Effect of Underground Corrosion on the Buckling of Al Alloy 6061-T4 Columns under Increasing Load

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Abstract

This research deals with the extent to which corrosion affects the behavior of buckling for 6061-T4 aluminum alloy under increasing compressive dynamic loads. Two types of columns, long, and intermediate were used.1% of the length column is the allowable lateral deflection. This is called the critical buckling of the columns. For the purpose of calculating the critical deflection, a digital dial gauge was used and set at a distance of 0.7 of column length from the fixed end condition for the column**.** The experimental analysis revealed that the corrosion time negatively affects the mechanical properties of materials such as the corroded specimens of 60 days (The least time to observe the corrosion of aluminum in the soil) which have approximately 2.7 % reduction in ultimate strength compared with the non-corroded specimen. Increasing the corrosion time reduces the critical load such as the maximum reduction will be 4.24% in critical buckling load for 60 days' corrosion time. The results obtained were experimentally compared with the theoretical formulas of the Perry-Robertson and Euler-Johnson formula with the results of the ANSYS. It was found that the Perry-Robertson formula has a good agreement with the experimental results with a safety factor of 1.2, while the Euler-Johnson formula agreed with the experimental results taking a safety factor of 1.5. The ANSYS results showed a good agreement between the measured and calculated values by taking 1.1 factor of safety.

Keywords: Dynamic Buckling, Aluminum Alloy 6061-T4 Column, Buckling, Corrosion, ANSYS

1. Introduction

There are several ways to determine the failure of structures such as the type of structure, the kind of load and the nature of the materials exercised. For example, an axle in a car may unexpectedly breakdown from the refined cycles of loading. This leads the structure loses its ability to complete its intended function. The best solution to avoid these types of failures is through structures designed to remain within the limits of maximum stress which can be tolerated. Thus, the strength and stiffness are significant factors in this design [1]. Buckling is one type of failure that leads to a sudden breakdown in structures when the column is exposed to axial compression stress. When a column of a structure is loaded with a small axial pressure, it is distorted with a noticeable change in geometry. At the point of critical load value, the structure unexpectedly experiences a large distortion and may lose its stability to carry the load. This stage is the buckling stage [2]. The columns are straight members whose length is larger than their cross-section area. Lateral deflection of the column (buckling) occurs when the column is subjected to an axial compression load, the lateral deflection increases by gradually increasing the load. The columns are called long or short depending on the dimensions of the column and its mechanical properties. At first, when the column loads are stable. However, when adding load that exceeds the load buckling, it becomes unstable, it is also possible to say that the least deviation of the column from its straight form leads to buckling. The point at which the buckling occurs is called the point of bifurcation [3]. The corrosion of the buried metals in the soil is one of the biggest engineering and economical problems. The corrosion in the soft wet soils is more violent than corrosion in dry soils and soils in water, because of occurrence of the corrosion process requires the presence of moisture and oxygen together, known as soil dry lack of moisture and saturated soil lacks oxygen. This type is called wet corrosion while, dry corrosion occurs at high temperatures, such as oxidation, and the different layers of corrosion are formed on the surface in terms of chemical and physical properties, and these layers vary by changing the mean corrosion air [4]. The increasing development in the structural application of aluminum alloy is due to its several particular features over classical carbon steel, including satisfying corrosion resistance, high strength-to-weight ratio, and good formability. It also displays comparable ease of manufacture, low maintenance costs, and superior aesthetics [5].

Maljaars and et al [6] presented the buckling of aluminum columns with different temperatures. (FEM) was performed. The data of this method were compared with experiments. They investigated that simple calculation model for flexural buckling of fire exposed aluminum columns in E N 1999 -1 - 2 does not give an exact forecast of the buckling resistance in a fire compared to the (FEM). A modern design model, depending on the inelastic critical buckling load of Shanley, gives a perfect forecast of the ultimate buckling resistance than the two methods stated above. **Alalkawi and Aziz [7]** studied the Euler and Johnson theories depended on experiment tests under compression dynamic buckling load by using 20 specimens (columns) made from two materials, 1020 hot rolled and 5052 Aluminum alloy. They concluded that Euler (for long columns) and Johnson (for short columns) theories can be used to estimate the dynamic critical buckling load with design factor of 3 or more. **Avcar [8]** studied the influence of the boundary cases, cross-sections and slenderness ratios on the buckling load of the steel column. Two different boundary conditions such as Fixed-free (F - F) and pinned-pinned (P - P) with three various cross-sections area, such as square, rectangle and circle cross sections were used. Finite element model (FEM) has been performed and compared with numerical computations. They found that the buckling load of fixed-free (F – F) column was less than pinned-pinned (P – P) column. **Oszvald and Dunai [9]** studied the influence of corrosion on the buckling behavior and resistance of corroded steel angle section members. Buckling tests were executed on 24 mm thickness of steel angle section specimens. The influences of the corrosion location and the reduction of the cross-section were studied by experimental investigations where the corrosion was modeled by artificial thickness reduction. It was found that the buckling resistance was reduced by corrosion in different rates: different corrosion locations, cross-section, and volume reduction causes large scatter in the buckling resistance reduction. **Kashani [10]** studied the effect of corrosion on the resistance of buckling. Corrosion has negatively effects on the elasticity of the column. The numerical model developed in this study is capable of responding to the linear bending of the reinforced concrete until the total collapse. The results obtained that it is unsuitable to suppose that corrosion only impacts the main vertical strengthening in the column.

