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Investigation of Aluminum Material Behavior: An Integrated Experimental and Simulation-Based Approach

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Abstract – In this research, the importance of experimental studies and simulations is emphasized, and it is stated that these two methodologies complement each other and are used to understand and optimize material behavior. For this purpose, three-point bending test was applied to an aluminum sample, and the results were supported by ANSYS Software simulations. It is stated that the simulation results agree with the experimental data and are a powerful tool for understanding the material's behavior. Thus, a cross-validation mechanism is established by comparing experimental data with simulation results, and it is stated that this integrated approach allows for a wide range of investigation possibilities. It is also emphasized that experimental studies and simulations play an essential role in validating and solving complex theoretical models in materials science and engineering. It is presented both graphically and visually that basic material properties such as yield point, elastic region, and plastic deformation are similar according to the data obtained from experimental and simulation results.

Keywords – *Three-Point Bending, Simulation, Aluminum, Flexural Stress, Displacement*

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I. Introduction

Aluminum, one of the most widely used materials in today's industry, is encountered in every aspect of our lives. Aluminum has metallic properties and is "the most abundant metal in nature." On the other hand, it is the most widely used metal in industrial fields after iron and steel for the last 50 years. After World War II and the Industrial Revolution, the need for increased energy, lighter and high-strength components, ease of production, and recycling brought aluminum to the forefront of industrial use. [1]. Aluminum alloys are preferred in the automotive and aerospace industries due to their high specific strength (strength/density), corrosion and wear resistance, high electrical and thermal conductivity, easy machinability, castability, and environmental friendliness. Reducing the weight of the parts produced and the energy efficiency that arises naturally makes aluminum alloys superior to other competitors. In 1889, aluminum started its industrial journey with kitchen utensils. After finding a place of use in the naval and aviation sector, canned food, large-scale pipes, and bridge constructions, it continues its adventure in the 2000s with its preference for the production of engine blocks, automotive wheels, natural gas liquefaction units, and armor plates [2, 3]. Aluminum is currently one of the most essential materials in the defense industry. Aluminum alloys have a wide range of applications due to their lightweight and relatively high strength. With its light yet robust properties, aluminum has found an essential place in structural applications, the automotive industry, and aerospace. Since the crystal structure of aluminum allows a significant amount of plastic deformation before fracture, it is also suitable for forming. When the literature is examined, there are many studies on aluminum. When these studies are examined, data is obtained by destructive testing methods in almost all of the mechanical properties. The test equipment used for automated tests requires maintenance and causes a loss of time for days in case of failure. In addition, a minimum of five experiments are needed, especially in the three-point bending test, and the materials used in the test become unusable again [4-8].

Experimental studies and simulations are two fundamental approaches that play an essential role in validating and solving complex theoretical models in science and engineering. Although they have different implementation methods, these two methodologies often complement each other, bridging the gap between theory and practice. Experimental studies are often used to test the applicability of a theory or technology in real-world applications. Simulations are computer-based models that mimic real-world processes, systems, or phenomena. They can provide researchers with successful solutions, especially when experimentation is impractical, dangerous, or costly. Simulations can be used to validate experimental results, and experimental results can be used to validate simulations. When the results of both approaches are in agreement with each other, the acceptance of the accuracy of the studies increases. Simulations can help researchers to perform various tests efficiently before conducting expensive or lengthy experiments. They also provide a safe and controlled environment for education and training activities, allowing individuals to gain practical experience without real-world risks.

Nowadays, the use of structural computational simulations based on finite element analysis is a standard method for designing new industrial products [9]. Simulation of the structural properties of materials is one of the essential solutions of materials science and engineering to prove the tests' accuracy. Understanding how materials behave at the atomic or molecular level helps researchers or engineers to design and optimize materials for various applications. While different computational techniques and simulation methods can be used to study the structural properties of materials, they play a crucial role in designing, developing, and optimizing materials for a wide range of applications in science and engineering. The three-point bending test is a standard experimental method used to evaluate materials' mechanical properties and structural behavior, especially those used in engineering applications. This test involves applying a load to a sample in such a way as to produce a bending moment and cause the material to deform. Three-point bending tests can be widely used to evaluate the flexural behavior of materials such as metals, polymers, ceramics, and composites. They also help engineers make the right decisions about material selection and design.

