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Evaluation of Buckling of 2024-T3 under High Temperatures

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ABSTRACT

The mechanical and buckling behavior of AA 2024 – T3 at high temperatures has been presented. The material was examined by thermal tensile test rig with 400℃ capacity. While buckling tests were carried out using a thermal rotating buckling test machine. Several observations were drawn from the experimental results, such as the mechanical and buckling properties are reduced by application of high temperatures. The experimental results of (UTS), (YS), (BHN) and (E) were decreased by 13.77%, 19.76%, 28.8% and 24.65% respectively due to application of 250c comparing to that at room temperature. The critical buckling load (P_{cr}) is increased when the column length and (SR) are reduced. The critical buckling load (P_{cr}) results were reduced from 910N to 610N when the applied temperature increased from (RT) to 250℃. Therefore, using a high temperature true of 250℃ gives a reduction percentage of 33% in critical buckling load result. The estimation of Euler theory was overestimated the buckling properties, but when using a safety factor the estimation seems to be resemble.

1. INTRODUCTION

Maljaars et al. [1] used columns flexural buckling which is exposed to high temperature for examination square hallow and I shaped section of aluminum FEM showed good results to explain flexural buckling of aluminum columns Also it showed a useful model of calculation for flexural buckling of aluminum columns exposed to temperature. In Euro code 9. It's prediction for buckling resistance with temperature was not accurate. Kadhim [2] studied the buckling behavior of slender fiber reinforced polymer columns subjected to static axial loading under various temperatures. The experimental results showed that the value of critical load and Young's Modulus were decreased with the increase in temperatures. Buckling behavior for aluminum alloy columns under high temperature conditions was examined by Jiang et al. [3]. They tested 60 rectangular and 48 circular tubes using awal static load at high and ambient temperatures. Their experimental results were compared with that calculated by using ANSYS. They suggest a formula to predict the stability coefficients of aluminum alloy columns on five conditions. Their formula was accurate to evaluate the ultimate loads of aluminum alloy columns at temperature (20-300) [4]. FEM Also used by sea wan to study the characteristics of elastic buckling for a steel circular tube in fire. They used a ratio of a critical load to initial buckling Strength with exposure time. The elastic buckling strength was decreased 20% in 10 minutes of a five occurring -Also the strength is decreased 20% or less if 50% of the area is exposed to five for all models in 100 minutes. Moreover, the Strength decreased 30% or less in 100 minutes of 12.5% of the area is exposed to fire. Ma et al. [5] performed 6082 - T6 aluminum alloy Columns of H - section with axial Compression load at Various temperature. The showed the mechanical properties Such as Stress Strain curves and ultimate bearing capacity at different temperatures of each member. They propose a formula to calculate the coefficient of Stability for Columns subjected to axial compression at various temperatures comparing their results with that of Chines Code (GB), and European Code (EC9) showed more accurate stability coefficient for the Columns**.** They studied the flexural buckling behavior using experimental and numerical investigations for circular hollow section (CHS) Stainless steel columns after exposure to fire. The experimental results and numerical data were compared with the codified design provisions for stainless steel columns at ambient temperature [6].

Aziz and Al-Alkawi [7] apply Euler equation with long columns and Johnson equation with short using experimental work under dynamic buckling load. Twenty specimens made of two alloys, the first is 1050 hot rolled and the second is 5052 aluminum alloys were used. They found that the above theories are useful to calculate the critical load for three or more of the design factors. Also, the critical buckling load was affected by the initial deflection of the column. Javidinejad [8] examined the influence of the combined axial and horizontal side force on the buckling behavior of I-beam. They found that the behavior of buckling for a long I-beam is determined by the effective application location of the axial loading. From the elastic static theory, a theoretical formula was developed to estimate the critical load for coupled loading configuration. The Finite Element Analysis was used to stratify Buckling behavior and critical load of the beam was evaluated by applying axial load on the I- beam at different locations. Bhoi and Kalurkar [9] studied the buckling behavior of beam and column. These beams are subjected to heavy loads then failure will occur due to buckling.

The main goal of the present research is to study the effect of high temperatures on the behaviour of mechanical and fatigue properties of 2024-T3. Also, to use the analysis and design of column to make sure the applied load on the column is safe, and lower than the critical buckling load.

