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Nonlinear modeling of the mechanical properties of materials in CAD systems: from experiment to simulation

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Abstract: The article investigates the potential application of CAD systems for predicting the mechanical properties of structural materials by comparing experimental test results with data from nonlinear simulations. Real-world tests were conducted using a universal testing machine and specimens manufactured according to ASTM E8M standards, while SOLIDWORKS 2022 Professional with the SOLIDWORKS Simulation module was employed for modeling. Special attention was given to optimizing simulation parameters, including mesh configuration, time steps, and the selection of the "Nonlinear Elastic" material type, which enabled the accurate representation of complex material behavior under tensile loading. The comparison of experimental and simulated data revealed an error margin of 4% - 7%, confirming the high accuracy of the modeling approach. Observed deviations are attributed to simplifications in the stress-strain curve and limitations of the model. The study highlights the promising role of CAD systems in forecasting the mechanical characteristics of both existing and novel materials with unique properties, while also underscoring the need for further refinement of modeling techniques to account for real-world physical phenomena.

Keywords: CAD systems, nonlinear modeling, mechanical properties, simulation, plastic deformation

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Introduction

The rapid advancement of modern industry and technology has created a continuous demand for the development of new materials that combine unique properties,

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such as high strength, ductility, corrosion resistance, and wear resistance. These materials find applications across various sectors, including aerospace, automotive manufacturing, energy production, and medical equipment. However, the creation of new materials necessitates a thorough investigation of their characteristics, particularly mechanical properties, which determine material behavior under various loading conditions such as tension, compression, bending, or torsion. Such studies enable the prediction of durability, reliability, and safety of structures made from these materials, which is critical for ensuring their effective performance (Callister & Rethwisch, 2018).

Conducting experimental studies of mechanical properties using universal testing machines represents a traditional and well-established approach. These machines allow the determination of key parameters, including yield strength, ultimate tensile strength, modulus of elasticity, and elongation at fracture. Nevertheless, physical experiments have several limitations. Firstly, not all research facilities have access to modern equipment due to its high cost, complex calibration requirements, and the need for specialized testing conditions. Secondly, preparing specimens for experiments can be labor-intensive and expensive, particularly when involving a large number of tests or materials with non-standard characteristics. Thirdly, physical experiments often fail to rapidly assess the impact of varying loading conditions or the specimen's geometric parameters without producing new samples, thereby slowing the research process (Meyers & Chawla, 2009). In this context, computer modeling methods, particularly the use of Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) systems, are gaining increasing popularity. These systems enable virtual experiments, significantly saving time and resources while allowing the exploration of a wide range of conditions without the need for physical testing (Liu et al., 2025; Wang et al., 2024). Leading companies are actively employing CAD/CAM systems to address engineering challenges. For instance, the aviation giant Boeing utilizes CATIA for modeling the aerodynamic and mechanical properties of aircraft components, enabling optimization of designs at the prototyping stage and reducing the number of physical prototypes. Similarly, Tesla integrates Autodesk Fusion 360 and ANSYS (Moaveni, 2014) to simulate the strength and deformation of electric vehicle parts thus accelerating development and enhancing safety. In mechanical engineering, Siemens employs NX CAD/CAM for stress and deformation analysis in complex mechanisms, ensuring accurate predictions of material behavior under loading. These examples illustrate that computer modeling has become an integral part of modern research and development, allowing engineers and scientists to rapidly obtain reliable data (Leondes, 2001).

Despite the evident advantages of CAD systems, their application for determining the mechanical properties of materials requires rigorous validation of the obtained results. Computer simulations rely on mathematical models and assumptions that may not always fully account for real-world physical phenomena, such as microstructural defects, uneven stress distribution, or the influence of external conditions. Thus, a critical issue emerges for analysis. The results obtained from CAD system simulations can be as accurate as those derived from experimental testing. These systems are capable of replicating the complex behavior of materials, particularly

under conditions of nonlinear plastic deformation and failure. Addressing these challenges is of paramount importance for the widespread adoption of computer modeling in engineering practice, especially for researchers with limited access to experimental equipment.

The objective of this study was to compare real-world experimental results of the mechanical properties of ASTM A516 Grade 60 steel specimens with data obtained from simulations conducted in SOLIDWORKS. This approach aimed to evaluate the reliability of computer modeling as an alternative method for determining material characteristics, particularly under conditions of limited access to experimental equipment. Comparing experimental and simulation results was done to establish the accuracy with which SOLIDWORKS replicated material behavior under loading, a critical factor for its further application in engineering design.