In this work Study the effect of corrosion underground on the Buckling of Al Alloy 6061-T4 Columns under Increasing Load with fixed-pinned conditions. As well as the use of the Perry-Robertson formula, Euler- Johnson formula and numerical analysis to evaluate critical buckling and to determine their compatibility with experimental results. The deflection of the column is measured using a digital dial gauge indicator.

2. Theory

2.1 Euler formula

The first formula for the analysis of the buckling column was presented early by the Euler world in 1744. This classical theory is still valid to our time and is likely to remain so, the slender columns have a variety of constraints. Euler's equation discusses the small elastic deflection of ideal columns. However, we investigate first the nature of buckling and the difference between theory and practice [12].

In this case, the Euler load was derived for a column that is fixed- pinned condition as shown in figure 1

$$Pcr = \frac{20.19EI}{L^2} = \frac{2.046\pi^2 EI}{L^2} \text{ [1]} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Pcr: critical buckling load

E: module of elasticity

I: moment of inertia

L: total length of column

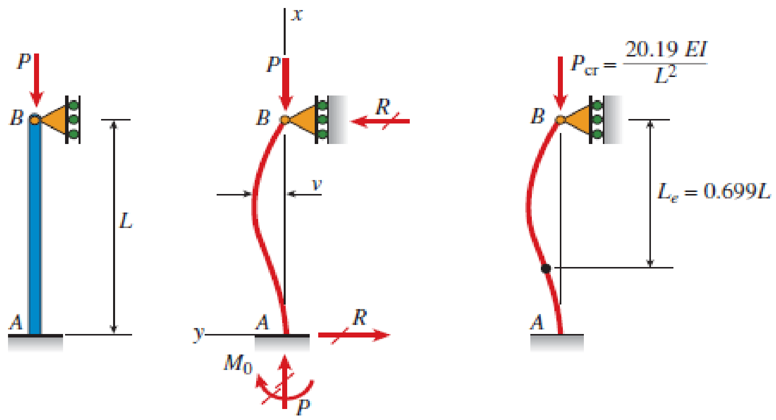

Figure 1: (fixes-pinned) Column condition [1].

2.2 Euler – Johnson Formula

The Euler formula can only be applied to long columns where the slenderness ratio is greater than the column constant. It is also possible to say that the Euler equation does not depend on the mechanical properties of the metal except the module of elasticity is entered into the calculation. The slenderness ratio is based only on the dimensions of the column. A column that is long and slender will have a higher slenderness ratio SR, than column constant Cc and therefore a low critical stress, Euler equation can be used to evaluate the critical load. The critical load Pcr is depending on the dimensions of the columns. The material strength is not involved in the above formula. A column that is intermediate or short and stubby will have a lower slenderness ratio S.R. than a column constant Cc and will buckle at a high stress, and Johnson formula can be applied. This formula may be written as

$$P_{cr} = A\sigma_y\left[1 - \frac{\sigma_y(\frac{L_e}{r})^2}{4\pi^2 E}\right][12] \quad ....(2)$$

σ_y: yield of strength.

A: cross section area of column.

The critical load P_{cr} is directly affected by the mechanical properties in addition to its module of elasticity [12].

2.3 Perry-Robertson formula

The Perry-Robertson formula was improved to take into account the shortcomings of the Euler equation for long columns as well as the Johnson equation for intermediate and short columns. This formula was developed from the assumption that all practical failures could be represented by a hypothetical initial curvature of the column. The Perry-Robertson formula depends on the hypothesis that any failure in the column, during wrong industry or eccentricity or material of loading, can be allowed for by presenting the strut of an initial curvature. [13]

$$p_{cr} = A[\frac{\sigma_y+(1+\eta)\sigma_e}{2} - \sqrt{(\frac{\sigma_y+(1+\eta)\sigma_e}{2})^2 - \sigma_y\sigma_e}\ ]...\ (3)$$

where

P_{cr}: critical axial load that leads to buckling in column (N).

Ƞ is a constant depending on the material.

For a brittle material

Ƞ = 0.015 L/r

For a ductile material

$\eta=0.3(\frac{L_e}{100r})^2$

Le = effective length of pinned end strut= Le = KL

K= end fixity constant. Fig.2 gives the theoretical and experimental Value of K for different end fixity.

r=radius of gyration = $\sqrt{\frac{I}{A}}$

σ_e= Euler buckling stress = $\frac{\pi^2 E}{(L_e/r)^2}$ (MPa)

σ_y=compressive yield stress (MPa)

The Slenderness Ratio (S. R)

S. R. is the ratio of the effective length to its least radius of gyration.

$$Sr = \frac{Le}{r} = \frac{kL}{r} \qquad (7)$$

The Column constant (Cc).

Cc may be defined as

$$Cc = \sqrt{\frac{2\pi^2 E}{\sigma_y}}$$

Where

E = modulus of elasticity of column material.

σ_y= yield stress of the material.

It is clear that the column constant depends on the mechanical properties of material used.

Column are divided into three categories, i.e short column, long column and columns of intermediate length. When the actual (S.R.) for a column $\frac{KL}{r}$ is less than the column constant (Cc) then the column is short. In this research. Experimental examination of the fixed-pinned case will be adopted. see Fig 2-c [11].