2. EXPERIMENTAL WORK

2.1 Material

Material used in this research is aluminum alloy (2024-T3). This material is widely used in aerospace applications such as aircraft wing and fuselage body under tension because of its good strength and fatigue resistance. Also this material is affected to thermal shock, therefore it is used as liquid penetrant in tests dealing with high temperature ranges. Copper is used with this alloy is heat treatable and malleable when it is fully soft, annealed and can be heat-treated to elevated temperature after farming [10, 11].

2.2 Chemical composition

The chemical composition of AA2024-T3 Experimental and standard are shown in Table 1.

2.3 Mechanical properties

2.3.1 Tensile test specimen

The geometry of the specimen must be chosen according to the shape of the grip that used in the UTM and to the shape of the tasted material (sheet, Rod, etc.) In all the tests, the gauge Section and the grips shoulder of the tensile Specimens are the same. The geometry of the specimens used was in a good agreement with (ASTM)-E8M-16A [13] as shown in Figure 1.

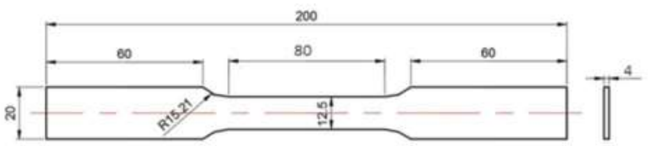

Figure 1. The geometry of the tensile sheet specimen in accordance with ASTM E8-E8M-16A (all dimensions in mm)

2.3.2 Tensile test rig

Universal tensile test Machine was used in this research which can be used for other tests like banding and Compression. This machine holds the specimen from its shoulders and exerting it to a uniaxial bad until the fracture [14]. The main purpose of this test is to get the stress stain curve. Most the tensile test machine are hydraulically. For electromechanically driven [15]. The difference between them belong to the power train mechanism. Electromechanical machines are driven by an electric servo-motor and a speed reducer system. Belt-pulley mechanism with two or four-ball screw was used to transmit the power to the crosshead in uniaxial motion. Usually the machine designer used two ball screw drives, also it was possible to used four screws if needed. The cross head Speeds can be increased by increasing the servo motor speeds.

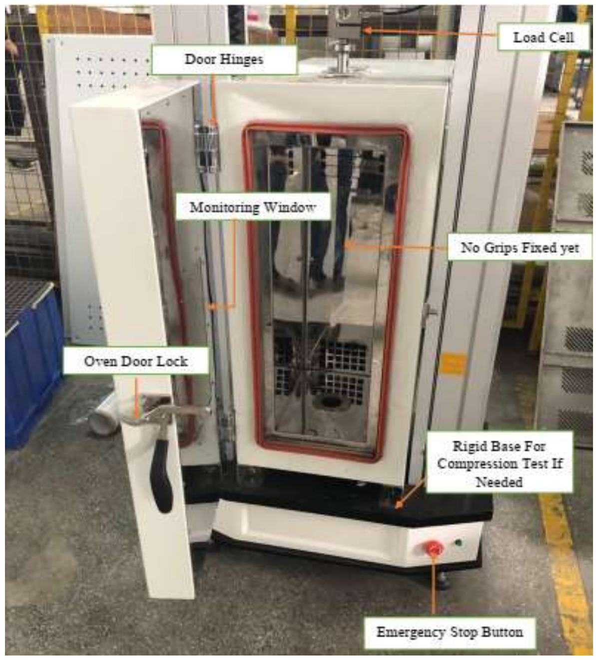

Figure 2. Initial oven fitting into the load frame

The tensile test machine was used to obtain the mechanical properties. The machine illustrated in Figure 2 is able to perform the tensile and compression tests at different temperatures up to 330°C with load Capacity of 20 KN (13). The overall capacity of the test rig is 400°C (Furnace) but the actual test was done at 330°C. Table 2 shows the tensile results. These tests was carried out using standard specimens according to standard specification (ASTM - E8M-16A), as shown in Figure 1.

Table 1. Chemical composition of AA2024-T3 experimental and standard

Component		Wt.%	Component	Wt.%	Component	Wt.%	Component	Wt.%
Exp.	Al	Balance	Mg	1.64	Si	0.46	Cr	0.09
	Cu	4.3	Fe	0.48	Ti	0.138	Zn	0.24
							Mn	0.69
Stand. [12]	Al	Balance	Cr	Max 0.1	Cu	3.8-4.9	Fe	Max 0.5
	Mg	102-1.8	Mn	0.3-0.9	Zn	Max 0.25	Other, each	Max 0.05
							Other, total	Max 0.15
	Si	0.5	Ti	Max 0.15				