1. Analysis of recent studies

In the study (Polishchuk et al., 2023), the enhancement of a pneumohydraulic amplifier for press machines was investigated. The authors demonstrated that employing CAD systems to model stress and deformation in press components yields high consistency with experimental data following the optimization of simulation parameters. Specifically, they emphasized that the accurate input of material properties, such as stress-strain curves, is a critical factor in ensuring the reliability of results. In the research (Holiaka et al., 2024), the acoustic properties of rooms were explored using CAD systems. The authors showed that modeling acoustic characteristics, followed by comparison with experimental measurements, achieves high accuracy provided the parameters – such as mesh and time steps – are properly configured. They noted that CAD simulations are an effective tool but require further research to account for all physical phenomena, including material inhomogeneity.

Conversely, in the study Skakun et al. (2023), photonuclear reactions on tin isotopes were examined. Although this study does not directly pertain to CAD systems, the authors demonstrated that comparing experimental data with computer simulations using the MadGraph program is an effective method for evaluating theoretical models. They highlighted that simulations may exhibit errors due to model limitations, underscoring the necessity of validation with experimental data. In contrast, the work (Zeidan et al., 2023) investigated the mechanical properties of materials for dental prosthesis bases fabricated via 3D printing, CAD/CAM milling, and traditional consolidation methods. The authors found that CAD/CAM materials exhibit superior mechanical properties, such as flexural strength and hardness, compared to conventionally consolidated materials. They noted that while simulations can predict material behavior, their results require validation due to potential deviations caused by real-world operating conditions.

In the article (Perea-Lowery et al., 2020), the mechanical properties of five CAD/CAM materials for temporary restorations were analyzed. The authors demonstrated that material flexural strength and hardness vary depending on storage conditions (dry or wet environments). They concluded that CAD/CAM materials provide stable

results but require additional clinical studies to assess long-term effectiveness. In the study (Gumen et al., 2021), the impact of vacuum-condensation spraying of titanium-zirconium nitride (Ti-Zr-N) on P6M5 steel structure was described. However, a comprehensive assessment of coating-substrate bond strength is lacking, primarily due to equipment specificity and research methodology. This could be addressed through the simulation of the experiment using CAD/CAM systems. The study (Gumen et al., 2020) investigated the effect of intensive plastic deformation on iron-based materials. The data presented can be utilized to study changes in material properties under intensive deformation, though simulating such processes could mitigate limitations related to applied force magnitudes.

Despite prior research, including comparisons of experimental data with CAD/CAM simulation results as demonstrated in studies (Gumen et al., 2020; Gumen et al., 2021; Holiaka et al., 2024; Perea-Lowery et al., 2020; Polishchuk et al., 2023; Skakun et al., 2023; Zeidan et al., 2023), and others, several issues remain unresolved in optimizing modeling processes using CAD/CAM systems. Specifically, challenges persist in accurately accounting for real physical phenomena, such as microstructural defects, external condition effects, and uneven stress distribution, necessitating careful adjustment of simulation parameters to ensure result reliability.

2. Methodology

The objective of this study was to compare the real-world experimental results of the mechanical properties of ASTM A516 Grade 60 steel specimens with data obtained from simulations conducted in SOLIDWORKS. This approach aimed to evaluate the reliability of computer modeling as an alternative method for determining material characteristics, particularly under conditions of limited access to experimental equipment. Comparing experimental and simulation results was done to establish the accuracy with which SOLIDWORKS replicates material behavior under loading, a critical factor for its further application in engineering design.

The dimensions of the specimens for physical testing were selected in accordance with the ASTM E8M standard (ASTM E8/E8M-24), a widely recognized international standard for tensile testing of metallic materials. This standard is recommended for small-scale specimens, simplifying their manufacturing process and reducing material costs while maintaining high result accuracy. Specifically, the standard specifies specimens with a gauge section diameter of 3 mm and a length of 15 mm, which is well-suited for laboratory testing of ASTM A516 Grade 60 steel. Mechanical property tests were performed using the HD-B612-S 10T Universal Test Machine by HAIDA International Equipment Co. Ltd, China, which provides precise load control and deformation measurement. This equipment facilitated tensile testing with high precision, measuring force, deformation, and specimen displacement under load.

