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Critical Buckling Load Evaluation of Aluminum Columns Based on a Comparison of Euler Theory, Experimental Testing, and Finite Element Method

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Abstract: This study aims to evaluate the Buckling strength of aluminium alloy 2024-T3 columns based on Euler's theory and to compare the results with numerical simulations using the Finite Element Method (FEM) and experimental testing. The column lengths considered in this study are 400 mm, 450 mm, 500 mm, 550 mm, and 600 mm, with a constant cross-sectional dimension. The analysis is conducted for three Boundary Conditions, namely Pinned–Pinned, Fixed–Pinned, and Fixed–Fixed. Theoretical analysis is performed using Euler's Buckling equation, numerical simulation is carried out using ANSYS with the BEAM188 element through eigenvalue Buckling analysis, and experimental testing is conducted using the STS12 Euler Buckling of Struts by TecQuipment apparatus. The results show that the critical Buckling load decreases with increasing column length, with the Fixed–Fixed Condition producing the highest Buckling load and the Pinned–Pinned Condition the lowest. The FEM results show good agreement with Euler's theory, while the experimental results are slightly lower due to initial imperfections and non-ideal Boundary Conditions. The error relative to experimental results ranges from 0.84% to 8.30%. Based on these findings, it can be concluded that Euler's theory and FEM simulation are effective approaches for predicting the Buckling behaviour of aluminium 2024-T3 columns.

Keywords: Column Buckling, aluminium 2024-T3, Euler theory, FEM, ANSYS.

I. INTRODUCTION

Columns are structural elements designed to withstand axial compressive loads [1]. Under certain conditions, a column may fail not because its material strength has been exceeded, but due to structural instability known as buckling. Buckling is a critical phenomenon in structural engineering because this type of failure occurs suddenly and can lead to the complete collapse of a structural system [2]. Buckling occurs when a long and slender structural member is subjected to an axial compressive load that exceeds its critical limit, resulting in significant lateral deformation [3]. This phenomenon is highly dependent on the column dimensions, material properties, and boundary conditions (end conditions). The classical theory used to analyze buckling was first developed by Leonhard Euler in 1757, who demonstrated that the critical buckling load of an ideal column is given by the following equation:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

Although Euler's theory provides a reliable initial prediction of column buckling behavior, it has several limitations when applied to real-world conditions. As explained in [4], Euler's theory assumes that the column possesses perfect geometry, is subjected to a purely axial compressive load, and is free from material imperfections and geometric nonlinearities that are commonly encountered in practical engineering applications. Consequently, validation of this theory is essential to ensure the reliability and safety of structural designs.

Over the past few decades, the Finite Element Method (FEM) has become an indispensable tool in structural analysis and simulation. According to [5], FEM-based software packages, such as ANSYS, are capable of accurately analyzing complex structural behavior, including both linear and nonlinear buckling phenomena. Furthermore, these numerical tools can account for variations in material properties and more realistic boundary

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conditions, thereby providing a more comprehensive representation of actual structural performance.

Buckling is a form of structural instability commonly encountered in slender compression members such as columns [1]. It is characterized by a sudden lateral deformation caused by an axial compressive load exceeding a critical limit, even when the material remains within its elastic range. Aluminum is a lightweight material with a high strength-to-weight ratio and a lower modulus of elasticity than steel [6]. The buckling behavior of aluminum columns is highly dependent on the slenderness ratio and end-support conditions [7]. Due to its lower modulus of elasticity, aluminum columns are generally more susceptible to buckling than steel columns; however, their plastic deformation develops relatively slowly, making elastic buckling analysis particularly relevant.End-support conditions have a significant influence on the buckling capacity of columns. Columns with fixed–fixed end conditions exhibit greater buckling resistance than those with pinned–pinned or fixed–pinned end conditions. Previous studies have shown that variations in support conditions can result in significant changes in the critical buckling load, reaching up to 50% compared with the baseline condition [8].

