CORROSION – BUCKLING INTERACTION OF 6061-T4 AL ALLOY FIXED – PINNED COLUMNS – EXPERIMENTAL STUDY

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ABSTRACT:

Compression buckling experimental tests was carried out for long and intermediate columns made of 6061-T4 AL- alloy. Two different soil corrosion time were adopted i.e.30 days and 60 days using 27 samples. The experimental analysis revealed that increasing the corrosion time negatively affects the mechanical properties of metals such as the specimens of 60 days corroded have 1.68% reduction in ultimate strength, also increasing the corrosion time reduces the critical load such as the maximum reduction was 4.24% in critical buckling load for 60 days corrosion time. Perry-Robertson theory was applied to the experimental data and it was found that the above theory can satisfactory predicted the critical buckling load (Pcr) with a factor of safety equal to 1.2. The ratio of corroded Pcr to dry Pcr was always less than unity. This indication explains the effect of pitting corrosion on buckling behavior of 6061-T4 AL- alloy.

KEY WORDS: Buckling , corrosion , Slenderness Ratio , 6061-T4 AL-alloy experimental,

الانبعاج المقترن بالتاكل للالمنيوم(Al6061-T4) للاعمدة المثبتة – المتمفصلة . دراسة عملية

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الخلاصة

أجريت اختبارات ضغط الانبعاج الجانبية للأعمدة طويلة و متوسطة مصنوعة من سبائك الالمنيوم 6061-T4 تم اعتماد وقتين مختلفين لتأكل التربة أي 30 يوما و60 يوما باستخدام 27 عينة. وأظهر التحليل التجريبي أن زيادة زمن التآكل يؤثر سلبا على الخواص الميكانيكية للمعادن فكان انخفاض العينات المدفونة 60 يوما في التربة بنسبة 1.68% في اقصى اجهاد ، كما أن زيادة زمن التآكل يقلل من الحمل الحرج مثل اقصى نقصان كان 4.24% من الحمل الحرج الانبعاج لمدة 60 يوما من وقت التآكل. تم تطبيق نظرية بيري-روبرتسون على البيانات التجريبية ووجد أن النظرية المذكورة أعلاه يمكن أن تكون مرضية لتنبؤ بالحمل الحرج للانبعاج الجانبي (Pcr)مع عامل أمان يساوي 1.2 كانت نسبة Pcr المتآكل إلى Pcr الجاف دائما أقل من الوحدة. هذا الدلالة يفسر تأثير تأليب التآكل على سلوك الانبعاج لسبائك الالمنيوم 6061-T4 .

Received : 2017- 8 - 17
Accepted : 2018 - 1 - 28

Nomenclature	**Definition**	**Units**
σy	Yield stress	(MPa)
σu	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)
δin	Initial column deflection	(mm)
δcr	Critical deflection	(mm)
Pcr	Critical buckling load	(N)
S.R	Slenderness ratio	

INTRODUCTION

Stability is one of the most critical limit states for columns through construction and through their service life. One of the most difficult challenges in structural stability is limiting the critical load under which a structure collapses due to the loss of stability; this is because of the complexity of this phenomenon and the many material properties that are affected by geometric and material imperfections and material nonlinearity [Pedro Fernandez , 2013].Buckling is a phenomenon, where a structure suddenly changes from one equilibrium configuration to another equilibrium configuration. The computation of buckling loads of a structure is of great significance, due to the possibility of unexpected failure of the structure, if the critical buckling load is reached. Some structures might lose all stability when the buckling load is reached, which could put people at danger if a roof or other similar structures lose all stability [Allan and Kasper,2012].One of the most important points in the design of structures and columns is to conduct the calculations of the maximum load that the structure or the structure bears accurately approaching reality. This precision in the calculations is highly dependent on the mathematical model used in the analysis process. When this model is represented in the case of elasticity, the accuracy will be greater in the analysis process. In single-load structures, accuracy can be obtained using simplified numerical methods to calculate the effect of plasticity. In general, the structure or column will fail because the material is subjected to stress when it reaches a higher limit than materiality. The columns with larger lengths will fail because of the spike and this is caused by a load called pregnancy critical make this column fails suddenly.[Al-Ani,2005]. Corrosion impairs structure safety and is a leading factor in the catastrophic failure of bridges, nuclear facilities, airplane components, . Corrosion is a indeterminate, slow-developed phenomenon. It is influenced by important factors such as metal, environment and electrochemical properties. Because it takes a long time to estimate the range of corrosion, it is often underestimated in industrial equipment and structure design [Branko,2015]. Aluminum alloy has been applied widely in construction all over the world such as bridge, buildings and other special structures. Because Aluminum alloy has excellent advantages such as light weight, good corrosion resistance, high strength to weight ratio and good low-temperature behavior .for these reasons aluminum alloys become more popular in structural engineering [Yuan ,2015].