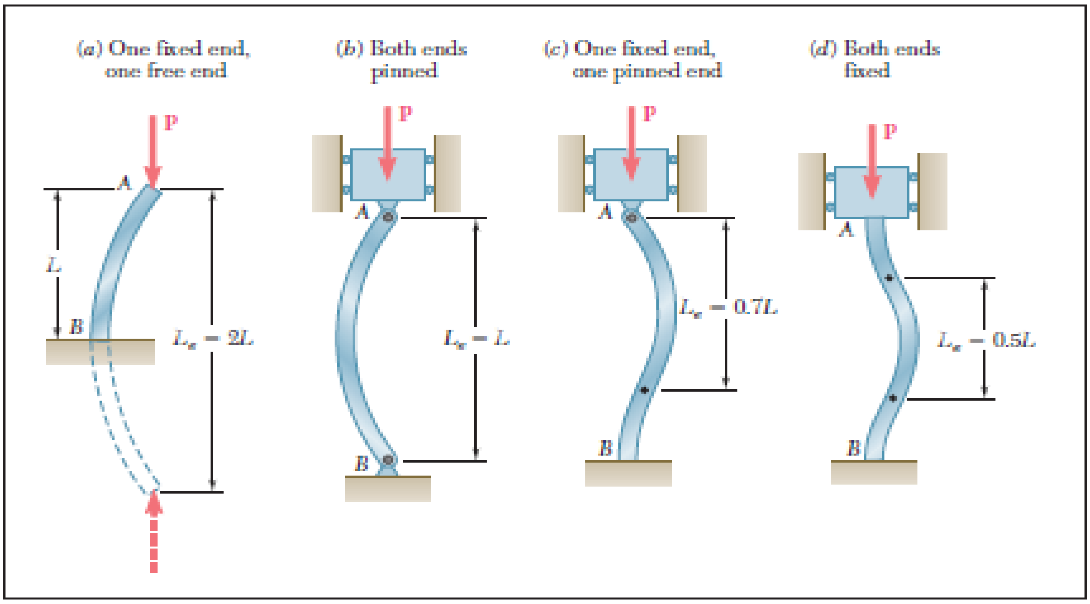

Figure 2: The types of end fixity [11]

3. Experimental work

3.1 Chemical composition

The chemical composition of Al 6061-T4 was shown in Table 1, this chemical test was completed in Company State for Engineering Rehabilitation and Inspection (SIER). The results, which are compared to the American standard.

Table 1: Chemical composition of 6061-T4 aluminum alloy (wt %)

6061-T4 Aluminum alloy	Cr%	Cu%	Fe%	Mg%	Mn %	Si%	Ti%	Z%	Al
Standard	0.04-0.35	0.15-0.4	Max 0.7	0.8-1.2	Max 0.15	0.4-0.8	Max 0.15	Max 0.25	Rem
Experimental	0.29	0.22	0.45	0.62	0.09	0.62	0.11	0.19	Rem

3.2 Buckling dimensions of the specimens

Two types of buckling specimens were prepared, long and intermediate. The material was received as columns of 6, 8, 10 mm in diameter (d). The dimensions of the specimens used are shown in Figure 3. The specimens used in testing of buckling were received in the form of rods of 6061-T4 aluminum alloy, in different lengths of submitted samples.

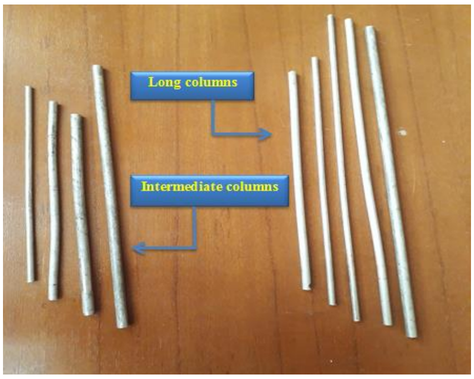

Figure 3: Buckling specimen for long and intermediate columns.

Table 2: Gives the dimensions of solid specimen used for 6061-T4 Aluminum alloy

Sp No	L mm	Le mm	D mm	r mm	I mm^4	A mm^2	SR	Cc	Type of column
1	400	280	10	2.5	490.87	78.53	112	105	long
2	400	280	8	2	201.06	50.26	140	105	
3	300	210	8	2	201.06	50.26	105	105	
4	400	280	6	1.5	63.61	28.27	186.66	105	
5	300	210	6	1.5	63.61	28.27	140	105	
6	200	140	8	2	201.06	50.26	70	105	intermediate
7	300	210	10	2.5	490.87	78.53	84	105	
8	200	140	10	2.5	490.87	78.53	56	105	
9	200	140	6	1.5	63.61	28.27	93.33	105	

3.3 Specimens Test Environment

Two groups of buckling specimens used in this study. Group (1) as received (without corrosion). Group (2) corroded specimens, which embedded in soil Figure 4. for 60 days and then subjected to increased buckling load. The chemical analysis of the soil was conducted in Iraq Geological survey, where the test results were (So3= 0.20 %), (PH= 6.6) and (T.D.S = 0.5 %).

3.4 Buckling test

6061-T4 aluminum alloy columns were tested by rotating buckling machine which is able to buckle the columns by apply axial compression load (The buckling machine is located in the strength laboratory in the Department of Electromechanical Engineering at the University of Technology). The numbers of specimens used in the dynamic axial compression test were 18 samples. 9 non-corroded columns tests were performed under an increased axial dynamic compression load, while the corrosion test was applied using 9 samples were buried for 60 days underground before testing. Column ends support of fixed-pinned with rotating speed of 17 rpm were adopted. All machine details can be found in the Ref [14]

3.5 Failure Definition

One percent of the specimen length is the allowable lateral deflection. When the lateral deflection of the specimen reaches this ratio and does not exceed it, the column returns to its normal state when the axial load is removed. This is called the critical buckling of the columns. When lateral deflection exceeds this ratio (1%L), the sample fails [13].

