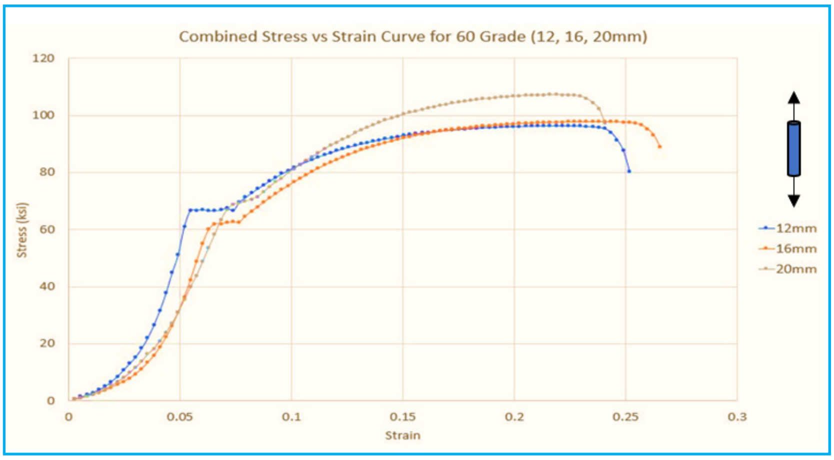

Figure 7. Combined Stress vs Strain Curve (60 grade, 12mm, 16mm, 20mm)

The curves for all diameters follow an initial linear elastic region, transitioning to a yield plateau, and then rising towards ultimate tensile strength before declining in the strain-hardening phase. The variation in peak stress reflects the influence of rebar diameter on tensile strength, with larger diameters generally demonstrating higher ultimate stress capacities. The figures of failure pattern of 12 mm, 16 mm, and 20 mm dia of 60 grade rebar are given in Figure 8 and 9.

Figure 8. Necking of (a) 12 mm, (b) 16 mm, (c) 20 mm of 60 grade rebar

Figure 9. Failure of (a) 12 mm, (b) 16 mm, (c) 20 mm of 60 grade rebar

In Figures 8 and 9, the analysis of the 12 mm, 16 mm, and 20 mm rebar samples indicates that they are all grade 60 rebar, with yield stresses slightly above 60 Ksi and tensile strengths close to 100 Ksi. For 12 mm rebar, a tensile-to-yield stress ratio of 1.5 and a variation in yield stress of 10% were found, with elongation around 18%. The necking zone and incomplete cup-cone fracture pattern were observed after failure. For 16 mm rebar, the tensile-to-yield ratio was nearly 1.6, with only a 3% variation in yield stress and 20% elongation, displaying a clear cup-and-cone fracture. In the 20 mm sample, yield stress was just under 70 Ksi, with a tensile-to-yield ratio above 1.5 and over 20% elongation, showing a similar cup-and-cone fracture (Table 2).

Table 2. Average properties of different samples of 60 grade Rebar

Properties	**Sample Diameter**		
	(12 mm)	**(16 mm)**	**(20 mm)**
Modulus of Elasticity, E (Ksi)	2470	2065	1920
Yield Stress, YS (Ksi)	66.233	61.975	69.246
Tensile Strength, TS (Ksi)	96.659	97.664	107.215
TS/YS	1.46	1.575	1.55
Elongation (%)	17.915	19.585	20.83
Failure pattern	Cup-cone fracture (necking found, i.e. Ductile)	Incomplete Cup-cone fracture (necking found, i.e. Ductile)	Incomplete Cup-cone fracture (necking slightly found, i.e. Ductile)

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Rebar (40 Grade)

The respective graph for 40 grade is shown in Figure 10. Grade 40 rebar with a 20 mm diameter was specifically chosen despite its lower strength, as it was needed to evaluate the tensile strength-to-yield strength (TS/YS) ratio under particular structural conditions.

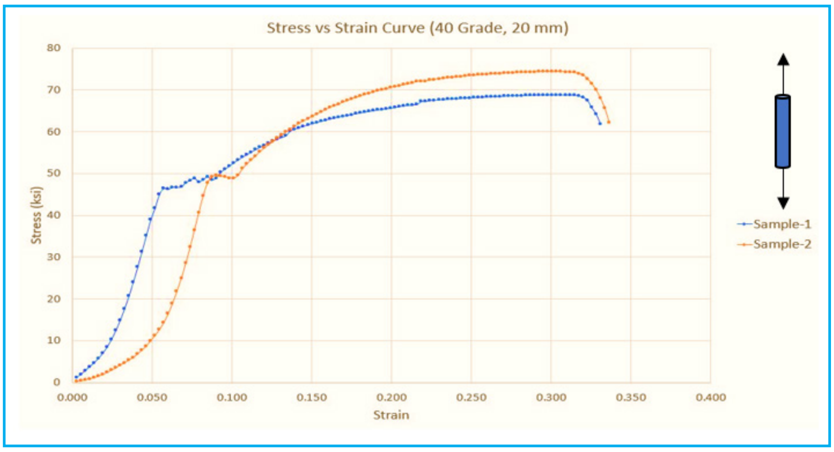

Figure 10. Stress vs Strain Curve (40 grade, 20mm)

According to Figure 10, two samples of 20 mm bar are used as 40 grade steel. Although the yield zone is close to each other, the graph's plastic stage is the primary focus area. Before reaching maximum tensile strength, the curve of Sample-1 is slightly fluctuated. Therefore, the curve of sample 2 is selected for the combined stress-strain curve.The figure of the failure pattern of 20 mm dia of 40 grade rebar is given in Figure 11 and 12.