Table 2. Tensile test results for various applied temperatures

alloy	(UB)MPa	YS (MPa)	BHN	(E) GPa	Elongation%	condition
2024-T3 RT 25°C	479	339	118	73	17.5	ExP.
2024-T3 120°C	466	318	107	69	20	ExP.
2024-T3 200°C	449	294	94	62	22	ExP.
2024-T3 330°C	413	272	84	55	24.5	ExP.
Standard	485	345	120	73	18	standard

2.4 Buckling test rig

Figure 3. Actual thermal buckling test machine

To study the effect of the load and temperature on the column, it is necessary to create a modern system used in the test rig. This rig can handle solid and hollow specimens with diameters ranging from 2 to 14mm. As a result, specimens can be examined with various slenderness ratios (short, intermediate, long) under different temperature by using this test apparatus. Figure 3 shows the actual thermal buckling test machine. The initial deflection of column (buckling specimens) was measured as 0.1 mm to 0.2 mm and this value cannot be effected the final results and it assumed negligible.

3. EXPERIMENTAL RESULTS

3.1 Tensile properties

The tensile test results of AA2024-T3 samples are shown in Table 2. The specimens were tested for each temperature and the average data was recorded. The stress-strain curves at various temperatures are shown in Figure 4 and the curves fitting is least square method. The temperature effects on the mechanical properties of AA2024-T3 are shown in Table 3.

Table 3. The reduction percentage (R%) of mechanical properties at various temperatures for AA2024-T3

R% at 120℃				R% at 200℃				R% at 330℃			
UTS	**YS**	**BHN**	**E**	**UTS**	**YS**	**BHN**	**E**	**UTS**	**YS**	**BHN**	**E**
2.7	6.2	9.3	5.4	6.26	13.27	20.3	15	13.77	19.76	28.8	24.65

Table 4. Elevated temperature buckling results

spec. No.	L_{mm}	D_{mm}	$Leff_{mm}$	SR	C_c	δ_{mm}	$Pcr_{(N)}$	Test condition
1	700	7	490	280	65.2	0.8	301	Room temp
2	600	7	420	240	65.2	0.6	392	(25℃)
3	500	7	350	200	65.2	0.9	528	(RT)
4	400	7	280	160	65.2	0.7	910	σ_y = 339MPa, E73GPa
5	700	7	490	280	65.44	0.7	266	120℃
6	600	7	420	240	65.44	0.8	333	σ_y =318
7	500	7	350	200	65.44	1	498	E=69MPa
8	400	7	280	160	65.44	1.1	866	
9	700	7	490	280	64.52	0.9	218	200℃
10	600	7	420	240	64.52	1.2	300	σ_y =294MPa
11	500	7	350	200	64.52	1	442	E=62GPa
12	400	7	280	160	64.52	0.8	770	
13	700	7	490	280	63.52	0.7	205	250℃
14	600	7	420	240	63.52	0.8	262	σ_y =272MPa
15	500	7	350	200	63.52	0.6	392	E=55GPa
16	400	7	280	160	63.52	1.1	610	

Table 5. The comparison between experimental and Euler buckling results at various temperatures

Temperature (℃)	SR	P_{cr} (N) EXP.	P_{cr} (N) Euler	P_{cr} (safe)
RT	280	301	354	118
	240	392	481	160
	200	528	693	231
	160	910	1083	361
120℃	280	266	334	111
	240	333	455	151
	200	498	655	218
	160	866	1024	341
200℃	280	218	300	100
	240	300	409	136
	200	442	589	196
	160	770	920	306
330℃	280	205	266	88
	240	262	363	121
	200	392	522	174
	160	610	816	272

It is clear that at elevated temperature the mechanical properties of components are reduced when the temperature increased. Tensile test was carried out at temperatures range from 25℃ (RT) to 330℃. It was found that the alloy strength was reduced at 330℃ by 13.77% compared to that at (RT) condition. The (UTS), (YS), (BHN) and (E) are rapidly decreased when they exposed to high temperature because the strength of the alloy depends on the coarsening of the fine precipitates. Also the mechanical properties of 2xxx series 2014 and 2024 were decreased at elevated temperatures [14, 15]. Due to raising the temperature thermal expansion will increase the resulted in reduction of mechanical properties.

3.2 Results of buckling elevated temperature

The results of buckling at elevated temperature for AA2024–T3 was illustrated in Table 4.