ANSYS is a widely used analysis program for engineering simulation and provides comprehensive solutions for structural analysis and simulations. ANSYS Structural enables engineers to analyze the behavior of structures and components under various loading conditions and obtain data, helping them examine design values, optimize designs, and ensure structural integrity. It includes a wide range of material models to simulate material types, while users can define linear or nonlinear material behavior, including elasticity, plasticity, hyperelasticity, and viscoelasticity. ANSYS Structural is used in various industries, including aerospace, automotive, civil engineering, and electronics, for analyses ranging from simple component analysis to complex structural evaluations of entire systems. This reduces the need for physical prototypes and expensive testing. In most of the studies available in the literature, either experimental or numerical methods have been developed and used to understand the influence of these parameters. Sometimes, both methods of analysis have been used together. In their study, Kagzi et al. performed stress analysis of the frame structure of three roller bending machines using Finite Element Analysis (FEA). They also considered the possible changes in the structure by using the shape optimization feature of the Ansys Program [10]. In another study, modeling was performed to predict the behavior of composite sandwich panels under static bending conditions. For this purpose, experiments were conducted for both 2D and 3D models using the Ansys Program. Comparison of FE model predictions with experimental data on sandwich panel flexural properties helped to establish the appropriate modeling approach. Analytical solutions were also used to verify some mechanical properties, such as flexural stress and shear stress, with FEM results [11]. Al-Anazi et al. performed a three-point bending test to investigate the tensile shear response of HVOF AMDRY 9954 coating on Ti-6Al-4V alloy under bending load. Microstructural analysis was performed using scanning electron microscopy (SEM). They also used the finite element method (FEM) to simulate bending and analyze the stress distribution on the material [12]. In another study, a coating was applied on a steel sheet, and three-point bending tests were carried out to investigate the mechanical properties of this coating. The simulation of the stress fields generated during the tests was carried out using the finite element method (FEM) program Ansys. Simulations were performed for both 2D and 3D models. They reported that two-dimensional predictions showed better agreement with experimental data, so two-dimensional models were used in the simulations [13].

In conclusion, experimental studies and simulations are fundamental methods in pursuing knowledge and technological progress. Researchers in various fields utilize these methodologies to validate theories, develop new technologies, and solve practical problems. In this research paper, it is presented how experimental studies and simulations support each other and, therefore, contribute to the advancement of the processes before the production of products, in comparison with the analysis results obtained. For this purpose, three-point bending tests of aluminum samples were carried out with a three-point bending apparatus in a computer-controlled Shimadzu brand bending device with a capacity of 100 kN, and the results obtained were compared with the simulation results obtained with the Ansys structural analysis program. In the materials and methods section of the article, information about the technique of both experimental and simulation studies is given, the numerical values obtained are presented in the findings section, and finally, the research is concluded by mentioning future research in the results section.

II. MATERIALS AND METHOD

This study demonstrated that both experimental and simulation methodologies are mutually supportive. This integrated approach leverages the strengths of experimental data collection and computational modeling, allowing for a multifaceted investigation. The application of experimental and simulation techniques facilitated the understanding of material behavior and moved away from a singular methodological approach. The experimental aspect of this research consists of three-point bending tests of aluminum samples performed with a three-point bending apparatus in a computer-controlled Shimadzu brand bending device with a capacity of 100 kN. The empirical data obtained from the experiments provided information on the material behavior, providing an essential basis for the overall analysis. In conjunction with the experimental studies, a parallel simulation study was carried out to support the accuracy of the experimental data with simulations. Ansys package was used as simulation software, and realistic 3D modeling was performed under similar conditions. This computational approach provides a perspective that complements and extends the empirical findings by allowing the investigation of variables such as total deformation and equivalent stress. This dual methodological approach extends the scope of our research and improves its quality. The integration of experimental and simulation methodologies facilitates comprehensibility and serves as a cross-validation mechanism that strengthens the reliability and generalizability of the study's results. The following sections detail the materials used, the methodologies employed for the experimental and simulation components, and the data collected.

A. Three-Point Bending Test

The samples used in the study are 6060 series Aluminum 1.4x43x60. If we look at the TS 205 definitions of TSE for bending test, It is defined as the deformation of a flat test piece, usually with a circular or rectangular cross-section, which is freely seated on two supports, when a bending force is applied to the center without changing direction. In addition to the qualitative result, qualitative values such as bending moment (Me), bending strength (σe), modulus of elasticity (Ee), and amount of bending (δ) are calculated.

Three-point bending tests were performed on aluminum samples with a computer-controlled Shimadzu machine with a capacity of 100 kN and load was applied at a constant rate of 2 mm/min. The test combination was repeated at least three times for different 6060 aluminum samples. Flexural strength values were calculated using Equation (1).

$$TRS = \frac{3FL}{2h^2w} \quad (1)$$

In Equation (1), TRS: Flexural Strength (MPa); F: Force applied to the sample at fracture (N); L: Distance between bearing centers (40 mm); h: Thickness of the sample; w: Width of the sample. Figure 1 shows the three-point bending assembly.