Figure 4: specimens in soil

4. Results and discussion

4.1 Tensile test results

The tensile test was completed using the WDW-200E tensile testing machine with a capacity of 200KN. The testing machine is located in the Materials Engineering Department at the University of Technology. Then, the mechanical properties of the (6061-T4 aluminum alloy) are obtained according to American Society for Testing and Materials (ASTM A370). Tensile sample dimensions are listed in Fig.5.

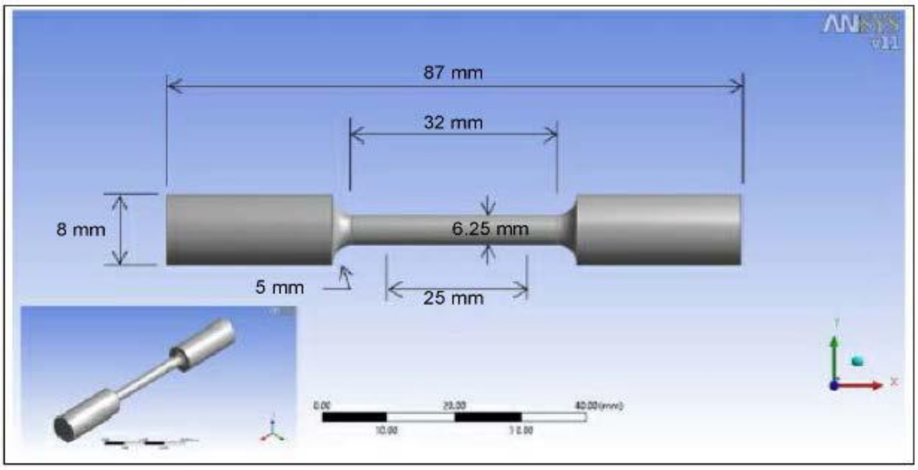

Figure 5: Tensile test sample with dimensions

Table 3: Tensile tests for non-corroded and corroded specimens of 6061-T4 Al-alloy.

6061-T4 Aluminum alloy	σ_u (MPa)	σ_y (MPa)	E (GPa)	G (GPa)	Poi. Ratio (μ)
Standard	252	145	68.9	26	0.33
AS received	241	149	71	27	0.32
60 days	237	143	68	26	0.33

It can be seen from Table 3, that corrosion eliminates the strengths of the material and affect the surface quality of a structure. It is clear that the results of corroded specimens are lower than that of non-corroded specimens this is due to corrosion affects the mechanical properties of metals and reduces the modulus elasticity. Increasing the corrosion time leads to reduce the mechanical properties. The specimens (three specimens) of 60 days corroded having 2.7 % reduction compared to the non-corroded specimens. These results agree with what was found by Ref [9].

4.2 Buckling Test Results

Table 4 presents the experimental results of the dynamic buckling test of (6061-T4 aluminum alloy) for long and intermediate column specimens without corrosion effect (as received). They also, show the experimental results of buckling test of corroded columns (group2). It can be seen from Table 4 that the corrosion leads to reduction in the critical buckling load. The buckling life (cycle) of pre-corroded column specimens decreased compared with that of without corrosion specimens. It appears that the corrosion condition at 60 days gives a small reduction of dynamic buckling resistance for the specimen of (group 2) compared with without corrosion columns specimen (group 1).

Table 4: Corrosion-buckling interaction for long and intermediate columns (fixed-pinned)

Sp No	L mm	D mm	AS received			60 day corrosion			Reduction in critical buckling load for 60 days %	Type of column
			P_{cr} (N)	δ_{IN} mm	δ_{cr} mm	P_{cr} (N)	δ_{IN} mm	δ_{cr} mm		
1	400	10	4592	0.52	4.3	4512	0.52	4.3	1.77	long
2	400	8	1554	0.8	4.3	1530	0.8	4.3	1.56	
3	300	8	2260	0.5	3.6	2212	0.51	3.6	2.1	
4	400	6	494	1.3	4.2	473	1.31	4.2	4.25	
5	300	6	812	0.7	3.7	779	0.7	3.7	4	
6	200	8	3532	0.6	3.1	3413	0.62	3.1	1.75	intermediate
7	300	10	5652	0.5	2.6	5553	0.5	2.62	1.9	
8	200	10	8478	0.3	2.3	8316	0.3	2.3	3.3	
9	200	6	1659	0.6	2.4	1636	0.6	2.4	1.38	

The effect of corrosion can be clearly noted on the dynamic buckling loads as reported in The table 4. The values of these buckling properties are reduced by about 2.36% to 5.7% for 60 days for long corroded columns and from 1.81% to 4.2% for 60 days of the intermediate corroded columns respectively. The maximum reduction has occurred at long column of dimensions (L= 400, D = 6 mm).