Buckling experiments are conducted to determine the actual critical load and observe the corresponding buckling mode shapes. Experimental and numerical studies on aluminum columns have demonstrated that buckling behavior is influenced not only by column slenderness but also by initial geometric imperfections and the nonlinear material characteristics of aluminum alloys [9]. Direct testing of metallic columns provides a realistic assessment of the effects of geometric imperfections and load eccentricity. Consequently, experimental results are typically lower than those predicted by Euler's theory because the idealized assumptions regarding geometry and material behavior cannot be fully achieved in practice [8].ANSYS, a finite element method (FEM)-based software package, is widely used for the numerical analysis of buckling behavior. In addition to predicting critical buckling loads, FEM simulations enable the investigation of higher-order buckling mode shapes. The buckling behavior of columns cannot be fully represented by Euler's theory alone because the theory assumes ideal conditions, including homogeneous material properties, perfectly straight columns, and purely axial loading. In real engineering applications, geometric imperfections and material nonlinearities result in complex structural responses that can be accurately captured only through finite element analysis [10].

A column is a structural member designed to resist axial compressive loads acting along its longitudinal axis. In mechanical and structural engineering applications, columns are commonly used to support vertical loads from superstructures and transfer them to underlying structural elements, such as foundations. From a mechanics perspective, columns may fail due to buckling, an elastic instability phenomenon that causes lateral deflection when the applied compressive load exceeds a critical value [11].Young's modulus was first introduced by the English physicist Thomas Young in the early nineteenth century through his studies on material elasticity. This fundamental concept has become an essential parameter in structural engineering calculations, including buckling analysis, where material stiffness plays a critical role in determining the magnitude of the critical load that a structure can sustain before experiencing instability [12].

II. MATERIALS AND METHODS

2.1 Equipment

The equipment used in this study is described as follows:

a) Buckling Testing Apparatus

The primary equipment used in this study was the STS12 – Euler Buckling of Struts apparatus manufactured by TecQuipment. This apparatus is specifically designed for the demonstration and experimental investigation of column buckling phenomena in accordance with Euler's buckling theory. It allows variations in column length, end-support conditions, and specimen materials, making it highly suitable for experimental studies of critical buckling loads.

b) Hexagon Tools

Hexagon tools, commonly known as hex keys or Allen keys, are essential auxiliary tools used with the STS12 Euler Buckling of Struts apparatus. These tools are utilized for adjusting, assembling, and securing the mechanical components of the testing equipment to ensure proper experimental setup and operation.

c) Vernier Caliper

A vernier caliper was used to accurately measure the cross-sectional dimensions of the strut specimens. Accurate dimensional measurements are essential to ensure that the actual dimensions of the aluminum columns conform to the design specifications used in the theoretical and numerical analyses.

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d) VDAS Software

The Virtual Data Acquisition System (VDAS) is a software package developed by TecQuipment for the automatic acquisition, visualization, and recording of experimental data in real time. In the STS12 Euler Buckling of Struts apparatus, VDAS is employed to monitor and analyze the compressive loads and deformations experienced by the strut specimens during buckling tests.

e) ANSYS Software

ANSYS (Analysis System) was used to perform numerical simulations of column buckling behavior. The simulations were conducted to provide a comparison with the experimental results and Euler's theoretical predictions. By employing the Finite Element Method (FEM), ANSYS can accurately predict critical buckling loads and corresponding buckling mode shapes, thereby serving as an effective tool for structural stability analysis.

Figure 1: Buckling Testing Apparatus

2.2 Materials

The material used in the buckling experiments was an aluminum column specimen (strut) made of Aluminum Alloy 2024-T3. The specimens were prepared with varying lengths while maintaining a constant cross-sectional dimension to investigate the effect of column length on the critical buckling load.

a) Aluminum Columns (Struts)

Table 1: Dimensions of Aluminum Column Specimens

Strut	Column Length (mm)	Width *(b)* (mm)	Thickness *(d)* (mm)
1	400	19.75	2
2	450	19.75	2
3	500	19.75	2
4	550	19.75	2
5	600	19.75	2

Figure 2: Aluminum Column Specimen

b) Material Properties

Table 2: Mechanical Properties of Aluminum Alloy 2024-T3

Property	Nilai
Young's Modulus	73 GPa
Density	2,780 kg/m^3
Yield Strength	345 MPa
Ultimate Tensile Strength	480 MPa
Momen Inersia	13.33 mm^4
Radius Gyration	577x 10^{-3} mm
Luas Penampang (A)	40 mm^2

2.3 Research Variables

The research variables considered in this study on the buckling behavior of aluminum columns are as follows:

a) Independent Variables

1. Aluminum column length: 400 mm, 450 mm, 500 mm, 550 mm, and 600 mm.
2. Column end-support conditions:
   - Pinned–Pinned
   - Fixed–Pinned
   - Fixed–Fixed
3. Loading condition: Axial compressive load.