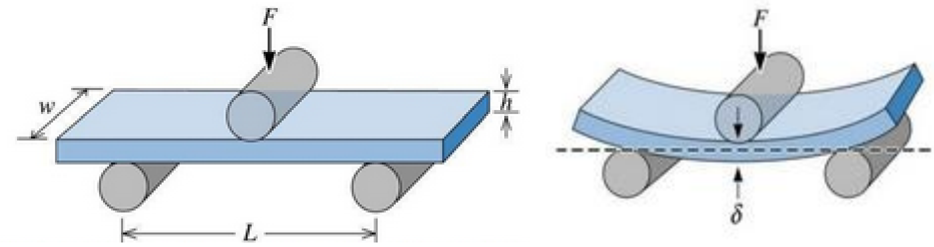

Figure 1. Three-point bending assembly [4].

When a force acts on the test sample, the sample is in bending if compressive stress occurs in a part of the sample cross-section and tensile stress occurs in the remaining part of the cross-section. In the cross-section of samples in bending, compressive stresses occur near the inner surface, and tensile stresses occur near the outer surface. As shown schematically in the figures below, there are various bending test methods. The most widely applied of these is the method of bending the s with the help of a mandrel on the cylindrical supports shown in Figure 1. The main objective of these methods is to bend the material in one direction until it cracks. In qualitative bending tests, materials with good ductility do not show cracking despite being folded 1800. As a result of the test of such materials, it is stated that no cracking is observed despite folding 1800. As can be understood from these explanations, the bending angle (α) is used as a criterion in qualitative bending tests.

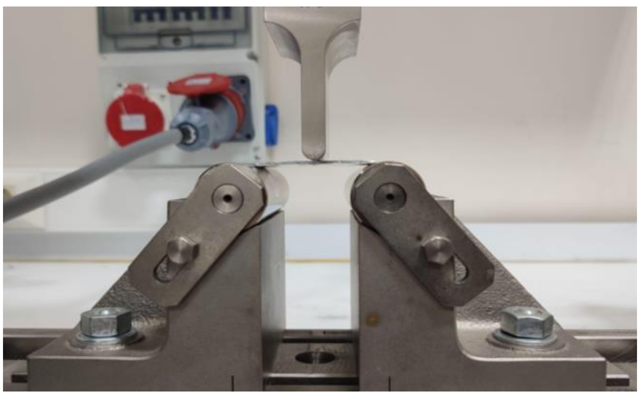
Figure 2. Experimental setup

The bending angle is defined as the outside angle between the two arms of the sample after bending is completed. Sometimes, the radius of curvature (r) of the bent part of the material at the end of bending can also be used as a criterion. The bending test result indicates whether cracking occurs when the sample is folded to the prescribed angle. If the material has cracked, it is sometimes desirable to indicate the angle at which the initial damage occurred. A visualization of the sample in the test environment before the bending load is shown in Figure 2.

B. 3D Modeling and Simulation

Static analysis solutions are used to predict the response of a structure to steady-state loads. Static structural analysis in ANSYS is a type of finite element analysis (FEA) that focuses on predicting the behavior of a structure or component when subjected to static loads and boundary conditions. In engineering and product design, evaluating variables such as stress distribution, deformation, and safety factors provides essential solutions to analyze various problems [14].

In this study, the following steps were followed to verify the experimental results with numerical data:

- First, 3D CAD models were created in accordance with the dimensions of the samples analyzed in the experimental studies, as shown in Figure 3. The thickness of the sample is 1.4 mm, the width is 43 mm, and the length is 60 mm.

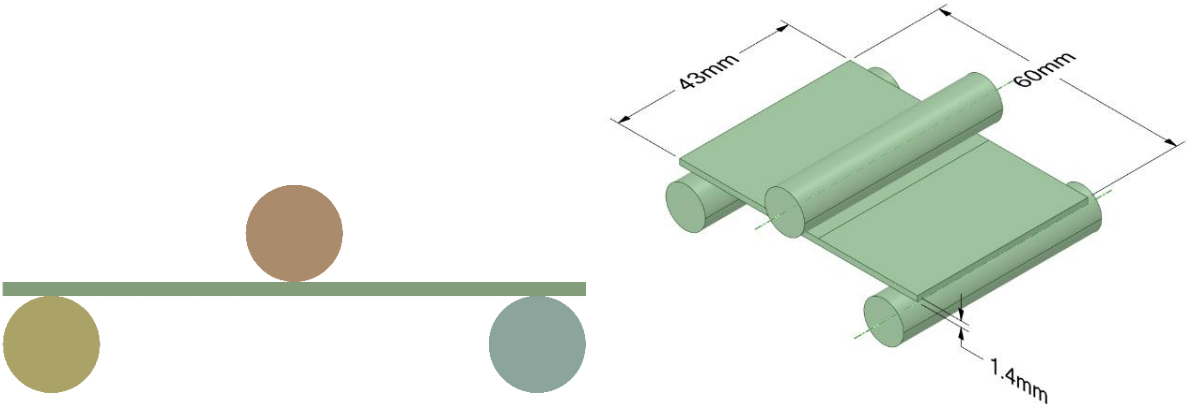

Figure 3. Dimensions of the sample

- Mesh structures that divide the models into more minor elements are defined. While determining the number of mesh, solution time and mesh quality were considered. Figure 4 shows a visualization of the created network structures