[Dongming Wei et al, 2013 **],** studied the critical buckling loads for Euler columns of different materials with different geometries and boundary conditions. The experimental results of the critical buckling loads were less conservative compared with the results of Euler - Engesser′s reduced loads. [Amir et al , 2012] , studied the buckling of the beams under combined loading of the axial and side bending loads with three axial load application configurations for the same beam. The experimental results of the critical buckling load obtained experimental were compared with the finite element method and it was observed that the results of the two methods are well agreed**.** [Al-Alkawi et al ,2016] presented some main experimental results of dynamic buckling under increasing compression load. The buckling of 304 stainless steel was inspected using Euler and Johnson formulas, which is the most commonly used in industrial applications. It has been proving that metallic materials can exhibit nonlinear buckling behavior with mechanical properties dependency. This attitude yields a nonlinear model which depends on Hong’s model but using the mechanical properties with cycles to failure. It was observed that the proposed model gave safe predictions while Hong’s model yields non-satisfactory predictions of critical buckling loads and also design electrical LASER alarm system to avoid the failure occurs in the specimen when access to critical buckling load. [Katalin Oszvald and László Dunai, 2012] studied the influence of corrosion on the buckling behavior and resistance of corroded steel angle section members. The site of corrosion and loss of cross section was studied through practical experiments. Compressive buckling test was performed on 24 samples. It was found that resistance to buckling is reduced due to corrosion at a different rate. **[**Kashani et al **,** 2016**]** presented that enables simulation of the nonlinear flexural response of corroded reinforced concrete (RC) components by using a numerical model. The model uses a force-based nonlinear fibre beam-column element. This model calculates for the impact of corrosion on buckling strength, postbuckling behaviour, and low-cycle fatigue degradation of vertical strengthening under cyclic loading. **[**Uwiringiyimana et al ,2016**]** summarized the effect of inhibitors on the corrosion of stainless steels and aluminum alloys in various media. the degeneration in stainless steels and aluminum alloys materials because of The exposure of they to corroding environments. Inhibitors are used to reduce the corrosion of these alloys in deferent corrosive media and increase their durability.

In this work, evaluated the effect of corrosion time on the underground columns made of aluminum alloy, as well as the impact of corrosion on the mechanical properties of the metal and its impact on the critical buckling load . In addition, the Perry- Robertson formula was used to determine the extent of its agreement with the experimental results .

Theory

Perry-Robertson formula

The Perry-Robertson proof is based on the assumption that any imperfections in the strut, through faulty workmanship or material or eccentricity of loading, can be allowed for by giving the strut an initial curvature. For ease of calculation this is assumed to be a cosine curve, although the actual shape assumed has very little effect on the result. the critical buckling load due to perry –robertson can be described by the equation [Hearn, 1997]

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

where
P_{cr}= critical axial load that leads to buckling in column (N).
η is a constant depending on the material.
For a brittle material
$\eta = 0.015$ L/k
For a ductile material

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

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

r=radius of gyration = $\sqrt{\frac{I}{A}}$ (3)

σ_e= Euler buckling stress $= \frac{\pi^2 E}{(L_e/r)^2}$ (Mpa) (4)

σ_y=compressive yield stress (Mpa)
K= end fixity constant. Fig.1 gives the theoretical and experimental Value of K for different end fixity .

