Buckling at Elevated Temperature for (6061-T6) Aluminum Alloy Columns under Increasing Load

Shaymaa Mezaal Mshattat¹, Hussein J Al-Alkawi¹ and Ahmed Hameed Reja¹
¹ Electromechanical Engineering Department / University of Technology / Iraq

e.me.19.43@grad.uotechnology.edu.iq
50089@uotechnology.edu.iq
50073@uotechnology.edu.iq

Abstract. A column is a structural member that bears an axial compressive load and is more likely to fail due to buckling than due to material strength. Some of these columns work at high temperature and this temperature effects the behavior of buckling. Then the designer must takes this factor into consideration. The present work involves the high-temperature buckling of 6061-T6 aluminum alloy rod(column) at different range of temperature (room temperature to 200°C). This work study the critical buckling load \( P_{cr} \) under the above temperature dynamically. The \( P_{cr} \) can be predicted by Euler theory. It has been observed that the Euler theory is not satisfy to applied under high temperature unless using temperature safety factor. The results show that elevated temperature weakens the structure and decreasing its mechanical and buckling properties. From the experimental results, empirical equations were derived to predict yield strength, ultimate tensile strength, modulus of elasticity, critical buckling load and temperature safety factor at high temperature.

1. Introduction
The use of aluminum has increased in recent years in structural engineering applications because they have high strength-to-weight ratio, great workability, outstanding corrosion resistance and good durability. The cross-section designation determines the design resistance of an aluminum structural member under compression. This is a standard method for dealing with the buckling phenomenon [1].

Buckling Phenomenon is a structural instability that is typically associated with high compressional loading and results in a failure mode of a long and slender structural element. It is a lateral deflection of structural element [beam or column] which makes it somewhat asymmetric at the point of the deformation with respect to its central axis. The deformation points are unpredictable since they differ. This phenomenon frequently occurs without notice at the axis in columns and beams with the smallest second moment of area and radius of gyration, resulting in a collapse mechanism, so their configuration must be carefully studied in order for the member (column) to carry its intended loading without buckling[2]. Researches on the buckling behavior of aluminum alloy columns under static
load or dynamic load have never stopped. Mei Liu et al.[3] studied experimental and numerical investigations on the buckling behavior of thin-walled aluminum columns under static axial loading. They tested 7 specimens made of 6063-T5 aluminum alloy. They compared between ultimate strength testing with those predicted by design codes, as well as the Direct Strength Method (DSM) on thin-walled structures. They found that current design requirements overestimate design power, while DSM provided more reliable results. Khenyab et al [4] estimated the buckling behaviour of 5056-H18 Aluminum alloy columns under compressive dynamic stresses. The experimental findings were compared to Euler, Perry-Robertson theories and ANSYS 17 program values. AL-alkawai et al [5] studied the influence of soil corrosion on the critical buckling load and the mechanical properties of circular solid columns made of 2014-T4 aluminum alloy. They found that the soil corrosion reduced the critical buckling load by 10.1% and 4.77% for long and intermediate columns respectively and the reduction percentage for ultimate tensile strength was (1.95%) and yield strength was (4.57%). At various temperatures, the buckling behaviour of aluminum alloy members had also been offered. Maljaars and others [6,7,8] examined flexural and local buckling of I-shaped and square hollow section aluminum columns subjected to temperature, and a new approach and alternative design model for predicting ultimate strength were proposed, which takes into calculation the shape of the stress–strain relationships of aluminum alloys at high temperatures. Liu, Chang et al [9] using a validated finite element model, researchers investigated the buckling behaviors of a thin-walled aluminum alloy column with irregular shaped cross section at room temperature and at various temperatures in a burn. They modified Eurocode’s design method for expecting ultimate stress in case of columns long at temperatures above 250 degrees Celsius. Jiang a et al [10] examined the behavior of buckling by testing 108 aluminum columns under compressive static pressure at ambient and high temperatures. They compared between experimental results and the values calculated from the ANSYS. They proposed method to evaluate behavior of flexural buckling for columns made of aluminum at high temperatures. Mei-Ni and Ben [11] the mechanical characteristics of aluminum alloys (6061-T6 and 6063-T5) at various temperature were researched. At different temperatures, the yield strength (i.e., 0.2% elastic limit stress), ultimate tensile strength, and Young’s modulus were calculated experimentally. They were proposed a more precise reduction factor for the material characteristics of aluminum alloys at various temperature. H. Ma et al [12] ] tested H-section (6082-T6) aluminum alloy columns for material and axial compression at different temperatures. At various temperatures, they showed properties of material, stress–strain curve, load– deflection curve, and ultimate strength of each member. They proposed formula to calculate the columns’ stability coefficient under axial compressive load at various temperature. The results of the test were compared to the fitting formula, the European code and the Chinese code. The results show that the fitting formula can provide a more precise stability coefficient for the columns at various temperatures. The main objective of this search is to study the influence of various temperature on the buckling behavior for 6061-T6 aluminum alloy columns under compression dynamic buckling load for pinned-fixed ends condition.