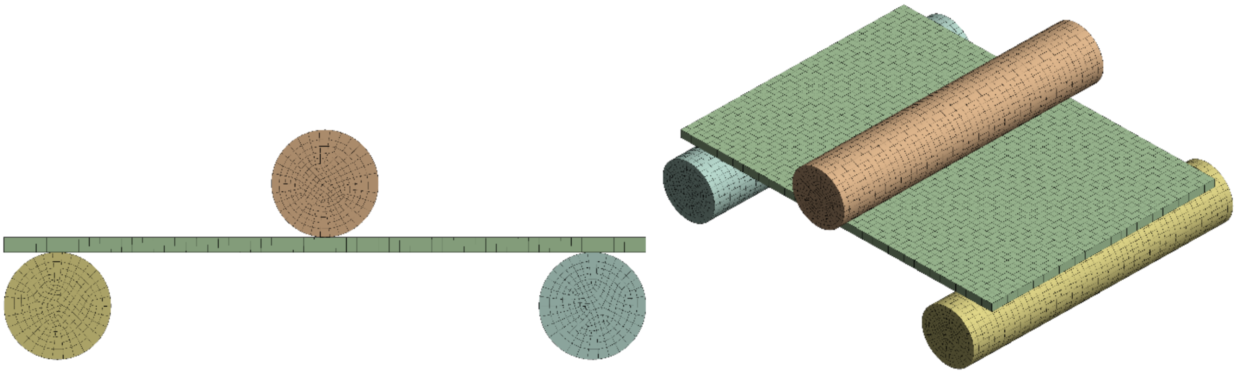
Figure 4. Mesh

- Then, the material properties of the samples were defined, and boundary conditions such as fixed supports and load were established. Contact surfaces were defined, and solver settings and convergence criteria were determined. Figure 5 shows the force direction and contact surfaces. Here, A stands for the direction of force application, and B and C for the fixed supports.

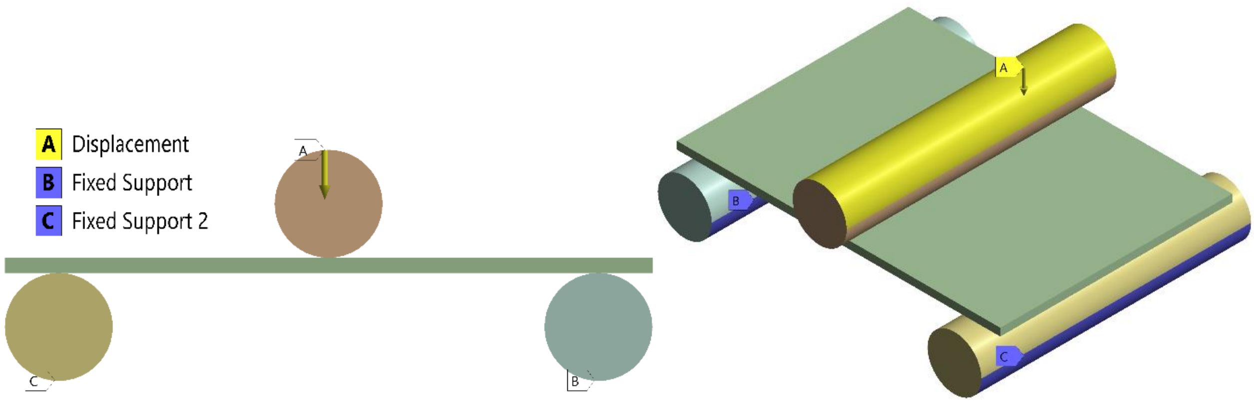

Figure 5. Force direction and contact surfaces

- After the analysis was set, the solver was run. In the results section, equivalent stress, force reaction, displacement images, and, flexural stress/strain, force/displacement graphs that occur in the material after the analysis is completed are given.