Figure 11. Necking of 20 mm of 40 grade rebar

Figure 12. Failure of 20 mm of 40 grade rebar

The analysis reveals that the 20 mm rebar samples are grade 40, with yield stresses under 50 Ksi and tensile strengths around 70 Ksi. Both samples exhibit over 20% elongation and significant yield stress variation. The failure pattern is a cup-cone fracture, indicating ductility and necking after testing (Table 3).

Table 3. Properties of different samples of 40 grade Rebar

Properties	Sample Diameter (20 mm)	
	Sample 1	Sample 2
Modulus of Elasticity, E (Ksi)	1250	1360
Yield Stress, YS (Ksi)	48.01	48.875
Tensile Strength, TS (Ksi)	68.849	74.432
TS/YS	1.43	1.52
Elongation (%)	20.83	21.6
Failure pattern	Incomplete Cup-cone fracture (necking slightly found, i.e. Ductile)	Incomplete Cup-cone fracture (necking slightly found, i.e. Ductile)

Comparison between each Grades of different diameter rebar

An examination of Figures 13–15 and Tables 3–5 indicates that the 60-grade rebar exhibits a comparatively higher TS/YS ratio and percentage elongation than the 72.5-grade rebar.

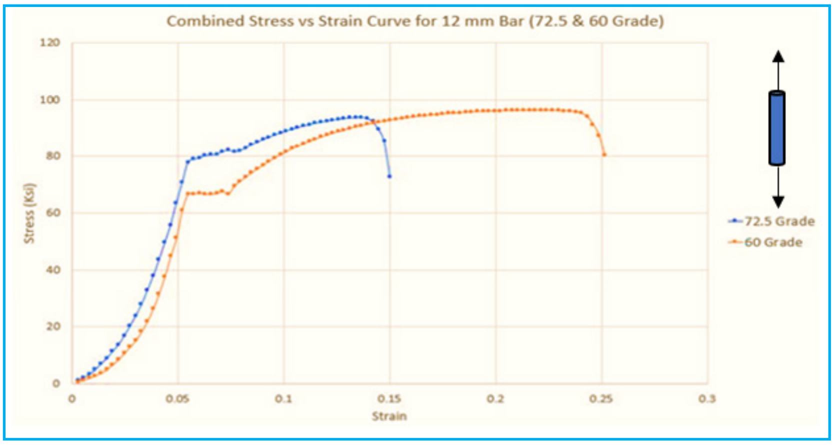

Figure 13. Combined Stress vs Strain Curve of 12 mm rebar for 72.5 and 60 grades

Figure 14. Combined Stress vs Strain Curve of 16 mm rebar for 72.5 and 60 grades

Table 4. Average properties of 12 mm rebar for 72.5 and 60 grades

Properties	72.5 Grade	60 Grade
Yield Stress, YS (ksi)	81.778	66.682
Tensile Strength, TS (Ksi)	93.883	96.384
TS/YS	1.15	1.45
Elongation (%)	7.5	17.5

Table 5. Average properties of 16 mm rebar for 72.5 and 60 grades

Properties	72.5 Grade	60 Grade
Yield Stress, YS (ksi)	80.334	61.954
Tensile Strength, TS (Ksi)	103.236	97.802
TS/YS	1.29	1.58
Elongation (%)	6.67	19.17

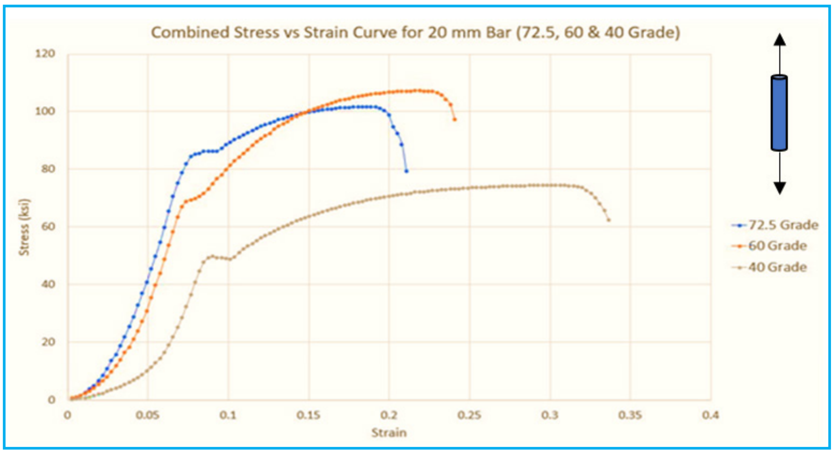

Figure 15. Combined Stress vs Strain Curve of 20 mm rebar for 72.5, 60, and 40 grades