The slenderness ratio (SR) was calculated by, SR = $\frac{L_{eff}}{r}$, where r is the smallest radius of gyration, r = $\sqrt{\frac{I}{A}}$, and the cross-section area A= $\frac{\pi}{4}$ $(7)^2$=38.48 mm^2, I = $\frac{\pi d^4}{64}$ = $\frac{\pi (7)^4}{64}$ = 117.85 mm^4, $r = \frac{d}{4} = 1.75\ mm$.

C_c is Column Constant and it was calculated by:

$$C_c = \sqrt{\frac{2\pi^2 E}{\sigma_y}} \tag{1}$$

3.3 Application of Euler's formula

The general equation of Euler theory is

$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{EI\pi^2}{Le^2} \tag{2}$$

or

$$P_{cr} = \frac{EI\pi^2}{Le^2} \tag{3}$$

According to the Euler equation, (P_{cr}) the critical buckling load is depending on the column geometry (L_e) and material stiffness [modulus of elasticity (E)].

The purpose of analysis and design of column is to keep the applied load on the column lower than the critical buckling load. The design factor must be taken into consideration.

$$\text{Design factor (DF)} = \frac{P_{cr}}{P_{allw}} \tag{4}$$

where, P_{allw} is the allowable buckling load, and the applied load (actual) must be less than P_{allw}.

Increasing by temperature lead to decreasing in mechanical properties and then effected to P_{cr}.

The specimens can be examined with various slenderness ratios (short, intermediate, long) under different temperature and the general processes and steps for testing are:

1. Fixed the tensile test specimens by grips.
2. Heating the specimens to the required temperature and then switch on the tensile test rig till fracture.

Table 5 and Figures 5, 6, 7, 8 shows experimental, theoretical and safe buckling load behaviors with slenderness ratio of AA2024-T3 at various temperatures. The experimental analyses of AA2024–T3 buckling behavior shows that the temperature has a considerable effect on buckling critical load. For the same diameter and length of column the increasing temperature leads to reduce the critical buckling load because the mechanical properties such as modules of elasticity (E) and yield stress (YS) exhibited decrease with increase in temperature. This result is well agreed with what concluded by Rincon et al. [16].

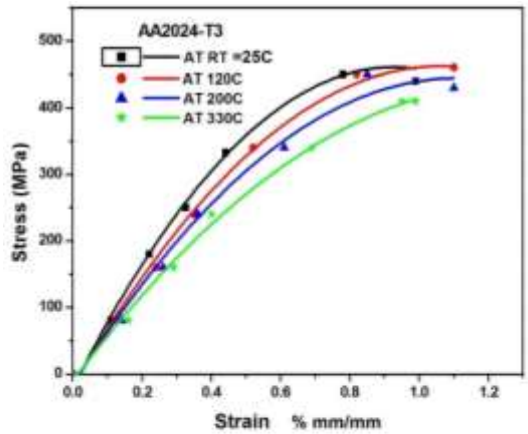

Figure 4. Stress-strain curves for AA2024-T3 at different environment temperatures

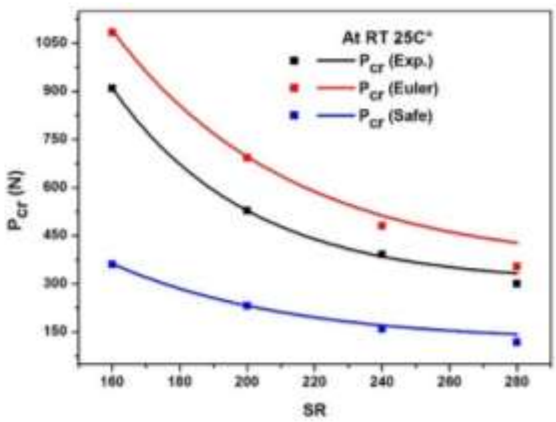

Figure 5. The comparison between experimental, theoretical and safe buckling load P_{cr} results with slenderness ratio SR for AA2024-T3 at room temperature RT

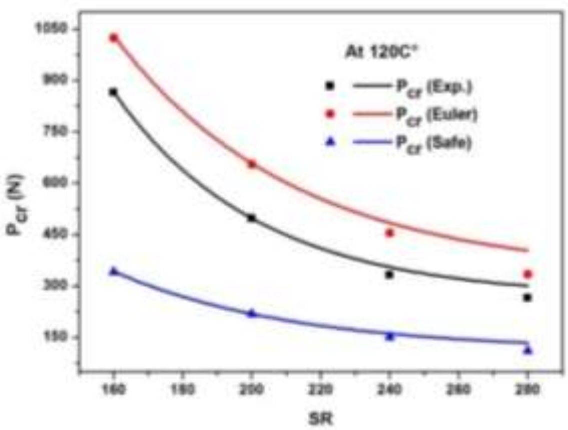

Figure 6. The comparison between experimental, theoretical and safe buckling load P_{cr} results with slenderness ratio SR for AA2024-T3 at 120℃