For modeling the tensile behavior of the specimens, the SOLIDWORKS 2022 Professional software, including the SOLIDWORKS Simulation module for nonlinear analysis, was employed. The selection of this version is justified by its extensive

capabilities for modeling complex mechanical phenomena, such as plastic deformation and failure, as well as its support for the “Prescribed Displacement” function, which enables accurate simulation of specified displacements.

The material chosen for the specimens, ASTM A516 Grade 60 steel, was selected due to its widespread use as a structural steel in various industries, owing to its combination of high strength, ductility, and wear resistance. This steel belongs to the category of low-alloy pearlitic steels, alloyed to ensure excellent mechanical properties, including a tensile strength range of 415 MPa - 550 MPa and sufficient elongation, making it suitable for studying both elastic and plastic behavior under tension. Its popularity stems from its availability, cost-effective production, and ability to withstand significant static and dynamic loads, which is critical for structures subjected to diverse stress conditions.

ASTM A516 Grade 60 is extensively utilized in mechanical engineering, bridge construction, and heavy equipment manufacturing. Specifically, it is employed to fabricate bridge components such as beams and trusses, which require high strength and fatigue resistance. In the automotive industry, it is used for chassis and suspension parts, where a balance of strength and ductility is essential. Additionally, this steel finds application in shipbuilding for vessel hulls and in the energy sector for turbine components subjected to substantial mechanical loads.

3. Results and discussion

The mechanical properties of specimens made from 10G2F steel were determined using the HD-B612-S 10T Universal Test Machine, with results presented in Figure 1. This equipment facilitated tensile testing with high precision, measuring force, deformation, and specimen displacement under load. Based on the data from Figure 1, the following mechanical properties were calculated according to formulas provided in (Dieter, 2020) yield strength $\sigma_p = 300$ MPa (defined as the stress at the onset of plastic deformation), ultimate tensile strength $\sigma_M = 500$ MPa (calculated as the maximum stress the specimen withstands before failure), maximum strain at fracture $\epsilon_{\max} = 0.65$ (65%), modulus of elasticity $E = 200$ GPa (determined in the elastic region according to Hooke’s law), maximum force $F_{\max} = 3534$ N (measured directly by the machine as the maximum load sustained before failure), and displacement at fracture $\Delta L = 9.75$ mm. This experimental data served as the foundation for subsequent comparisons with the simulation results in SOLIDWORKS, enabling an assessment of the accuracy of modeling the material’s mechanical behavior.

For modeling the mechanical behavior of ASTM A516 Grade 60 steel specimens in SOLIDWORKS 2022 Professional, a nonlinear analysis was conducted using the SOLIDWORKS Simulation module. Since ASTM A516 Grade 60 is not a standard material in the SOLIDWORKS material library, it was necessary to add a new material to the library. This was justified by the fact that the library typically includes only widely known alloys (e.g., AISI 1045 or 4130 steels), whereas ASTM A516 Grade 60 is a specialized carbon steel with unique properties, such as a tensile strength

of 500 MPa and an elongation of 65 %. To achieve this, a custom stress-strain curve was inputted, including points (0, 0 MPa), (0.02, 300 MPa), (0.3, 500 MPa), and (0.65, 400 MPa), based on experimental data, ensuring accurate representation of the material's plastic behavior.

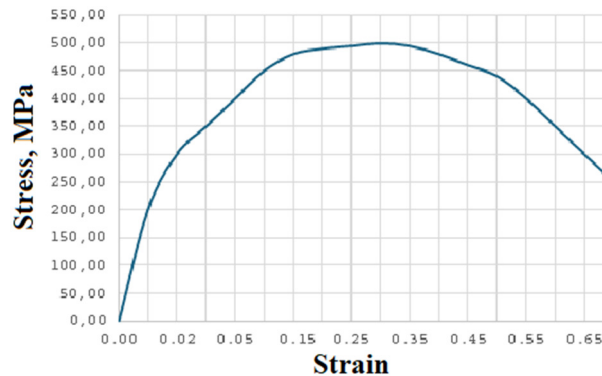


Fig. 1. Experimental data obtained from tests conducted on the HD-B612-S 10T Universal Test Machine (*own research*)

The specimen dimensions and geometry in the simulation were closely aligned with those used in the real experiment, adhering to the ASTM E8M standard. The model featured a gauge section with a diameter of 3 mm and a length of 15 mm, along with an overall length that accounted for enlarged ends with a diameter of 6 mm, matching the physical specimen tested on the HD-B612-S 10T Universal Test Machine. This approach ensured that geometric features and size ratios accurately reflected experimental conditions.