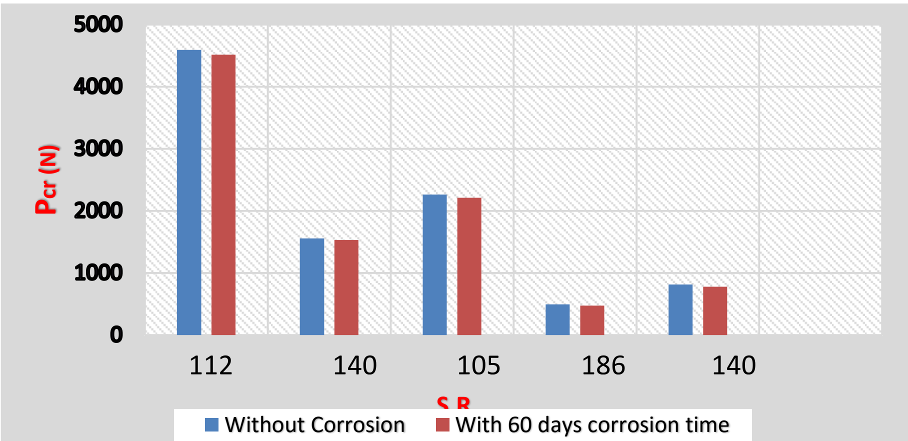

Figure 6: Corrosion-buckling interaction for long columns

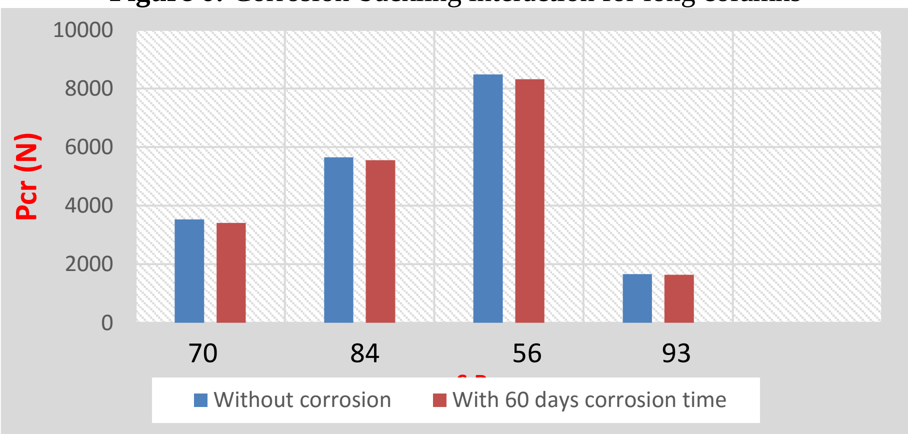

Figure 7: Corrosion-buckling interaction for intermediate columns

4.3 Application of Perry- Robertson formula

When comparing the Perry-Robertson results as shown in Table (5) with the experimental value of the critical load without corrosion, the prediction of Pcr due to Perry-Robertson (PR) is not satisfactory but if a factor of safety equals to (1.2) is used, this will give safety estimation for Pcr under dynamic loading.

Safety Factor $=\frac{Pcr\ (perry-Robertson)}{Pcr\ (Expermental)}$

Table 5: Comparison between Perry-Robertson results with experimental critical load value for long and intermediate columns

Sp No	L mm	D mm	P_{cr} Exp (N)		P_{cr} (Perry-Robertson) (N)		P_{cr} (Perry-Robertson) (N) with S.F of 1.2		Type of column
			AS received	60 days	AS received	60 days	AS received	60 days	
1	400	10	4592	4512	3641	3489	3034	2907	Long
2	400	8	1554	1530	1554	1462	1295	1218	
3	300	8	2260	2212	492	469	410	390	
4	400	6	494	473	2625	2515	2187	2095	
5	300	6	812	779	858	822	715	685	
6	200	8	3532	3413	6042	5788	5035	4823	Intermediate
7	300	10	5652	5553	5025	4821	4187	4017	
8	200	10	8478	8316	9638	9281	8031	7734	
9	200	6	1659	1636	1821	1745	1517	1454	

For S.R. greater than 105 the column may change to be long column. The value equal to 51 MPa can limit the type of column, i.e. greater than 51 MPa columns are said to be long and less than this value are called intermediate columns. Figure (10) displays the relation of stress at failure and slenderness ratio as presented by Perry-Robertson formula (3) for a long and intermediate columns compared with experimental result made of (6061-T4 aluminum alloy) with one end pinned and the other fixed (K = 0.7), having a yield strength of = 149 MPa. These results coincide with what was finding by ref [11], [14].