III. RESULTS AND DISCUSSIONS

3.1 Euler Theory Results

In this study, theoretical calculations were performed for five column lengths, namely 400 mm, 450 mm, 500 mm, 550 mm, and 600 mm, while maintaining constant cross-sectional dimensions. In addition, the critical buckling load was evaluated under three different end-support conditions: Pinned–Pinned, Fixed–Pinned, and Fixed–Fixed. Consequently, different critical

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buckling loads were obtained for each boundary condition.

Table 3: Critical Buckling Loads Predicted by Euler Theory

***Strut* Legth (mm)**	**Pcr Euler (*Pinned-Pinned*) N**	**Pcr Euler (*Fixed–Pinned*) N**	**Pcr Euler (*Fixed Fixed*) N**
600	26.4	57.7	121,0
550	31.40	69,1	145,9
500	37,9	84,2	179,9
450	46.8	104,9	225,7
400	59.3	134,3	292,8

Based on the results obtained from Euler's theory, the corresponding graphical representation is presented in Figure 3.

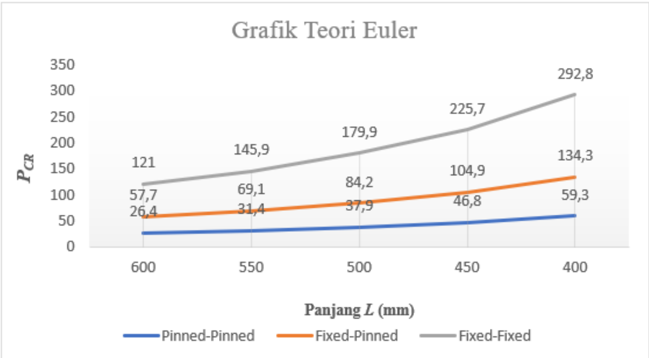

Figure 3: Euler Theory Results

3.2 3D FEM Simulation Results (ANSYS)

For the buckling simulation of Aluminum Alloy 2024-T3 columns, ANSYS software was employed to perform the finite element analysis. The structural model was developed using the BEAM188 element, a three-dimensional beam element specifically designed for the analysis of slender structural members subjected to axial, bending, and buckling loads.