Equivalent stress is a concept used in materials engineering and structural analysis to express a combination of various stresses acting on a material, such as tensile, compressive, and shear stresses, as a single equivalent stress. Equivalent stress is usually calculated using stress components from different directions and types, taking into account their relative effects on the material's behavior. The Von Mises stress method is used to determine the equivalent stress. With this method, the equivalent stress (σvm) is calculated using the principal stresses (σx, σy, σz) as in equation (2) [15]:

$$\sigma_{vm} = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2}{2}} \quad (2)$$

This equation expresses an equivalent stress that will have the same effect on the material as the combination of the three principal stresses. Using equivalent stress simplifies the analysis and design process by reducing a complex stress situation to a single value. It also facilitates comparison with material properties and design criteria.

A force/displacement graph, also known as a load/displacement or stress/strain curve, is a graphical representation of the relationship between the force (load) applied to a material and the resulting deformation (deflection-displacement). These graphs are widely used in materials testing and structural analysis to understand the mechanical behavior of materials. With a force/displacement graph, information such as Elastic Region, Yield Point, Plastic Region, Ultimate Strength, and Fracture Point can be obtained. The shape of the curve varies depending on the type of material (brittle or ductile) and its specific properties. There is usually a more gradual yielding and extended plastic zone for ductile materials such as metals. On the other hand, brittle materials exhibit less plastic deformation and fail abruptly. In short, force/displacement plots provide essential information about how a material responds to applied forces, helping engineers or researchers to understand the suitability of the material's mechanical properties for the required applications.

The flexural stress/strain curve provides information about the relationship between the applied bending moment (stress) and the resulting deformation or curvature (strain) of a material. This type of graph is widely used to analyze the behavior of materials, especially in the design and evaluation of structural components subjected to bending loads. This graph provides information about Elastic Region, Proportional Limit, Yield Point (if applicable), Plastic Deformation, and Ultimate Stress. In summary, a flexural stress/strain graph provides valuable information about how a material behaves under bending loads. Figure 6 shows the fundamental behavior of materials under load, such as elastic limit, yield point, elastic region, plastic region, and fracture point.

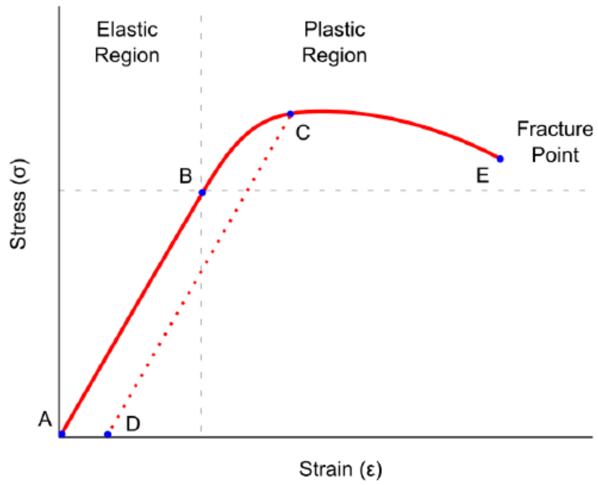

Figure 6. Stress/Strain Graph [16].

III. RESULTS

Three three-point bending tests were performed on aluminum samples, one of the most widely used materials, especially in industry. Figure 7 displays the photograph of the workpiece after the bending test. Here, the shape change in the sample is seen.

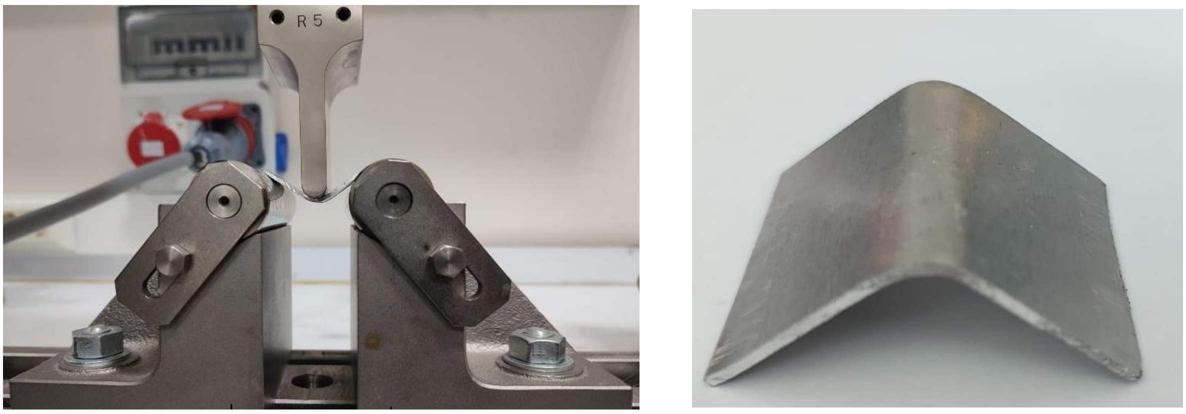

Figure 7. A photograph of the workpiece after the three-point bending test.