2. Theoretical investigation

2.1. Type of columns

Any slender bar or member subjected to compressive load is called strut or column. Piston rods, connecting rods, side links in forging machines are struts. The failure of such members may occur by pure compression, or by buckling, or by combination of pure combination of pure compression and buckling, depending upon a slenderness ratio (S.R.). All the research in this field seek to obtain safe load which is well below the buckling load can be obtained by

\[ \text{Safe load (Ps) = } \frac{\text{buckling critical load (Per)}}{\text{safety factor (SF)}} \]  \hspace{1cm} (1)

Depending upon the length to diameter, the columns are divided in to three classes[13].

1. Short columns: Their buckling stresses are generally negligible.
2. Intermediate columns: They are subjected to buckling stresses as well as direct stresses.
3-Long columns: Direct stresses are very small as compared with buckling stresses, and hence it is neglected.

The effective slenderness ratio is calculated by

\[ S.R. = \frac{L_e}{R_{min}} = \frac{KL}{R_{min}} \]  \hspace{1cm} (2)

\[ R_{min} = \left( \frac{I}{A} \right)^{1/2} \]  \hspace{1cm} (3)

Where:
- \( L_e \): The effective length.
- \( L \): Columns' actual length between supports.
- \( K \): Constant of end fixity (take 0.7 for fixed-pinned).
- \( R_{min} \): Smallest radius of gyration.
- \( I \): Least moment of inertia.
- \( A \): Cross section area.

The table below (1) illustrates the three types of columns dependent on slenderness ratio for various materials[14].

| Material    | Short column | Intermediate column | Long column |
|-------------|--------------|---------------------|-------------|
| steel       | S.R \leq 40  | 40 \leq S.R \leq 150| S.R \geq 150|
| AA6061 – Ti  | S.R \leq 9.5 | 9.5 \leq S.R \leq 66| S.R \geq 66|
| AA2014 – Ti  | S.R \leq 12  | 12 \leq S.R \leq 55 | S.R \geq 55|
| Wood        | S.R \leq 11  | 11 \leq S.R \leq (18-30) | (18-30) \leq S.R \leq 50|

There is another classification of columns depends on two formula, slenderness ratio and column constant(Cc).

\[ Cc = \left( \frac{2\pi^2E}{\sigma_y} \right)^{1/2} \]  \hspace{1cm} (4)

Where:
- \( \sigma_y \): Yield strength of column (in tension).
- \( E \): Elasticity modules for the material.

The column constant is determined by the column's mechanical properties. When the slenderness ratio (S.R.) for a column exceeds the column constant (Cc), the column is considered long. The column is short if the slenderness ratio (S.R) is less than the column constant [15].