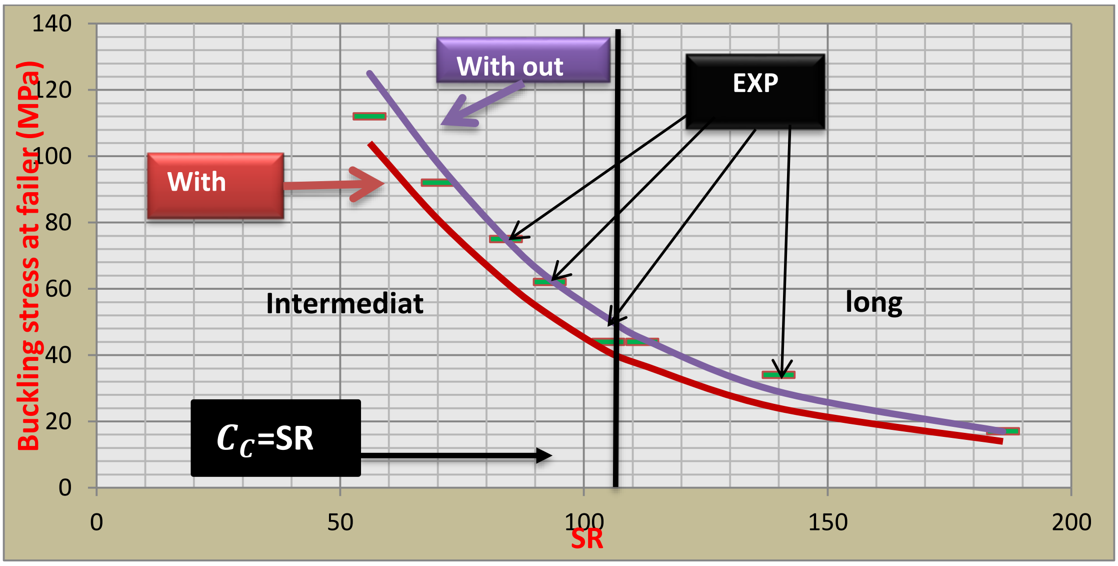

Figure 8: Perry-Robertson curve with the experimental results for 6061-T4 aluminum alloy

4.4 Application of Euler and Johnson Formulas to the Experimental Data

Euler's and Johnson's theories can be used for appreciation of critical stress, and it can be useful in the early stages of the design process. This study divides members into intermediate and long length, where Johnson's equation is valid with intermediate length and Euler's equation is valid for long members. The tangent point between Euler curve and Johnson curve for 6061-T4 aluminum alloy member with a yield stress of 149 MPa is S.R. = 105. Intermediate columns are defined by the minimum slenderness ratio, which equal to 56 for 6061-T4 aluminum alloy. Both defined as long members, i.e. Euler equation can be used but it should be noted that they are also within Johnson validations area. Johnson's equation estimates the critical buckling stress for the test parts to be lower than the critical buckling stress estimated with Euler's equation.

Table (6): Comparison between Euler-Johnson results with experimental critical load value for long and intermediate columns

Sp No	L mm	D mm	P_{cr} Exp (N)		P_{cr} Euler-Johnson (N)		P_{cr} Euler with S.F (N) of 1.5		Type of column
			AS received	60 days	AS received	60 days	AS received	60 days	
1	400	10	4592	4512	4387	4194	2924	2797	**Long**
2	400	8	1554	1530	1797	1720	1198	1146	
3	300	8	2260	2212	568	539	378	359	
4	400	6	494	473	3194	3058	2129	2038	
5	300	6	812	779	1010	958	673	638	
6	200	8	3532	3413	7312	7011	4874	4674	**Intermediate**
7	300	10	5652	5553	5538	5311	3692	3540	
8	200	10	8478	8316	9750	9358	6500	6238	
9	200	6	1659	1636	2261	2160	1507	1440	

Figure 9 displays the relation of stress at failure and slenderness ratio (SR) as presented by Euler and Johnson formulas for a column that made of (606l-T4 Aluminum alloy) with one end pinned and the other is fixed (K = 0.7), having a yield strength of σy= 149 MPa

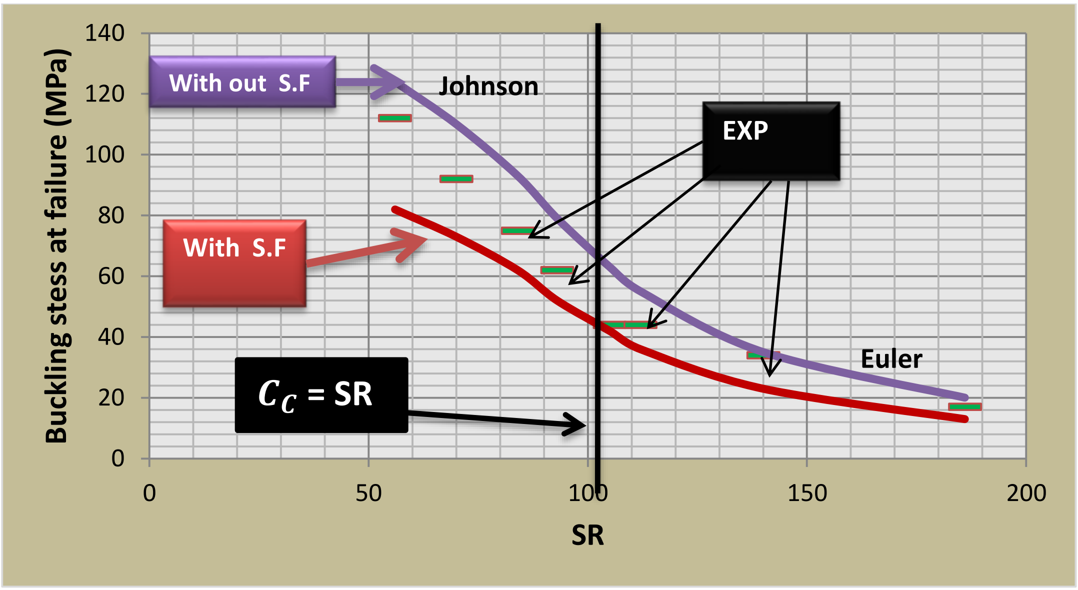

Figure 9: Johnson-Euler curve with the experimental results for 6061-T4 Aluminum alloy

4.5 Comparison between ANSYS and Experimental methods

Numerical model using ANSYS package was employed and its results were compared with the experimental results. Tables 7 give the percentage discrepancy between the experimental and numerical results for S.F = 1.1. The differences might be attributed to some reasons such as, the assumption made in the ANSYS package17 and the difficulties to control the measurement in the experimental work and some error may occur when reading the experimental data.