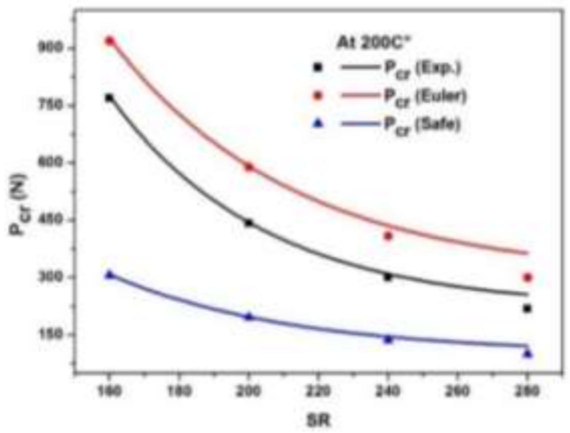

Figure 7. The comparison between experimental, theoretical and safe buckling load P_{cr} results with slenderness ratio SR for AA2024-T3 at 200℃

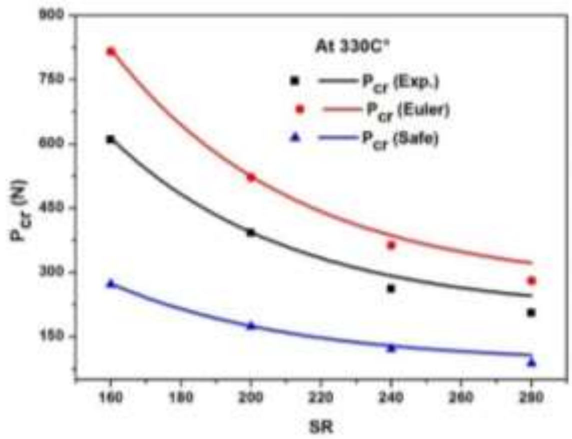

Figure 8. The comparison between experimental, theoretical and safe buckling load P_{cr} results with slenderness ratio SR for AA2024-T3 at 330℃

It appears that, the elevated temperature significantly reduces the critical buckling load for all columns. The reduction is belonged to softening the material resulting to eliminate the mechanical properties which leads to reduce the critical buckling load. It is also clear that the estimation of (P_{cr}) due to Euler is overestimate compared to the experimental results. The reasons:

1- It does not take into account the direct stress and the environment like, corrosion, temperature etc.
2- Euler theory is applicable to an ideal column. In practice there is always crookedness in the column and the load subjected is not exactly coaxial.

For the above reasons, the prediction results of Euler theory are always higher than the experimental results. This result is well agreed with Arnold [17].

For the experimental and predicted results using Euler theory, it is obvious that the strength of column depends upon the slenderness ratio (SR). The slenderness ratio (SR) is increased as the buckling critical strength of the column is decreased and as the tendency to buckle is increased. Also it is appeared that the temperature reduces the critical buckling load. For a given dimension of column SR=160, the experimental results of critical load reduce such that P_{cr} =910N at (RT) while at 330℃ P_{cr}=610N. This result indicates a 33% reduction in P_{cr} due to 330℃ elevated temperature. Mshattat et al. [18] proved this conclusion using 6061-T6 aluminum alloy.

Typical machine design applications, for long columns, where there is some uncertainty loads or the send fixity, or where special danger are presented, larger factors are advised. For the present work it is recommended to use 3 as a design factor. Mott [19] advised to use 3 for long columns when using Euler formula.

4. CONCLUSION

The effects of elevated temperatures on buckling behaviour of AA2024-T3 has been presented. The material was subjected to high compressive load at the selected elevated temperature. Several conclusions can be achieved from the experimental and theoretical results.

1. The mechanical properties of AA2024-T3 are reduced significantly by the application of elevated temperature when compared to (RT) test performed in lab-air. At 330℃, (UTS), (YS), BHN and E were reduced by 13.77%, 1976%, 28.8% and 24.65% respectively.
2. The buckling critical loads of AA2024-T3 was eliminated. The results of P_{cr} were reduced 33% compared to lab-air or (RT) for a given SR and column dimensions.