a) Column Geometry Model

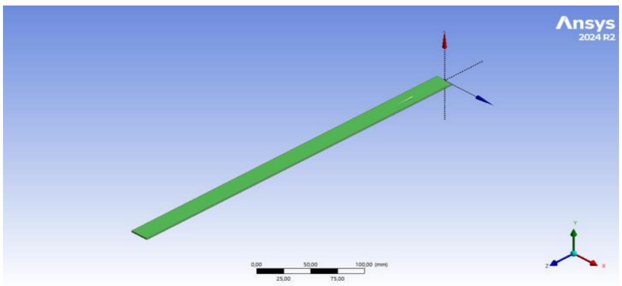

Figure 4: Geometry of the Column Model

b) Boundary Condition Pinned

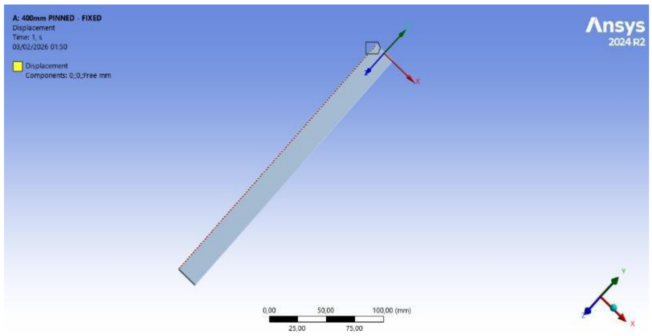

Figure 5: Pinned Condition

c) Kondisi Tumpuan Fixed

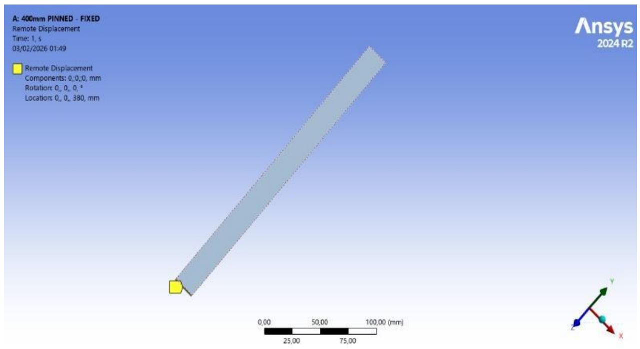

Figure 6: Fixed Condition

d) FEM Simulation Results (3D)

Table 4: FEM Simulation Results

Panjang L (mm)	PP Pcr (N)	FP Pcr (N)	FF Pcr (N)
600	26,34	57,93	122,2
550	31,34	69,40	147,5
500	37,92	84,66	181,5
450	46,82	105,6	229,0
400	59,26	135,2	297,7

Based on the FEM simulation results, the corresponding graphical representation is presented in Figure 7.

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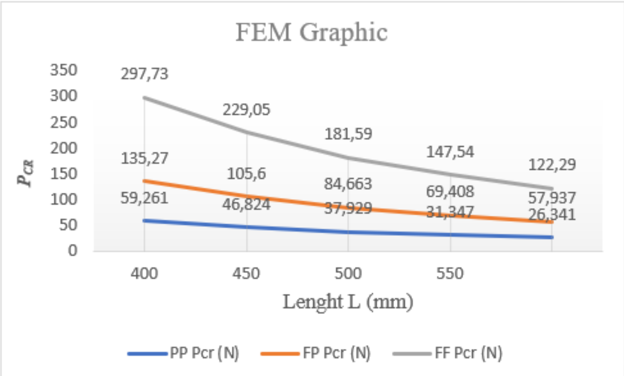

Figure 7: FEM Simulation Results

3.3 1D FEM Simulation Results (ANSYS)

In the buckling simulation of Aluminum Alloy 2024-T3 columns using ANSYS software, the finite element model was constructed using the BEAM188 element type.

a) Boundary Condition Pinned

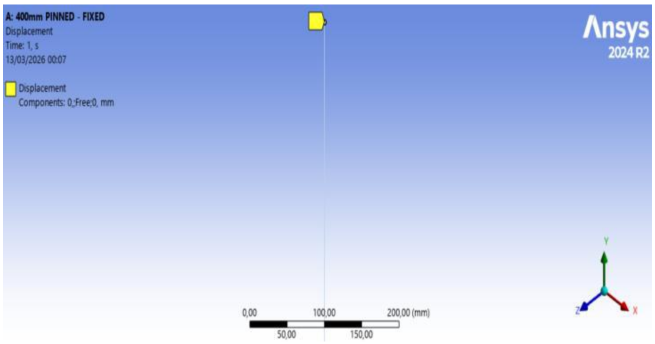

Figure 8: FEM 1D Pinned

b) Boundary Condition Fixed

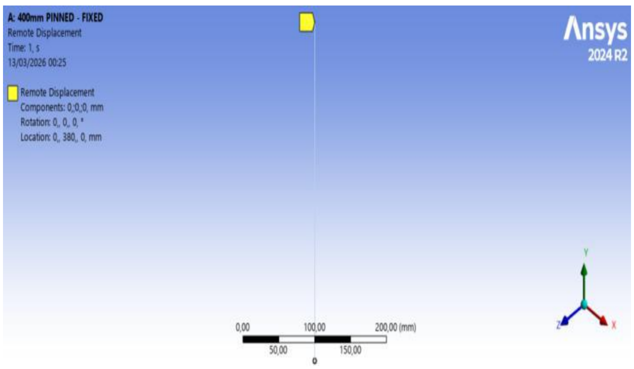

Figure 9: FEM 1D Fixed

c) FEM Simulation Results (1D)

Table 5: FEM Simulation Results

Panjang L (mm)	PP Pcr (N)	FP Pcr (N)	FF Pcr (N)
600	26,35	57,6	120,9
550	31,35	69,0	145,86
500	37,94	83,3	179,2
450	46,8	104,0	225,6
400	59,28	133,5	292,6

Based on the FEM simulation results, the corresponding graphical representation is presented in Figure 10.