2.2. Euler formula.

Leonard Euler proposed the first equation for analyzing the buckling behavior of a slender elastic column (1707-1783). The relationship between the critical buckling force for a compressed column in statics and the lateral deflection is presented by Euler's formula. In this study, the Euler equation was derived for a column that is fixed-pinned ended shown in figure (1)[16]. The critical buckling load( elastic stability limit) can be estimated by the equation:
\[ P_{cr} = \frac{\pi^2EI}{(KL)^2} \]  

(5)

2.3. Definition of failure
The maximum allowed sidelong deflection is 1% of the specimen length. When the axial force is removed, the column recovers to its normal state when the sample's sidelong deflection approaches this ratio and does not exceed it. The critical buckling of the columns is what it's termed. The sample fails when the lateral deflection exceeds this ratio (1 percent L)[17].

3. Experimental work
3.1. Compisition of chemicals
Table(2) shows the chemical composition was carried out in State Company for Inspection and Engineering Rehabilitation(SIER).

![Figure (1). fixed-pined column conditions][16].

| 6061-T6 Al-alloy | Al% | Cr% | Cu% | Fe% | Mn% | Si% | Ti% | Zn% |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| ASTM B-211       | Balance | 0.04-0.35 | 0.15 | 0.4 | 0.4-0.8 | Max. | 0.15 | Max. | 0.25 |
| Experimental     | Balance | 0.17 | 0.28 | 0.46 | 0.12 | 0.57 | 0.1 | 0.18 |

3.2. Mechanical properties
The mechanical properties were performed using the tensile testing machine offered as in Figure (2). This machine is capable of performing tensile tests at various temperatures from room temperature to 300°C with a capacity of 20KN[18]. The workable results are shown in table(3). The test carried out according to standard specification (ASTM- E8M-16a).
3.3. Buckling samples

In this paper, 24 samples are selected of long solid columns made of aluminum alloy (6061-T6) with different lengths and diameter presented in figure (3). The table (4) shows the dimensions of the sample that was used. Specimens had been tested under different compressive dynamic loading with different levels of elevated temperature (100°C, 150°C and 200°C) and at room temperature as reference.

| 6061-T6 AL alloy | Ultimate Tensile Strength (UTS) MPa | Yield Strength (YS) MPa | Modulus of Elasticity (E) GPa |
|-----------------|-----------------------------------|-------------------------|-------------------------------|
| AISI Standard   | 310                               | 276                     | 70                            |
| Experimental[17]| 306                               | 264                     | 71                            |

Table (3). Mechanical properties for 6061-T6 AL alloy at room temperature.

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**Figure (2)**. Tensile testing machine[18].

**Figure (3)**. Buckling samples.

| D mm | L mm | L_e mm | S.R. | C_c mm² | A mm² | I mm⁴ | R mm |
|------|------|--------|------|---------|-------|-------|------|
| 8    | 450  | 315    | 157.5| 72.3    | 50.3  | 201   | 2    |
| 8    | 400  | 280    | 140  | 72.3    | 50.3  | 201   | 2    |
| 8    | 350  | 245    | 122.5| 72.3    | 50.3  | 201   | 2    |
| 10   | 450  | 315    | 126  | 72.3    | 78.5  | 491   | 2.5  |
| 10   | 400  | 280    | 112  | 72.3    | 78.5  | 491   | 2.5  |
| 10   | 350  | 245    | 98   | 72.3    | 78.5  | 491   | 2.5  |

Table (4). The dimensions of solid sample for (6061-T6) AL alloy.
3.4. Dynamic buckling test-rig

Buckling properties were completed using the test-rig offered in above figure(4)[19]. The rig is collected from the following components in order to create a modern and unique system for studying the effect of the composite factor, which is the load and temperature simultaneously on a column. The parts of the designed test rig are as follows:-

- Mechanism of torsion.
- Mechanism of pressure.
- Electric oven.
- Device for measuring buckling and failure.