The predictions of buckling critical loads due to Euler theory were observed to be higher than the experimental for all the temperatures used. In order to keep the applied load on the long column is safe, a safety factor of 3 recommended to use.

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REFERENCES

[1] Maljaars, J., Twilt, L., Soetens, F. (2009). Flexural buckling of fire exposed aluminum columns. Fire Safety Journal, 44(5): 711-717. http://dx.doi.org/10.1016/j.firesaf.2009.02.002
[2] Kadhim, N. (2016). Effect of temperature on buckling of polymer matrix composite materials columns. Al-Nahrain Journal for Engineering Sciences (NJES), 20(3): 511-519.
[3] Jiang, S., Xiong, Z., Guo, X., He, Z. (2018). Buckling behavior of aluminum alloy columns under fire conditions. Thin-Walled Structures Journal, 124: 523-537. https://doi.org/10.1016/j.tws.2017.12.035
[4] Seo, J., Won, D., Park, W.S., Kim, S. (2018). Buckling behavior of circular steel tubes under fire. Key Engineering Materials, 763: 270-278. https://doi.org/10.4028/www.scientific.net/KEM.763.270.
[5] Ma, H., Hou, Q., Yu, Z., Ni., P. (2020). Stability of 6082-T6 aluminum alloy columns under axial forces at high temperatures. Thin–Walled Structures Journal, 157(3):

83-107. https://doi.org/10.1016/j.tws.2020.107083
[6] He, A., Li, H.T., Lan, X., Liang, Y., Zhao, O. (2020). Flexural buckling behavior and residual strengths of stainless steel CHS columns after exposure to fire. Thin–Walled Structures Journal, 152: 106715. https://doi.org/10.1016/j.tws.2020.106715
[7] Abdul Aziz, H., Al-Alkawi, H.J.M. (2009). An appraisal of Euler and Johnson buckling theories under dynamic compression buckling loading. The Iraqi Journal for Mechanical and Material Engineering, 9(2): 173-181.
[8] Javidinejad, A. (2012). Buckling of beams and columns under combined axial and horizontal loading with various axial loading application location. Journal of Theoretical and Applied Mechanics, Sofia, 42(4): 19-30. http://dx.doi.org/10.2478/v10254-012-0017-9
[9] Bhoi, M.R., Kalurkar, L.G. (2014). Study of buckling behavior of beam and column. OSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 11(4): 36-40.
[10] https://en.wikipedia.org/wiki/2024_aluminium_alloy, accessed on 19 May 2022.
[11] https://unitedaluminum.com/2024-aluminum-alloy/, accessed on 19 May 2022.
[12] ASM Aerospace specification metal inc. http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma2024t3, accessed on 19 May 2022.
[13] Aluminum and Aluminum Alloys ASM International. (2001). https://www.asminternational.org/search//journal_content/56/10192/06610, accessed on 19 May 2022.
[14] Anilchandra, A.R., Arnberg, L., Bonollo, F., Fiorese, E., Timelli, G. (2017). Evaluating the tensile properties of aluminum foundry alloys through reference castings - A review. Materials, 10(9): 1-12. https://doi.org/10.3390/ma10091011
[15] Mdletshe, Z. (2017). Design and Manufacturing of a Temperature Controlled Chamber for a Tensile Testing Machine. https://core.ac.uk/download/pdf/151666731.pdf.
[16] Rincon, E., Mancha, H.F., Cisneros, M., Mancha, H. (2009). Temperature effects on the tensile properties of cast and heat treated aluminum alloy A319. Material Science and Engineering (A), 519(1-2): 128-140. http://dx.doi.org/10.1016/j.msea.2009.05.022
[17] Arnold, M. (2013). Euler buckling of column. MSc Thesis, University of Surrey. https://djes.info/index.php/djes/article/view/952.
[18] Mshattat, S., Alalkawi, H., Reja, A.H. (2021). Buckling at elevated temperature for (6061–T6) aluminura alloy columns under increasing load. Journal of Physics. https://doi.org/10.1088/1742-6596/1973/1/012106
[19] Mott, L.R. (2004). Machine Design Elements. Perajman Press. https://ftp.idu.ac.id/wpcontent/uploads/ebook/tdg/DESIGN%20SISTEM%20DAYA%20GERAK/Machine%20Elements%20in%20Mechanical%20Design.pdf.