The simulation incorporated a nonlinear analysis accounting for large deformations (Large Displacement), which was critical due to the significant plastic deformation of the specimen (65%). The material type was set to “Nonlinear Elastic”, as this enabled the modeling of the complex behavior of 10G2F steel, including the stress drop after the peak strength (from 500 MPa to 400 MPa at 65 % strain). The choice of “Nonlinear Elastic” was justified because standard elastic models cannot replicate the nonlinear stress-strain relationship post-peak, while purely plastic models without accounting for stress decline may overestimate strength. This selection allowed the simulation to accurately model the entire tensile cycle, including failure.

The simulation conditions included:

- application of “Prescribed Displacement” with a value of 9.75 mm at the free end of the specimen, corresponding to the experimental displacement at fracture;
- fixation of the opposite end using “Fixed Geometry” to provide a stable support;
- mesh configuration with an element size of 0.2 mm - 0.3 mm in the gauge section and the “Blended Curvature-based Mesher” type, ensuring high resolution in the maximum stress zone;
- time-step settings with Initial Time Increments of 50-100 and a Minimum Time Increment of 0.0001, with “Automatic Time Stepping” enabled, allowing

the simulation to smoothly traverse all deformation phases, including the peak and decline.

During the simulation analysis, certain erroneous values were encountered, indicating accuracy issues. Initially, using the “Force Control” method with a force of 3534 N, the simulation halted at a peak stress of 500 MPa at 30 % strain and 4.5 mm displacement, failing to reach the 65 % strain and 9.75 mm displacement observed experimentally. This discrepancy arose because the model could not overcome the peak strength without accounting for stress decline. Additionally, early simulation attempts with insufficient mesh resolution (0.5 mm elements) or an inadequate number of time steps (10-20) resulted in convergence failures, such as “Convergence Failure” errors, indicating a lack of detail in the model.

To address these inconsistencies and achieve the most accurate results, the following adjustments were implemented:

- transition from “Force Control” to “Prescribed Displacement” with a specified value of 9.75 mm, enabling the simulation to complete the full deformation cycle, including a stress drop to 400 MPa at 65 %;
- reduction of mesh element size to 0.2 mm - 0.3 mm and adoption of the “Blended Curvature-based Mesher”, enhancing resolution in critical zones;
- increase of Initial Time Increments to 50-100 and setting the Minimum Time Increment to 0.0001 with “Automatic Time Stepping” enabled, ensuring smooth deformation progression;
- activation of “Large Displacement” and selection of “Nonlinear Elastic”, allowing for the consideration of significant plastic deformations and stress decline.

The most accurate simulation conditions and results are illustrated in the figures, which include screenshots from SOLIDWORKS 2022 Professional. Figure 2 presents the von Mises stress distribution (Fig. 2a), the equivalent strain distribution (Fig. 2b), and the displacement distribution (Fig. 2c).

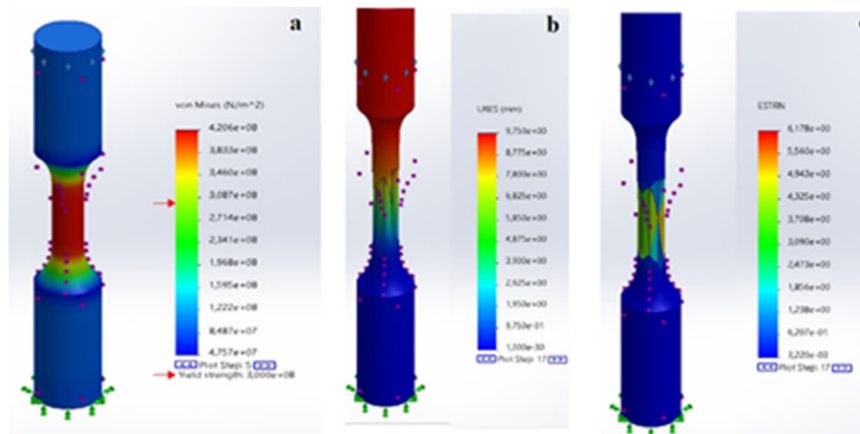


Fig. 2. Simulation results from SOLIDWORKS 2022 Professional: a) von Mises stress distribution, b) equivalent strain distribution, c) displacement distribution) (*own research*)