Table 6. Average properties of 20 mm rebar for 72.5, 60, and 40 grades

Properties	72.5 Grade	60 Grade	40 Grade
Yield Stress, YS (ksi)	86.348	69.246	48.445
Tensile Strength, TS (Ksi)	101.719	107.215	71.641
TS/YS	1.18	1.55	1.48
Elongation (%)	10.83	20.83	21.215

From Table 4-6, the results indicate that Grade 40 and Grade 60 rebars satisfy the ASTM A706 and ASTM A615 requirement of a minimum TS/YS ratio of 1.25. Based on ASTM 615M-2017, tensile strength of each grade must higher about 1.5 times for grade 40 and 60, and 1.33 times for grade 75 from yield strength value. In contrast, for Grade 72.5 rebars, the 12 mm and 20 mm diameters fall below this threshold. The percentage elongation is also greater for Grade 40 and Grade 60 rebars, reflecting enhanced ductility compared with their higher-grade counterparts. In accordance with ASTM A615, the minimum elongation requirement is specified as 14% for rebar sizes No. 3 (10 mm) through No. 6 (19 mm), 12% for sizes No. 7 (22 mm) through No. 11 (36 mm), and 10% for sizes No. 14 (43 mm) and No. 18 (57 mm). For 20 mm rebar, 60 grade rebar shows

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better performance in all aspects. Results of the TS/YS ratio and %elongation for 40 grade rebar are also satisfactory. Tensile strength for 60 grade rebar is found higher than 72.5 grade.

The comparison highlights that the modulus of elasticity is highest in 72.5-grade rebars, indicating superior resistance to elastic deformation, whereas lower grades exhibit reduced stiffness. Yield stress corresponds to the nominal grade values, with 60-grade rebars closely aligning with 60 Ksi, while 72.5 and 40 grades show higher deviations. Among the grades, 60-grade rebars display the least yield stress variance, the highest tensile strength, and the optimal tensile strength-to-yield stress (TS/YS) ratio, signifying better energy absorption before failure. Although 40-grade rebars exhibit the highest elongation, their lower TS/YS ratio indicates inferior performance. In contrast, 60-grade rebars demonstrate balanced tensile strength, ductility, and consistency, outperforming 72.5 and 40 grades.

Conclusion

The main objective of this study is to investigate the ratio of the tensile strength-to-yield stress (TS/YS) and its implications for the ductility and performance of steel in structural applications, with a particular focus on earthquake-resistant design. This study provides an investigation of several steel grades and diameters, specifically grades 40, 60, and 72.5 with respect to 12mm, 16mm and 20mm rebar. From the aforementioned study and analysis, the following conclusions are found:

- The 40-grade and 60-grade rebar consistently showed a higher TS/YS ratio (around 1.5), indicating superior energy absorption before failure. This characteristic is especially beneficial for seismic applications, as a higher TS/YS ratio improves the rebar's ability to absorb stress during extreme events like earthquakes. In comparison, 72.5-grade rebar had a TS/YS ratio below 1.25, making it less effective in such scenarios.
- While 72.5-grade rebar exhibited a slightly higher modulus of elasticity (2690 Ksi), 60-grade rebar outperformed 40-grade rebar in terms of stiffness. The lower modulus of elasticity of 40-grade rebar limits its use in structural applications requiring high stiffness, further reinforcing the preference for 60-grade rebar in load-bearing structures.
- In terms of %elongation, both 40-grade, 60 grade rebars satisfy code requirement which is at least 14% for 10 mm to 19 mm rebar. However, the HSS bars (72.5-grade) resulted in lower %elongation.
- In terms of failure mode, all grades of rebars exhibited necking prior to fracture, indicating the presence of significant localized plastic deformation. However, for the 16 mm and 20 mm diameter rebars, the fracture surface showed an incomplete cup-and-cone profile rather than the typical fully developed cup-and-cone shape. This suggests a less uniform distribution of plastic strain and a tendency toward shear-dominated fracture in these larger diameters.

- In conclusion, Grade 60 rebar emerged as the most suitable choice for structural and seismic applications, combining superior energy absorption, greater stiffness, and more reliable ductility. These advantages are supported by its favorable TS/YS ratio, higher elongation capacity, and consistent ductile fracture profile, which collectively indicate strong strain-hardening behavior and stable post-yield performance. While Grade 72.5 rebar exhibited a higher elastic modulus, its lower ductility, reduced strain-hardening capacity, and occurrence of incomplete cup-and-cone fractures in specific diameters limit its suitability in scenarios where energy dissipation and post-yield resilience are essential.

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Conflicts of Interest

The authors declare that they have no competing interests.

Author Contributions

Md. Munirul Islam: project administration, supervision, writing-original draft, investigation, visualization. **Md. Nafiuzzaman:** data curation, formal analysis, writing - original draft. **Md. Mushfiqur Rahman Chayon:** methodology. **Tahia Rahman Sinthia:** conceptualization. **Shahriar Montasir:** writing-review & editing.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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