Table 7: Comparison between ANSYS results with experimental critical load value for long and intermediate columns

Sp No	L mm	D mm	P_{cr} Exp (N)		P_{cr} ANSYS (N)		P_{cr} Euler with S.F (N) of 1.1		Type of column
			AS received	60 days	AS received	60 days	AS received	60 days	
1	400	10	4592	4512	4377	4192	3979	3810	**Long**
2	400	8	1554	1530	1668	1592	1516	1447	
3	300	8	2260	2212	2243	2109	2039	1917	
4	400	6	494	473	520	496	472	450	
5	300	6	812	779	895	853	813	775	
6	200	8	3532	3413	3498	3343	3180	3039	**Intermediate**
7	300	10	5652	5553	6015	5687	5468	5170	
8	200	10	8478	8316	9052	8317	8229	7560	
9	200	6	1659	1636	1778	1691	1616	1537	

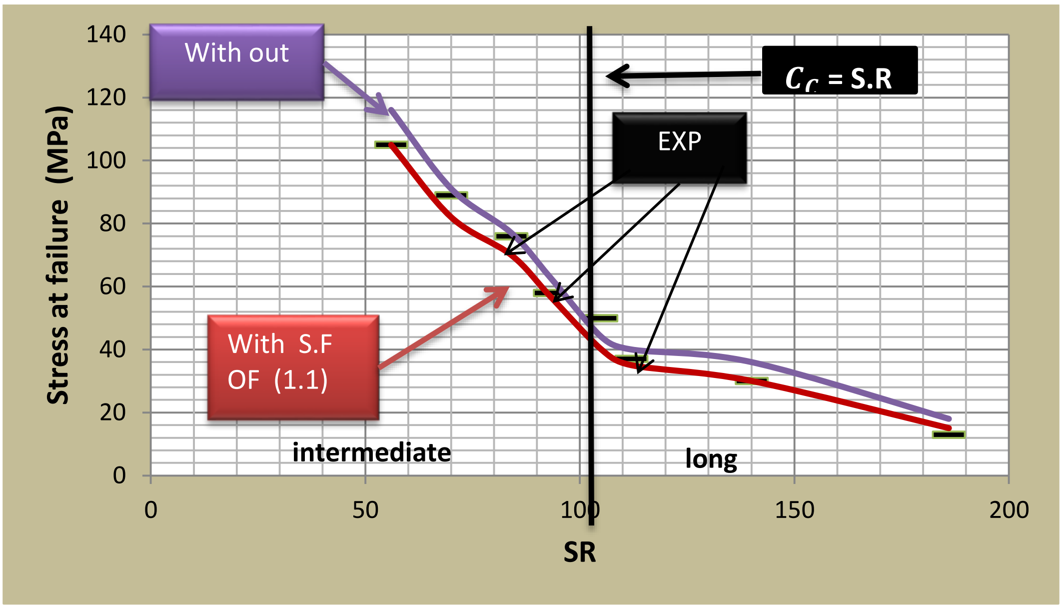

Figure 10: ANSYS curve with the experimental results for 6061-T4 aluminum alloy.

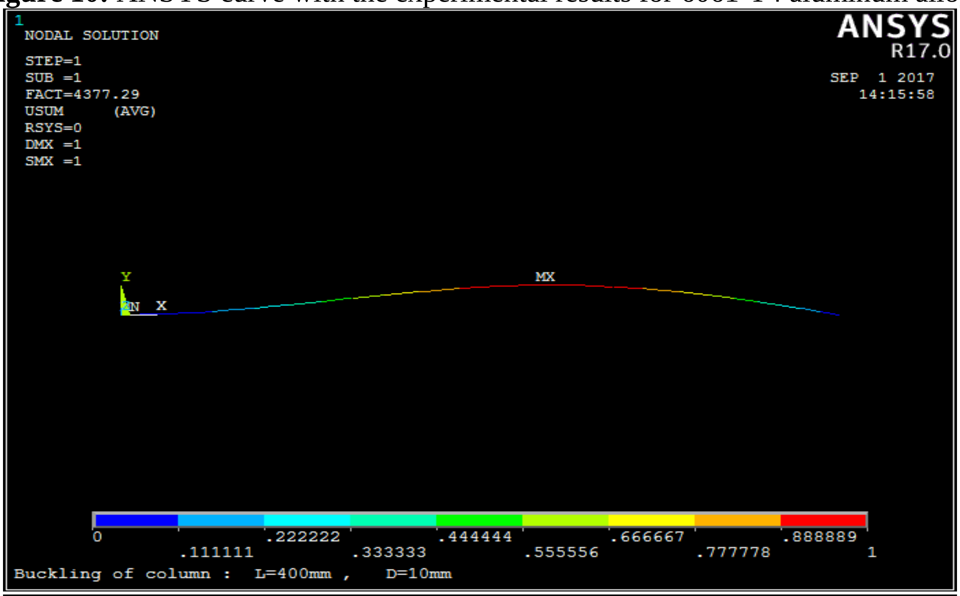

Figure 11 The deflection shape for Lateral buckling for long column.