![Figure(4). Rig test device[19].](image)

4. Results and discussion.

In this section, mechanical properties, buckling properties and efficiency of Euler formula can be presented without and with the effect of high temperature.

4.1. Mechanical properties

Table(5) shows the mechanical properties and their reduction when subjected to high temperature i.e.(100C, 150C and 200C).

| Property                        | at 100C | at 150C | at 200C |
|---------------------------------|---------|---------|---------|
| Ultimate Tensile Strength (UTS) |         |         |         |
| MPa                             | 297     | 288     | 278     |
| Yield Strength (YS)             |         |         |         |
| MPa                             | 251     | 239     | 219     |
| Modulus of Elasticity (E)       |         |         |         |
| GPa                             | 67      | 61      | 54      |

The average of three reading of tensile test results at different temperatures (R.T.,100,150 and 200C) can be described by the following equations listed in table (6).
Table (6). Tensile test results.

| Property               | Equation                  |
|------------------------|---------------------------|
| Ultimate Tensile Stress (UTS) MPa | $UTS=352 \ T^{-0.0413}$ |
| Yield Strength (YS) MPa     | $YS=344 \ T^{-0.0769}$   |
| Modulus of Elasticity (E) GPa | $E=105 \ T^{-0.1129}$   |

The above equation can be used to obtained the mechanical properties of AA 6061-T6 for different temperature. The high temperature in general has the overall effect on the structure and eliminates the strength of material. In other words high temperature weakens the structure and decreasing its mechanical properties. This finding agreed well the conclusion mentioned in reference[11]. The behavior of AA 6061-T6 can be illustrated in figure (5). The reduction percentages in above mechanical properties can be illustrated in table(7).

![Tensile stress vs Temperature](image)

Figure (5). Variation of mechanical properties with temperature.

Table (7). Reduction percentage in mechanical properties under high temperature.

| Property | At 100°C | At 150°C | At 200°C |
|----------|----------|----------|----------|
| (UTS)%   | 2.94%    | 5.88%    | 9.15%    | reduction |
| (YS)%    | 4.92%    | 9.47%    | 17.04%   | reduction |
| E%       | 5.63%    | 14.08%   | 23.94%   | reduction |

4.2. Buckling properties
The experimental critical buckling load ($P_{cr}$) under dynamic load can be shown in table(8) for both (8 mm and 10 mm) diameters. For (8 and 10 mm) diameters, the critical buckling load at various temperatures...
(R.T., 100, 150 and 200°C) can be described by the following equations listed in table (9). The equations in table(9) can be used to obtain the critical buckling load of AA6061-T6 for different temperatures. From tables(5) and (7), it is clear that high temperature negatively affects the ultimate tensile strength (UTS), modulus of elasticity (E) and yield strength (YS) and this leads to decrease critical buckling load ($P_{cr}$) of the aluminum alloy specimens as shown in table (9). The buckling behavior of AA 6061-T6 under various temperature can be seen in figure (6).

**Table (8). Results for columns under increasing buckling load at room and elevated temperature.**

| D mm | $\delta_{cr}$ mm at R.T. | $P_{cr}$ Exper.(N) at R.T. | $\delta_{cr}$ mm at(100,150 and 200°C) | $P_{cr}$ Exper.(N) at 100°C | $P_{cr}$ Exper.(N) at 150°C | $P_{cr}$ Exper.(N) at 200°C |
|------|--------------------------|-----------------------------|--------------------------------------|-----------------------------|-----------------------------|-----------------------------|
| 8    | 6.5                      | 663.4                       | 6                                    | 472.4                       | 365.8                       | 301.6                       |
| 8    | 6.1                      | 733.8                       | 6                                    | 550.7                       | 455.2                       | 371.8                       |
| 8    | 5.3                      | 904.7                       | 6                                    | 712.9                       | 585.2                       | 475.6                       |
| 10   | 6.4                      | 1483.7                      | 6                                    | 1326.7                      | 1020.7                      | 811.3                       |
| 10   | 6.1                      | 1679.9                      | 6                                    | 1452.3                      | 1177.5                      | 984.6                       |
| 10   | 4.6                      | 2150.9                      | 4                                    | 1781.9                      | 1491.5                      | 1267.3                      |