As a result of the simulation, the displacement occurring in the 3D model is visually presented in Figure 8. According to this, it can be seen that the maximum shape change is at the application point of the force in the middle part of the material, with 14.292 mm.

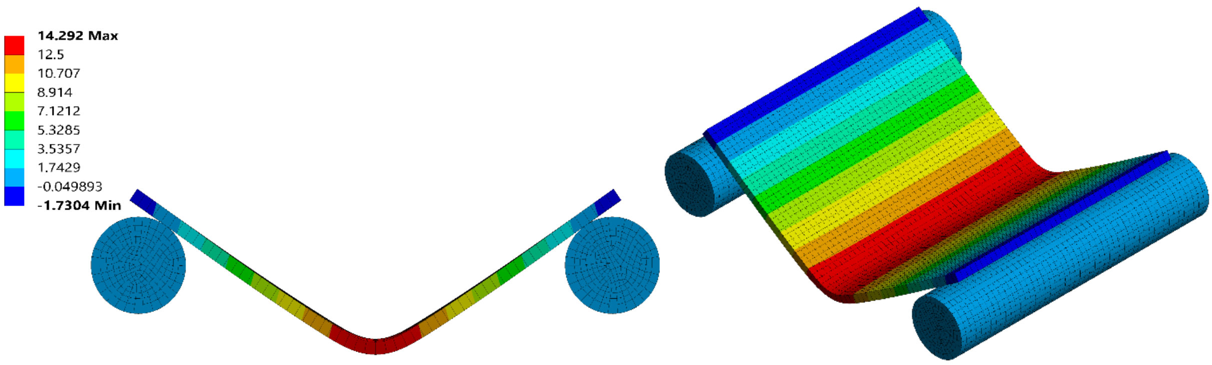

Figure 8. Displacement

After the three-point bending test simulation, the equivalent stress value reached a maximum value of 263.33 MPa in Figure 9. As expected, the minimum equivalent stress values were obtained close to the support points of the sample.

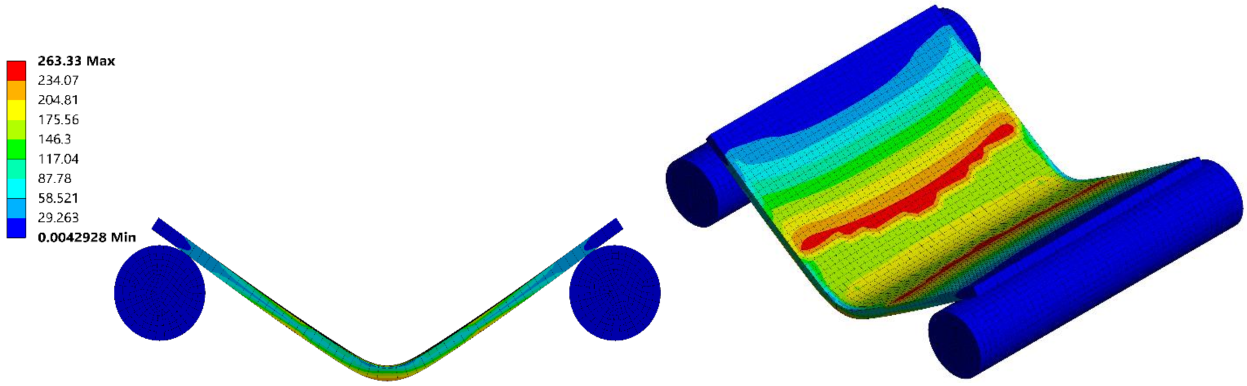

Figure 9. Von Mises equivalent stresses generated in the simulation of the three-point bending test.

Figure 10 displays the flexural stress/strain curves obtained from both the experiment and simulation. The yield point is critical in a stress-strain graph showing the transition from the elastic to the plastic region. The yield point is a crucial point where the material transitions from the elastic to the plastic region. At this point, the material will permanently deform under the applied stress. According to the flexural stress/strain graph, the yield point is 370 MPa and 1% strain. This means that the material does not deform in the elastic region until the applied stress; after this point, the material will experience permanent deformation as the stress increases. According to this information, it can be said that the material has a distinct yield point starting with 1% strain. This gives information about the material's strength and plastic deformation resistance and shows the agreement between the experimental study and the simulation study.