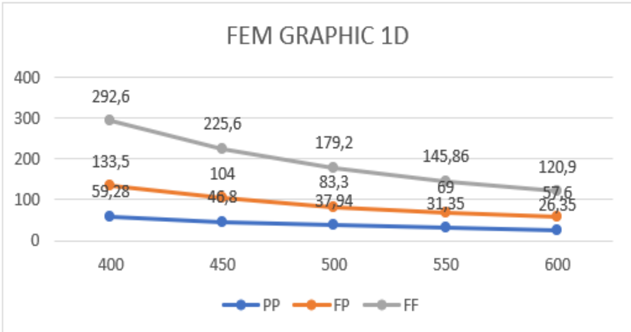

Figure 10: FEM Simulation Results

3.4 Experimental Buckling Results

Experimental testing was conducted to investigate the actual buckling behavior of Aluminum Alloy 2024-T3 columns under axial compressive loading. The experiments were performed using the STS12 Euler Buckling of Struts apparatus manufactured by TecQuipment, which is specifically designed to evaluate column stability and determine the critical buckling load under various column lengths and end-support conditions.

Table 6: Experimental Results (Pinned–Pinned EndCondition)

E = 73 GPa			*Fixing Condtion; Pinned- Pinned Ends*			
Strut Legth (mm)	$1/L^2$	Breadth *b* (mm)	Depth *d* (mm)	*I* value (m^4)	Slenderness Ratio *S*	Measured *Load P* (N)
600	2,78	19,75	2	1,32 x 10^{-11}	1039	28
550	3,331	19,75	2	1,32 x 10^{-11}	953	33,7
500	4,00	19,75	2	1,32 x 10^{-11}	866	39,4
450	4,94	19,75	2	1,32 x 10^{-11}	799	49,6
400	6,25	19,75	2	1,32 x 10^{-11}	693	60,8

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Table 7: Experimental Results (Fixed–Pinned EndCondition)

E = 73 GPa					*Fixing Condtion*: *Pinned- Fixed Ends*	
Strut Legth (mm)	Test Length *L*	1/L²	Breadth *b* (mm)	Depth *d* (mm)	*I* value (m⁴)	Measured *Load P* (N)
600	580	2,97	19,75	2	1,32 x 10^{-11}	54,2
550	530	3,56	19,75	2	1,32 x 10^{-11}	64,4
500	480	4,34	19,75	2	1,32 x 10^{-11}	78,9
450	430	5,41	19,75	2	1,32 x 10^{-11}	100,3
400	380	6,93	19,75	2	1,32 x 10^{-11}	124,9

Table 8: Experimental Results (Fixed–Fixed EndCondition)

E = 73 GPa					*Fixing Condtion*: *Fixed - Fixed Ends*	
Strut Legth (mm)	Test Length *L*	1/L²	Breadth *b* (mm)	Depth *d* (mm)	*I* value (m⁴)	Measured *Load P* (N)
600	560	3,19	19,75	2	1,32 x 10^{-11}	115,0
550	510	3,84	19,75	2	1,32 x 10^{-11}	136,2
500	460	4,73	19,75	2	1,32 x 10^{-11}	168,9
450	410	5,95	19,75	2	1,32 x 10^{-11}	219,3
400	360	7,72	19,75	2	1,32 x 10^{-11}	279,2

3.5 Comparison of Euler Theory, FEM Simulations, and Experimental Results

The comparison results indicate that all methods exhibit a consistent trend, in which the critical buckling load (Pcr) decreases as the column length increases. The FEM (ANSYS) results show excellent agreement with Euler's theoretical predictions. This is because the eigenvalue buckling analysis performed in ANSYS is fundamentally based on the prediction of ideal elastic buckling behavior and generates a buckling load factor (load multiplier), which can be converted into the critical buckling load by multiplying it by a reference load. In the present study, a reference load of 1 N was applied; therefore, the load multiplier directly represents the critical buckling load (Pcr).

