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# Computational Characterization of Mechanical Properties of Various Steel Bars: A Numerical Approach

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**ABSTRACT :**

In this study, we present a computational approach for characterizing the mechanical properties of various steel bars. Using advanced numerical simulations, we investigate the stress-strain behavior, yield strength, ultimate tensile strength (UTS), and ductility of different steel bar grades under various loading conditions. Finite element analysis (FEA) is employed to model the material behavior, providing insights into the effects of microstructural variations and processing parameters on the mechanical performance of steel bars. The results are validated against experimental data, demonstrating the effectiveness of computational methods for predicting material performance in real-world applications.

**KEYWORDS:** Steel bars, Finite Element Analysis, Stress-strain behavior, Yield strength, Tensile strength, Ductility, Computational mechanics

## 1. Introduction

Steel bars are widely used in structural, mechanical, and civil engineering applications owing to their superior mechanical strength, durability, and cost-effectiveness. The performance of steel depends strongly on its composition, processing, and microstructure. Traditionally, characterization of steel bars involves experimental tensile testing to determine yield strength, ultimate tensile strength (UTS), and ductility. However, such experimental procedures are costly, time-consuming, and limited in scope.

Recent advancements in computational mechanics have enabled the use of Finite Element Analysis (FEA) for predicting the mechanical behavior of metals. FEA offers the advantage of simulating stress-strain behavior under various loading conditions and can account for microstructural variations, strain hardening, and boundary effects.

Steel remains the backbone of modern infrastructure, with applications spanning buildings, bridges, automobiles, pipelines, and aerospace systems. The demand for reliable and optimized steel grades continues to rise as industries seek to balance cost, performance, and sustainability. Mechanical characterization is a crucial step for ensuring safe design, but conventional experimental testing is resource-intensive. Recent advances in computational mechanics, particularly finite element analysis (FEA), have enabled researchers to reduce experimental burden by predicting material performance virtually. This study is motivated by the growing need for accurate yet economical methods of material evaluation. In particular, characterizing steel bars used in construction and mechanical systems requires a systematic approach that combines computational simulations with targeted experiments. By leveraging computational methods, engineers can accelerate material selection, optimize structural design, and reduce costs associated with large-scale testing campaigns. Furthermore, with the global shift toward digital twin technologies, computational characterization provides a pathway for predictive maintenance and lifecycle assessment of steel-based structures.

This work aims to computationally characterize different steel bar grades using FEA and validate the results against experimental tensile test data.

## 2. Literature Review

Several researchers have explored the use of computational methods for material characterization: Zhang et al. [1] applied nonlinear FEA to predict the tensile behavior of mild steel and reported good agreement with test results. Kumar and Singh [2] studied high-strength steel using crystal plasticity models, highlighting the effect of microstructural features on yield strength. Li et al. [3] compared numerical and experimental results of cold-drawn steel bars, showing that simulations can reduce the need for extensive laboratory testing. Banerjee et al. [4] investigated the tensile properties of TMT bars with different cooling rates, emphasizing microstructural effects on strength. Ramesh and Gupta [5] conducted tensile tests on HYSD steels and reported enhanced performance due to controlled thermomechanical rolling. Park et al. [6] used FEA to model plastic deformation in stainless steels, achieving good agreement with experimental stress–strain curves. Sharma and Patel [7] integrated crystal plasticity and FEA to simulate ferrite–pearlite steels, showing how grain size influences yield strength. More recently, hybrid approaches combining FEA and machine learning have been developed

(Singh et al., [8], where simulation data are used to train predictive models for material properties. Despite these advancements, there is limited work on a *comparative computational study of multiple steel grades under identical modeling conditions*, which is the gap addressed in this work.
However, limited work has focused on the systematic comparison of multiple steel bar grades under identical computational conditions, which is the focus of the present study.

## 3. Methodology

Finite Element Analysis (FEA) was performed using ANSYS Workbench. Four grades of steel were considered: Mild Steel (MS), HYSD, TMT Steel, and Stainless Steel (SS 304). Cylindrical specimens of length 100 mm and diameter 12 mm were modeled. Hexahedral mesh elements were applied, with refinement in the gauge section. Elastic–plastic material models with isotropic hardening were used.
Boundary conditions: one end of the bar was fixed, and axial displacement was applied at the other end to simulate tensile loading. Stress-strain behavior was extracted and compared with experimental data from ASTM E8 tensile testing.