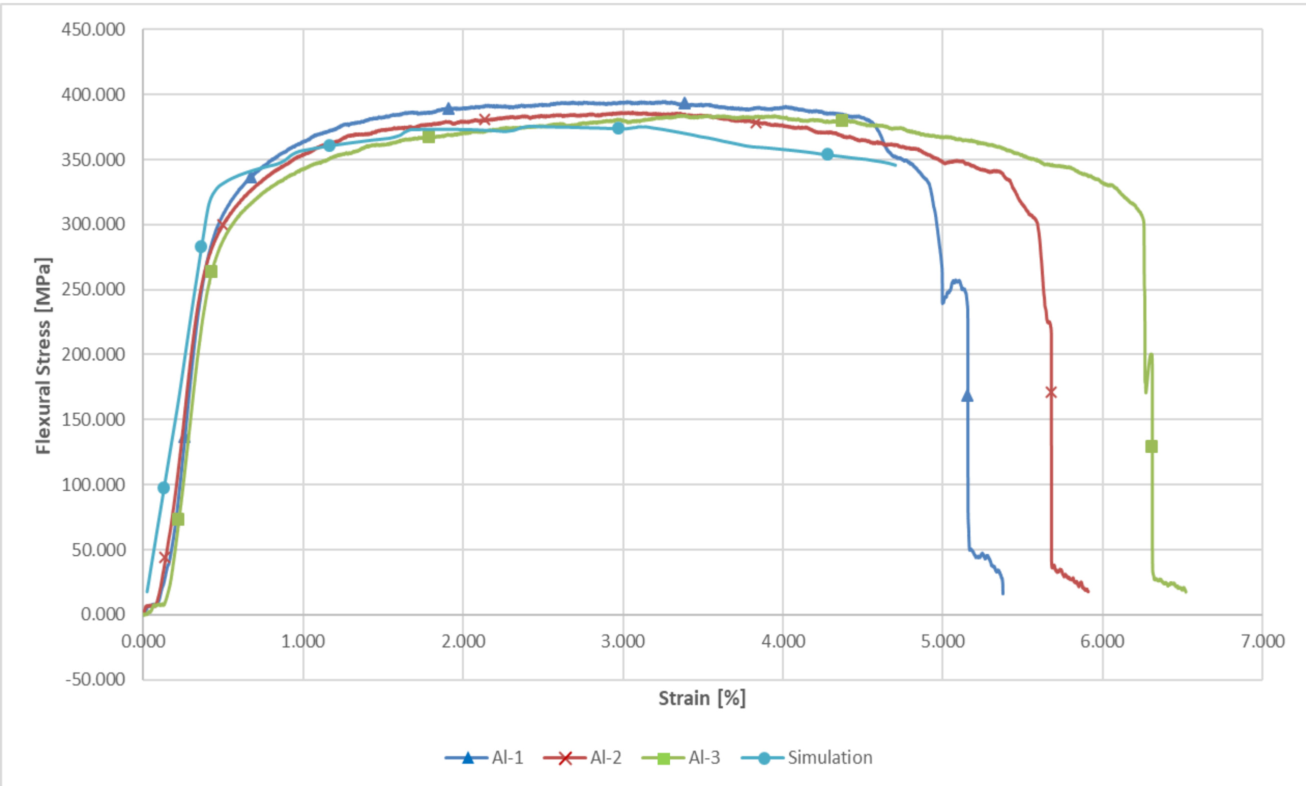

Figure 10. Flexural Stress/Strain Graph

The curves are in agreement, resulting in realistic stress and strain predictions. When a force acts on the sample, the sample is in bending if a compressive stress occurs in a part of the sample cross-section and a tensile stress occurs in the rest of the cross-section. For this reason, both the yield point and the maximum force point are essential in the graphs. Since aluminum is a ductile material, there was no crack in the experimental studies. The graph shows that the yield starting point is approximately 370 N, the maximum tensile value is about 430 N, and the homogeneous plastic deformation zone is about 370 N. In the continuation of the graph, an irregular plastic deformation is observed at stresses lower than 370 N. Since plastic deformation was observed irregularly at displacements after 14 mm in the experimental studies, the simulation study was concluded at 14 mm.