Table 9: Comparison of Results (Pinned–Pinned End Condition)

E = 73 GPa					*Fixing Condtion*: *Pinned- Pinned Ends*				
Strut Legth (mm)	1/L²	*Breadth b* (mm)	*Depth d* (mm)	*I value* (m⁴)	*Slenderness Ratio S*	*Measured* Load *P* (N)	Calculated *Buckling* Load P_{cr} (N)	FEM 3D	FEM 1D
600	2,78	19,75	2	1,32 x 10^{-11}	1039	28	26,4	26,34	26,35
550	3,331	19,75	2	1,32 x 10^{-11}	953	33,7	31,4	31,34	31,35
500	4,00	19,75	2	1,32 x 10^{-11}	866	39,4	37,9	37,92	37,94
450	4,94	19,75	2	1,32 x 10^{-11}	799	49,6	46,8	46,82	46,8
400	6,25	19,75	2	1,32 x 10^{-11}	693	60,8	59,3	59,26	59,28

Table 10: Comparison of Results (Fixed–Pinned End Condition)

E = 73 GPa					*Fixing Condtion*: *Pinned- Fixed Ends*				
Strut Legth (mm)	*Test Length L*	1/L²	*Breadth b* (mm)	*Depth d* (mm)	*I value* (m⁴)	*Measured* Load *P* (N)	Calculated *Buckling* Load P_{cr} (N)	FEM 3D	FEM 1D
600	580	2,97	19,75	2	1,32 x 10^{-11}	54,2	57,7	57,93	57,6
550	530	3,56	19,75	2	1,32 x 10^{-11}	64,4	69,1	69,40	69,0
500	480	4,34	19,75	2	1,32 x 10^{-11}	78,9	84,2	84,66	83,3
450	430	5,41	19,75	2	1,32 x 10^{-11}	100,3	104,9	105,6	104,0
400	380	6,93	19,75	2	1,32 x 10^{-11}	124,9	134,3	135,2	133,5

Table 11: Comparison of Results (Fixed–Fixed End Condition)

E = 73 GPa					*Fixing Condtion*: *Fixed - Fixed Ends*				
Strut Legth (mm)	*Test Length L*	1/L²	*Breadth b* (mm)	*Depth d* (mm)	*I value* (m⁴)	*Measured* Load *P* (N)	Calculated *Buckling* Load P_{cr} (N)	FEM 3D	FEM 1D
600	560	3,19	19,75	2	1,32 x 10^{-11}	115,0	121,0	122,2	120,9
550	510	3,84	19,75	2	1,32 x 10^{-11}	136,2	145,9	147,5	145,86
500	460	4,73	19,75	2	1,32 x 10^{-11}	168,9	179,9	181,5	179,2
450	410	5,95	19,75	2	1,32 x 10^{-11}	219,3	225,7	229,0	225,6
400	360	7,72	19,75	2	1,32 x 10^{-11}	279,2	292,8	297,7	292,6

Based on the comparison results obtained from Euler's theory, FEM simulations, and experimental testing, the corresponding graphical representations are presented in the following figures.

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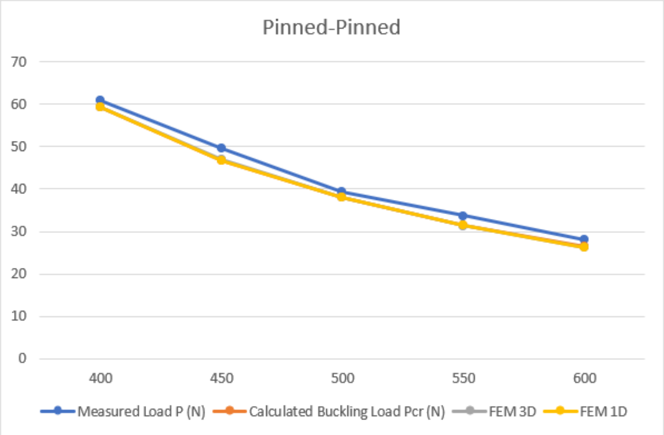