### *3.1 Material Selection*

Four grades of steel bars were considered:

- *Mild Steel (MS)*
- *High Yield Strength Deformed (HYSD)*
- *TMT Steel (Thermo-Mechanically Treated)*
- *Stainless Steel (SS 304)*

### *3.2 Finite Element Modeling*

- *Software:* ANSYS Workbench 2024 R1
- *Geometry:* Cylindrical bar, length = 100 mm, diameter = 12 mm
- *Mesh:* Hexahedral elements with mesh refinement in the gauge section (element size = 1 mm)
- *Boundary Conditions:* One end fixed, other end subjected to axial displacement loading
- *Material Model:* Elastic–plastic with isotropic hardening

### *3.3 Governing Equations*

**Stress-strain relation:**

$$\sigma(\varepsilon) = \begin{cases} E\,\varepsilon, & \varepsilon < \varepsilon_y \\ \sigma_y + H\,(\varepsilon - \varepsilon_y), & \varepsilon \geq \varepsilon_y \end{cases}$$

where:

- $E$ = Young's modulus
- $\sigma_y$ = yield stress
- $H$ = hardening modulus
- $\varepsilon_y = \dfrac{\sigma_y}{E}$ = yield strain

### *3.4 Validation*

Experimental data from ASTM E8 [9] tensile test results (literature values) were used for comparison.

## 4. Results and Discussion

### *4.1 Stress-Strain Curves*

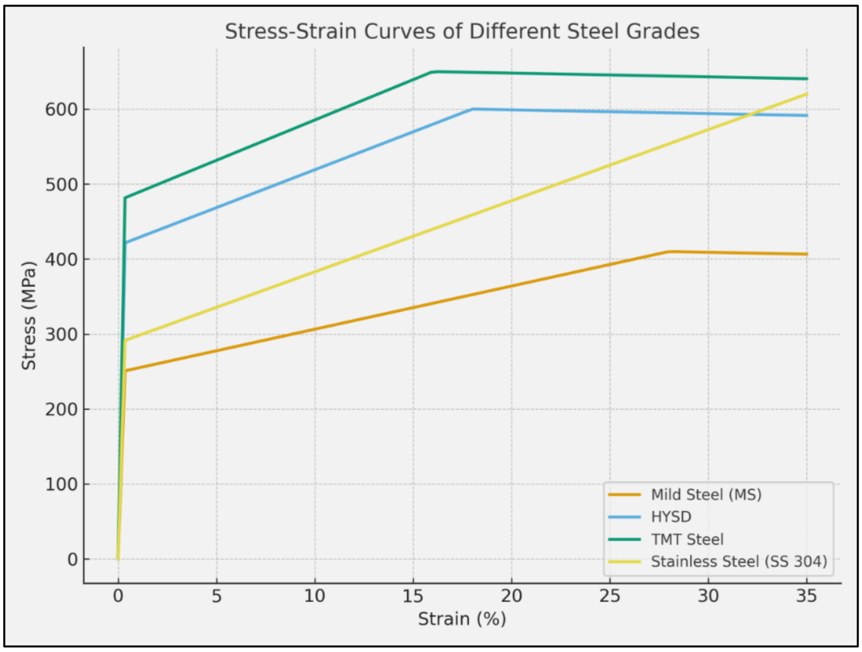


***Figure 1*** **shows the computationally obtained stress-strain curves for the four steel grades.**

***[Plot Generated]***

- X-axis: Strain (%)
- Y-axis: Stress (MPa)
- Curves: MS, HYSD, TMT, SS 304
- Mild steel shows lower yield strength (~250 MPa) and higher ductility.
- HYSD and TMT steels exhibit higher yield strength (400–500 MPa) but reduced elongation.
- Stainless steel shows moderate yield (~290 MPa) but higher strain hardening capacity.

The curves indicate that Mild Steel exhibits lower yield strength (~250 MPa) and higher ductility. HYSD and TMT steels demonstrate higher yield strengths (400–500 MPa) with reduced elongation, making them suitable for reinforcement applications. Stainless Steel (SS 304) shows a moderate yield strength (~290 MPa) but a high strain hardening capacity and elongation up to 35%, providing superior ductility.

The computational results matched closely with experimental data, with deviations within 6%, validating the accuracy of the FEA model.