**Table (9). Critical buckling load test results under high temperature.**

| Critical buckling load ($P_{cr}$) (N) for diameter = 8 mm | $P_{cr} = 2181 T^{-0.3148} \times (100/S.R.)$ |
|-----------------------------------------------------------|------------------------------------------------|
| Critical buckling load ($P_{cr}$) (N) for diameter = 10 mm| $P_{cr} = 3960 T^{-0.2391} \times (100/S.R.)$ |

4.3. **Efficiency of Euler formula**

Table (10) illustrates the Euler results in comparison to experimental data. It is clear that the increase temperature safety factor (TSF) coming from increase in temperature due to weakness of material of column. But Euler formula does not effected by applied temperature, so the Euler theory is not satisfy to applied under high temperature unless using (TSF) then Euler formula may be rewritten as

$$P_{cr} = \frac{n^2E I}{(KL)^2 \times (TSF)}$$

(6)

Comparison between the experimental and Euler formula results for prediction the critical buckling load ($P_{cr}$) can now be made. The Euler method has been shown not to be satisfactory for predicting the ($P_{cr}$) under high temperature unless using the (TSF) which can be calculated from the equation.

$$TSF = 0.878 T^{-0.298} + \left(\frac{100}{S.R.}\right)$$

(7)
The suitable (TSF) may be used in order to make the (Pcr) prediction is conservative and safe. Figure (7) shows the variation of temperature safety factor (TSF) with temperature.

![Graph showing variation of temperature safety factor (TSF) with temperature.](image)

**Figure (6).** Variation of critical buckling load with temperature.

**Table (10).** Comparison between Euler formula and experimental at room and elevated temperatures.

| D mm | $P_{cr}(Euler)$ (N) | $\frac{P_{cr}(Euler)}{P_{cr}(exp.)}$ at R.T | $\frac{P_{cr}(Euler)}{P_{cr}(exp.)}$ at 100°C | $\frac{P_{cr}(Euler)}{P_{cr}(exp.)}$ at 150°C | $\frac{P_{cr}(Euler)}{P_{cr}(exp.)}$ at 200°C |
|------|---------------------|------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 8    | 1420                | 2.14                                    | 3                               | 3.88                            | 4.7                             |
| 8    | 1797                | 2.45                                    | 3.26                            | 3.95                            | 4.83                            |
| 8    | 2347                | 2.59                                    | 3.29                            | 4.01                            | 4.93                            |
| 10   | 3468                | 2.34                                    | 2.61                            | 3.4                             | 4.27                            |
| 10   | 4389                | 2.61                                    | 3.02                            | 3.73                            | 4.46                            |
| 10   | 5732                | 2.66                                    | 3.22                            | 3.84                            | 4.52                            |

*Temperature safety factor $= \frac{P_{cr}(Euler)}{P_{cr}(exp.)}$


Temperature (°C)

![Graph](image)

**Figure (7).** Variation of temperature safety factor with temperature.

### 5. Conclusion

From the current work, the interaction of mechanical and buckling properties of AA6061-T6, the following remarks can be drawn:

1. Mechanical and buckling properties were significantly reduced under high temperature because the high temperature in general has the overall effect on the structure and eliminates the strength of material.

2. Euler formula gave overestimation for critical buckling load under high temperature compared to the experimental results. While if taking a temperature safety factor obtained from the empirical equations gave satisfactory predictions.

3. The temperature safety factor (TSF) can be described by the following empirical equation.

\[
TSF = 0.878 T^{0.298} + \left(\frac{100}{S \cdot R}\right)
\]

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