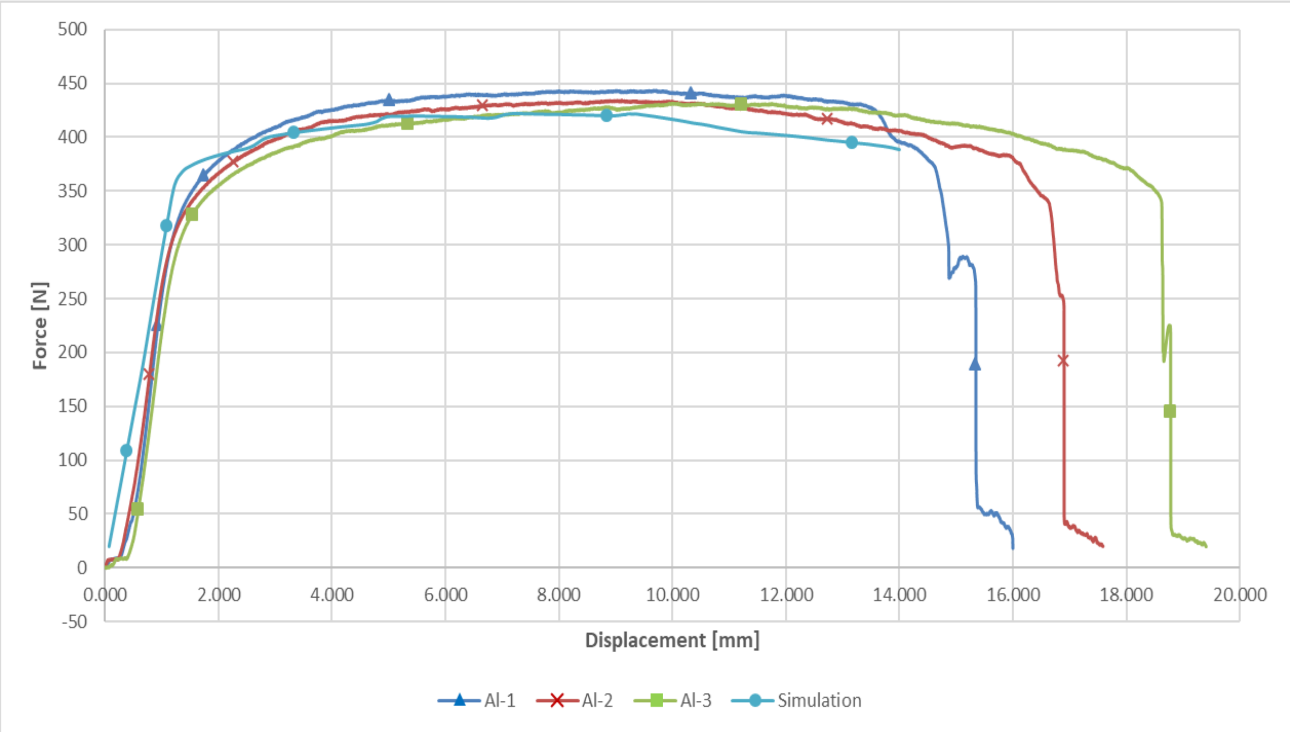

Figure 11. Force displacement behavior obtained from three-point experiment and used in the FEM (ANSYS) simulations.

IV. DISCUSSION

In this research, a study was conducted in which experimental data were collected by subjecting aluminum to three-point bending test, and these data were verified with ANSYS simulation software. Thus, it is aimed to prove that experimental and simulation methodologies are used in a mutually supportive manner. In this direction, the experimental studies included three-point bending tests of aluminum samples, and the data obtained provided information on the mechanical properties and behavior of the material, such as bending strength, bending moment, and modulus of elasticity. Simulations were performed using the ANSYS program to support the accuracy of the experimental data. The simulation results obtained were used to evaluate and compare the material's behavior with the experimental data. The results show that the experimental and simulation data are in agreement.

In three-point bending tests on aluminum samples, shape changes were observed. Since aluminum is a ductile material, there was no crack in the experimental studies. In addition, the results of the 3D model simulation show that the maximum deformation is 14.292 mm, and this change occurs in the middle part of the material, where the force is applied. According to the simulation results, the maximum value of equivalent stress is 263.33 MPa. The minimum equivalent stress values were obtained near the support points of the sample, as expected. In the stress-strain plot showing the transition from the elastic to the plastic region, the yield point was determined to be at 1% strain. These results show that the experimental and simulation studies are in agreement and provide information about the strength and plastic deformation resistance of the material.

In conclusion, the importance of aluminum in industrial use was emphasized, and it was stated that the complementary use of experimental and simulation methodologies helps to obtain reliable results. Instead of this integrated approach, a proper simulation analysis can provide time and cost optimization before production. In addition, future studies may include further use and extension of this integrated approach, such as more detailed analysis of material behavior, investigation of different bending conditions, or similar studies of other materials.

V. CONCLUSION

In conclusion, the importance of aluminum in industrial use was emphasized, and it was stated that the complementary use of experimental and simulation methodologies helps to obtain reliable results. Instead of this integrated approach, a proper simulation analysis can provide time and cost optimization before production. In addition, future studies may include further use and extension of this integrated approach, such as more detailed analysis of material behavior, investigation of different bending conditions, or similar studies of other materials.

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Authors' Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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