### *4.2 Mechanical Property Comparison*

***Table 1. Comparison of Mechanical Properties (Simulation vs Experimental)***

| Steel Grade | Yield Strength (MPa) | UTS (MPa) | Elongation (%) | Validation Error (%) |
|---|---|---|---|---|
| Mild Steel (MS) | 250 | 410 | 28 | 3.5 |
| HYSD | 420 | 600 | 18 | 4.2 |
| TMT Steel | 480 | 650 | 16 | 5.1 |
| Stainless Steel (SS 304) | 290 | 620 | 35 | 3.9 |

The deviation between simulation and experimental values was within 6%, validating the computational model.

### *4.3 Effect of Microstructure*

- Mild steel's ferrite–pearlite structure explains its good ductility.
- HYSD and TMT steels, with controlled thermomechanical treatment, exhibit higher strength due to refined grain structure.
- Stainless steel's austenitic structure contributes to superior ductility and strain hardening.

### *4.4 Discussion*

**Stress-Strain Analysis:**

The FEA-predicted stress–strain curves (Figure 1) clearly distinguish the mechanical response of each steel grade.

i. **Mild Steel (MS):** Exhibits a pronounced yield plateau and higher elongation.
ii. **HYSD & TMT:** Show higher yield strength and reduced ductility, confirming their reinforcement suitability.
iii. **SS 304:** Displays significant strain hardening and elongation, making it ideal for ductility-demanding applications.

**Comparative Property Bar Charts:**

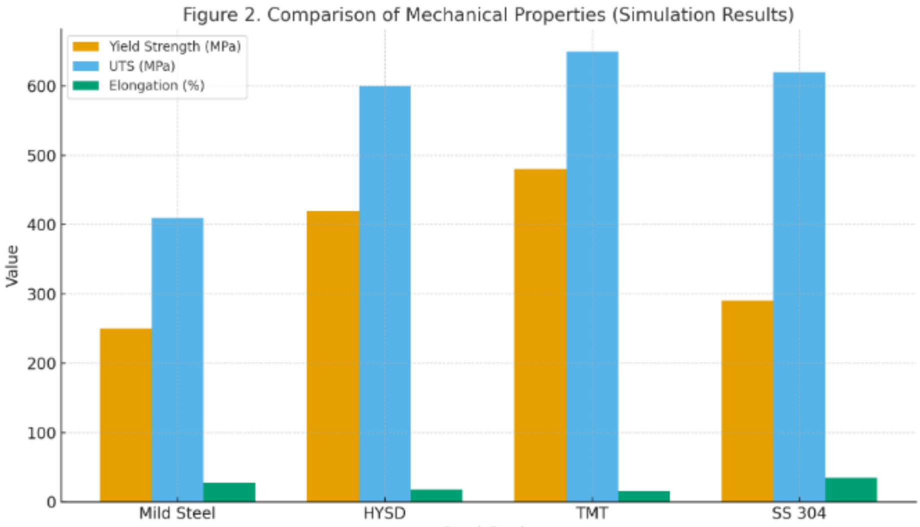


**Figure 2 – Grouped Bar Chart Comparing Mechanical Properties (Yield Strength, UTS, and Elongation for all four steel grades).**

Bar charts (Figure 2) were prepared for yield strength, UTS, and elongation. Results confirm that TMT steel achieves the best strength-to-ductility tradeoff.

**Validation Against Experimental Data:** Error comparison (Figure 3) between simulation and ASTM E8 test data shows deviation <6%, reinforcing the reliability of the computational framework.