Figure 11: Pinned–Pinned Comparison

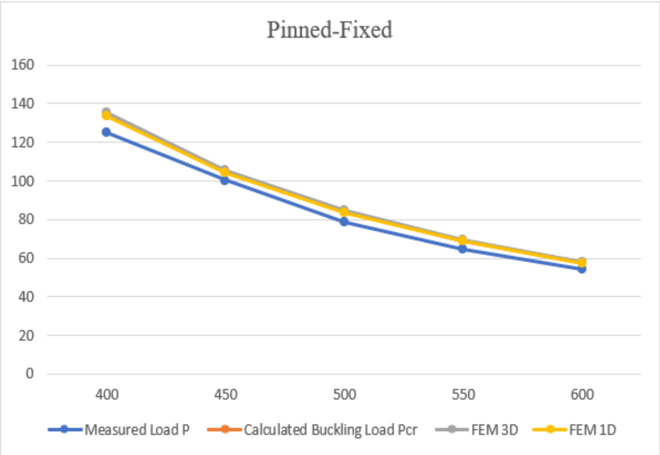

Figure 12: Pinned–Fixed Comparison

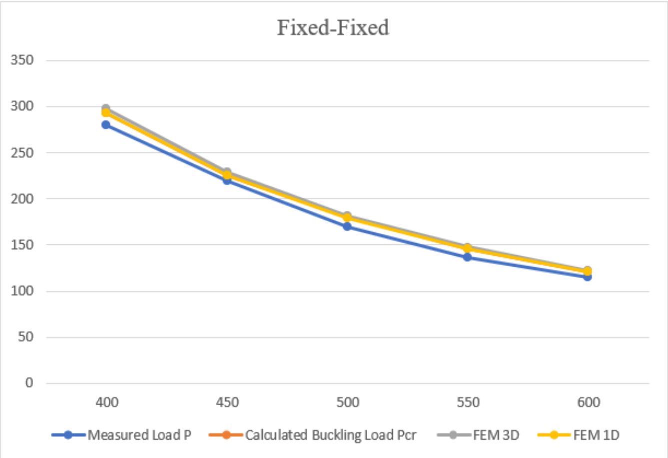

Figure 13: Fixed–Fixed Comparison

IV. CONCLUSION

Based on the analysis and discussion regarding the evaluation of the buckling strength of Aluminum Alloy 2024-T3 columns using Euler's theory, FEM simulations performed in ANSYS, and laboratory experimental testing, the following conclusions can be drawn:

1. The critical buckling load of Aluminum Alloy 2024-T3 columns is significantly influenced by column length and end-support conditions. The critical buckling load (Pcr) decreases with increasing column length and increases with greater support stiffness.
2. The Euler theory calculations indicate that, under the Pinned–Pinned end condition, the critical buckling load decreases from 59.3 N for a column length of 400 mm to 26.4 N for a column length of 600 mm. In contrast, the Fixed–Fixed end condition produces the highest critical buckling load, reaching 292.8 N at a column length of 400 mm.
3. The experimental results follow the same trend predicted by Euler's theory, with maximum buckling loads of 59.8 N for the Pinned–Pinned condition and 279.2 N for the Fixed–Fixed condition at a column length of 400 mm. The minimum buckling loads recorded were 28 N and 115 N, respectively, for a column length of 600 mm.
4. FEM simulations performed using ANSYS produced critical buckling loads that were in excellent agreement with the predictions of Euler's theory. For example, under the Pinned–Pinned condition with a column length of 450 mm, the FEM simulation predicted a critical load of 46.82 N, compared with 46.8 N obtained from Euler's theory, demonstrating the validity and accuracy of the FEM approach.
5. The differences among the theoretical, numerical, and experimental results were relatively small, with errors ranging from 0.84% to 8.30%. These discrepancies can be attributed to specimen imperfections, load eccentricity, and non-ideal end-support conditions. Therefore, experimental validation remains essential for accurately assessing the buckling behavior of practical structural systems.

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