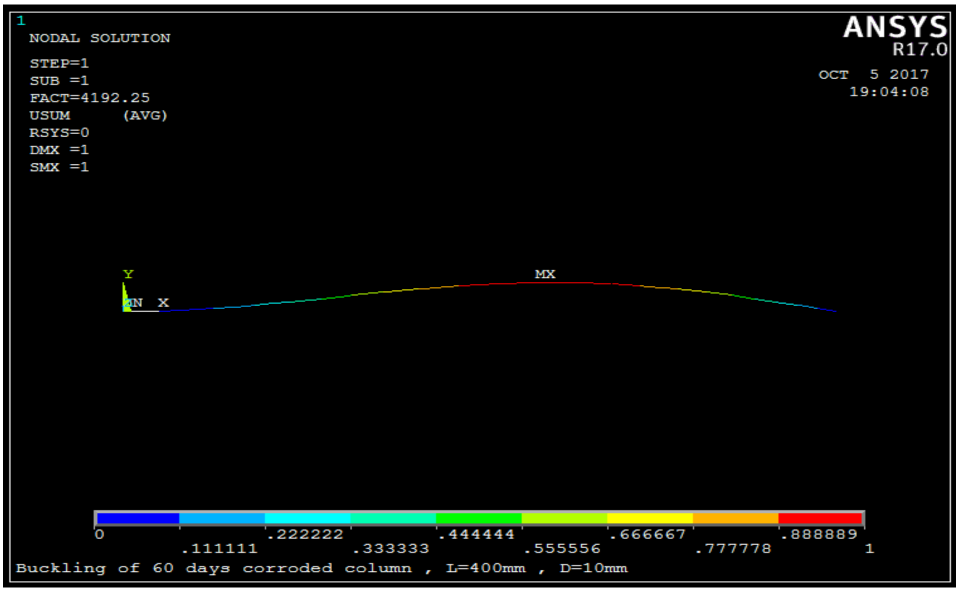

Figure 12: The deflection shape for Lateral buckling for 60 days corroded columns.

5. Conclusions

The effect of corrosion time (60 days) on the buckling behavior was investigated for 6061-T4 aluminum alloy columns. The following conclusions can be drawn:-

1- Increasing the corrosion time leads to reduce the mechanical properties. The specimens of 60 days corroded has 2.7 % reduction compared to the non-corroded specimens.

2-The corrosion time reduces the critical load such as the range reduction was from 2.36% to 5.7% for 60 days for long corroded columns and from 1.81% to 4.2% for 60 days for the intermediate corroded columns.

3-The Perry-Robertson formula gives an approximation of the experimental results but with a safety factor of 1.2 that gives more satisfied expectations.

4- The Euler equation for the long columns and Jenson for the short and intermediate columns give unsatisfying results compared with the experimental results for the critical buckling but with a safety factor of 1.5 it is giving accurate results.

5-ANSYS program used in calculating the buckling stresses showed good agreement in comparison with the analytical and experimental results, with a 1.1 factor of safety.

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Nomenclature	Definition	Units
σ_y	Yield stress	(MPa)
σ_u	Ultimate stress	(MPa)
L	Total column length	(mm)
Le	Effective column length	(mm)
I	Moment of inertia	(mm^4)
Cc	Column constant	
A	Cross section area	(mm^2)
D	Diameter of column	(mm)
E	Modulus of elasticity	(GPa)
r	Reduce of gyration	(mm)
δ_{in}	Initial column deflection	(mm)
δ_{cr}	Critical deflection	(mm)
P_{cr}	Critical buckling load	(N)
S.R	Slenderness ratio	
APDL	ANSYS Parametric Design Language	

تأثير التآكل تحت الأرض على الانبعاج الجانبي لأعمدة سبيكة الالمنيوم (6061- T4) تحت تأثير زيادة الاحمال

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الخلاصة

يتناول هذا البحث مدى تأثير التآكل على سلوك الانبعاج الجانبي لسبيكة الالمنيوم (T4- 6061) تحت زيادة احمال الضغط الديناميكية. تم استخدام نوعين من الأعمدة، طويلة و متوسطة. 1٪ من طول العمود هو الانحراف الجانبي المسموح به. ولغرض حساب الانحراف الأولي، استخدم جهاز (digital) dial gauge وتم تثبيت المقياس على بعد 0.7 من طول العمود من جهة التثبيت. وأظهر التحليل التجريبي أن زيادة وقت التآكل يؤثر سلبا على الخواص الميكانيكية للمعادن . فكان معدل النقصان في اقصى اجهاد للعينات المدفونة 60 يوما (اقل وقت لملاحظة وقت التأكل في التربة) هو ٪ 2.7 مقارنتا مع العينات غير المتآكلة ، كما ان زيادة وقت التآكل يقلل من الحمل الحرج مثل أقصى نقصان كان ٪ 4.24 في حمل الانبعاج الحرج لعينات مدفونة 60 يوما في التربة. تم مقارنة النتائج التي تم الحصول عليها تجريبيا مع الصيغ النظرية لبيري- روبرتسون و صيغة يولر- جونسون ومع نتائج برنامج (ANSYS). وقد وجد أن صيغة بيري- روبرتسون أبدت توافق جيد مع النتائج التجريبية مع عامل أمان 1.2، وكانت صيغة يولر- جونسون مناسبة للنتائج التجريبية مع الاخذ بعامل أمان 1.5 . نتائج برنامج (ANSYS) أظهرت توافق جيد بين القيم المقاسة والمحسوبة مع أخذ عامل امان 1.1