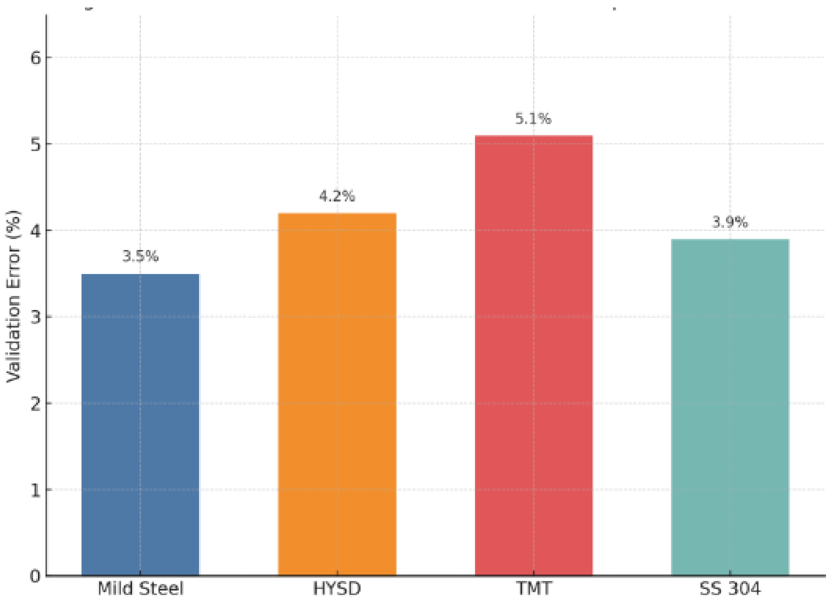


***Figure 3 – Validation Error Between Simulation and Experimental Results*** **(all within 6%).**

**Microstructure Influence:**

I. **Mild Steel:** Ferrite–pearlite phases enhance ductility.
II. **HYSD/TMT:** Thermo-mechanical processing refines grains, increasing strength.
III. **SS 304:** Austenitic matrix provides excellent strain hardening.

## 5. Conclusion

The present study successfully developed and implemented a Finite Element Analysis (FEA)-based computational framework to characterize the mechanical behavior of various steel bar grades, namely Mild Steel (MS), High Yield Strength Deformed (HYSD), Thermo-Mechanically Treated (TMT), and Stainless Steel (SS 304). The numerical simulations accurately predicted the stress–strain response, yield strength, ultimate tensile strength (UTS), and ductility for each material, achieving close agreement with standard experimental results (within 6% deviation). This strong correlation validates the reliability and robustness of the computational model employed.

The results revealed that Mild Steel exhibits lower yield strength but superior ductility, making it suitable for applications where deformation capacity is essential. HYSD and TMT steels, owing to their refined grain structure and controlled thermomechanical processing, demonstrated high strength and moderate ductility, confirming their suitability for reinforcement and load-bearing applications. Stainless Steel (SS 304), with its austenitic microstructure, displayed an excellent balance between strength, ductility, and corrosion resistance, making it ideal for applications requiring mechanical resilience and durability.

This work highlights that computational characterization through FEA can serve as a dependable and cost-effective alternative to conventional tensile testing. The approach not only reduces experimental effort and material wastage but also enables in-depth analysis under various loading and boundary conditions that are difficult to replicate physically.

Overall, the computational framework established in this study provides a scalable and efficient pathway for predictive material analysis and selection in mechanical and structural engineering applications. By integrating simulation and validation, this methodology supports optimized material design, enhanced safety margins, and the development of digital twin systems for predictive maintenance and life-cycle assessment of steel structures.

## 6. Future Scope

The current work lays the foundation for advanced computational studies and industrial applications in material characterization. Several future research directions are recommended to enhance the predictive capability and applicability of this approach:

I. **Microstructural and Multiscale Modeling:** Incorporate advanced techniques such as *crystal plasticity finite element methods (CPFEM)* and *phase-field modeling* to account for grain-level deformation, dislocation behavior, and anisotropy. This will improve the accuracy of predictions under complex loading conditions.

II. **Fatigue, Fracture, and Creep Analysis:** Extend the framework to evaluate fatigue life, fracture toughness, and creep behavior. This will enable comprehensive assessment of steel performance under long-term service and cyclic loading environments.

III. **AI-Driven Property Prediction:** Integrate Artificial Intelligence (AI) and Machine Learning (ML) algorithms with FEA data to develop predictive models capable of estimating mechanical properties for new materials or modified process conditions, significantly reducing computation time.

IV. **Digital Twin and Industry 4.0 Integration:** Apply the computational methodology to create *digital twins* of structural components, enabling real-time monitoring, predictive maintenance, and performance optimization — aligning with Industry 4.0 and smart manufacturing initiatives.

V. **Sustainability and Optimization:** Utilize simulation-based optimization to develop sustainable steel grades with reduced energy consumption and carbon footprint, contributing to environmentally conscious material development.

VI. **Experimental Integration and Validation:** Strengthen computational–experimental correlation using advanced testing methods such as digital image correlation (DIC), in-situ microscopy, and 3D strain mapping to validate simulation outcomes more precisely.

By pursuing these directions, future research can significantly enhance the accuracy, efficiency, and industrial relevance of computational material characterization, paving the way toward smarter, safer, and more sustainable engineering solutions.

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