Note: the purple points indicate the locations where the specimen begins to fail, accompanied by the localization of the fracture

The simulation utilized the “Prescribed Displacement” method with a specified displacement of 9.75 mm, enabling the completion of the full deformation cycle, including the stress decline. The obtained results were:

- maximum von Mises stress: 400 MPa at 65 % strain, with a peak of 520 MPa at 30 % strain, as evident from the stress-strain graph generated using the “Probe” tool;
- maximum equivalent strain: 0.62 (62 %) in the gauge section of the specimen;
- maximum displacement: 9.75 mm, precisely matching the specified value.

To assess the reliability of the simulation, the results were compared with experimental data obtained from the HD-B612-S 10T Universal Test Machine. The comparison is presented in Table 1.

The comparison revealed that the simulation results in SOLIDWORKS exhibit deviations from experimental data within the range of 4.0 % - 7.0 %, which is acceptable for computer modeling given the complexity of the nonlinear behavior of A516 Grade 60 steel. The maximum stress at 65 % strain (428 MPa versus 400 MPa) and the ultimate tensile strength (520 MPa versus 500 MPa) are overestimated, likely due to inaccuracies in the stress-strain curve or insufficient model detail in the failure zone. Strain (62 % versus 65 %) and displacement (9.1 mm versus 9.75 mm) are underestimated, potentially linked to limitations of the “Prescribed Displacement” method in replicating the final stages of deformation. The yield strength (285 MPa versus 300 MPa) and modulus of elasticity (192 GPa versus 200 GPa) also show errors attributable to simplifications in the elastic zone of the simulation.

Table 1. Comparison of experimental and simulated data (*own research*)

Characteristic	Experimental value	Simulated value	Error [%]	Explanation
Yield strength [MPa]	300	285	-5	Simulation slightly underestimates yield strength due to simplifications in the elastic zone.
Ultimate tensile strength [MPa]	500	520	+4	Maximum stress is overestimated due to inaccuracies in the peak stress-strain curve.
Max stress at fracture [MPa]	400 (at failure)	428	+7	Stress is overestimated due to model limitations.
Maximum strain [%]	65	62	-4.6	Strain is underestimated due to inaccuracies in the plastic zone.
Displacement [mm]	9.75	9.75	0	Displacement matches the specified and experimental value exactly.
Modulus of elasticity [GPa]	200	192	-4	Modulus is slightly underestimated due to simplifications in elastic behavior in the simulation.

An error margin of 4 % - 7 % indicates high modeling accuracy in SOLIDWORKS 2022 Professional, especially considering the challenges of replicating plastic

behavior and stress decline. To reduce errors in future studies, it is recommended to refine the stress-strain curve by adding more intermediate points and to optimize mesh parameters and time steps.

Conclusions

This study demonstrates the effectiveness of SOLIDWORKS Professional for predicting the mechanical properties of materials by comparing experimental test results from a universal testing machine with computer simulation data. Key specimen characteristics, including yield strength, ultimate tensile strength, maximum stress at fracture, strain, displacement, and modulus of elasticity, were experimentally determined. The simulation, employing the “Prescribed Displacement” method and the “Nonlinear Elastic” material type, successfully replicated specimen behavior with a minor error margin, affirming the high accuracy of the modeling approach. Discrepancies between experimental and simulated data are attributed to simplifications in the stress-strain curve and model limitations; however, their magnitude validates the reliability of SOLIDWORKS as a tool for engineering research. Optimization of the simulation, including mesh configuration, time steps, and modeling conditions, ensured close alignment between the obtained results. The accuracy of numerical results depends on the correct definition of simulation parameters, making instrumental validation a critical component. This validation enables the optimization of settings for future analyses of other materials, ensuring greater reliability and precision in modeling. This research is relevant and promising for future work, as it opens avenues for improving modeling techniques and expanding the application of CAD systems in predicting mechanical properties – not only for existing materials but also for new ones with unique characteristics. Consequently, future research is highly relevant for refining modeling techniques, enhancing the accuracy of mechanical property predictions, and promoting broader adoption of CAD/CAM systems in engineering production and educational practices.

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