The Slenderness Ratio (S. R.)

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

Sr $= \frac{Le}{r} = \frac{kL}{r}$ [Fadhil ,2014] (5)

The Column constant (Cc).

Cc may be defined as

Cc $= \sqrt{\frac{2\pi^2 E}{\sigma_y}}$ [Fadhil ,2014] (6)

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, we will examine the case of (Fixed-Pinned) see fig (1-C) [Fadhil ,2014] .

EXPERIMENTAL WORK

Chemical composition

Chemical analysis of the material used was done at S.C. of Geological survey and mining using X-Rays method. The results, which are compared to the American standard, are summarized in table (1).

Tensile properties

The mechanical properties of (6061-T4 aluminum alloy) were obtained according to ASTM A370 specification. The tensile specimen can be shown in fig. (2)
The experimental results are the average of three specimens. The tensile tests are done in university of technology-material engineering department, are summarized in table (3)

Buckling Dimensions of the Specimens

For 6061-T4 Aluminum alloy the Table (2) illustrates the dimensions of the specimens used. The selection of the above dimensions is designed to study the corrosion -buckling interaction for both columns , long and intermediate in order to compare between them.

buckling test

6061-T4 aluminum alloy columns with and without corrosion 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) as shown in fig(4) .Column ends support of fixed-pinnd with rotating speed of 17 rpm were adopted .

Specimens Test Environment

There are two groups of buckling specimens that use in this study .Group(1) as received (without corrosion) . Group (2) corroded specimens, which embedded in soil for (30, 60) days and then subjected to increasing buckling load. See fig(3)

Failure of buckling specimen

The value of critical buckling load (p_{cr}) was defined when the maximum deflection of specimen reached the critical value (δ_{cr}) which is equal to (1%) of the specimen length plus initial deflection (δ_{in})[Al-Alkawi,2016] .For more accuracy, the deflection of column is measured using a dial gage and laser cell circuit tool with alarm sound fixed on digital vernier with accuracy 0.01 mm. figure(4) shows the failure circuit with the mechanical dial gauge.

RESULTS AND DISCUSSION

Tensile test results

Table (3) shows results of the tensile test for dry and corrosion state of (6061-T4 aluminum alloy) column specimens with an average of three readings. it can see that (table 3) corrosion eliminates the strengths of the material and effect on the surface quality of a structure, because of corrosion weakens the surface and decreasing its hardness and increasing the roughness.
It is clear that the results of corroded specimens are lower than that of un corroded member. Increasing the corrosion time leading to reduce the mechanical properties. The specimens (three specimens) of 30 days corroded have approximately 1.26 % reduction in

ultimate strength while the specimen with 60 days corroded having 1.68 % reduction compared to the un corroded specimens. These results coincide with what was finding by ref [Oszvald K .Dunal L , 2011].

Buckling Test Results

Table (4) presents the experimental results of dynamic buckling test of (6061-T4 aluminum alloy) column specimens without corrosion effect (as received). Also, shows the experimental results of buckling test of corroded columns (group2). It can be seen from Table (4), increasing in corrosion time leading to the reduction in critical buckling load increase also, the buckling life (cycle) of pre-corroded column specimens decreased compared with that of as reserved specimens. The reason for this finding is that the obstruction of column corroded surface to ensure the buckling load. 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 non-corroded columns specimen group 1.

It can be clearly noted the effect of corrosion on the dynamic buckling loads are reported in table (4). The value of these buckling properties are reduced by of about 0.05% to 3.1% and from 1.38% to 4.25% for 30 and 60 days corroded respectively. The maximum reduction was occurred at long column of dimensions (L= 400, D = 6 mm). Increasing the corroded time resulting for higher corrosion levels.

The corrosion phenomena strongly affects the buckling behavior of columns subjected to dynamic increase compression load . On the basis of the experimental results , it has to be remarked the importance of corrosion effects on the critical buckling loads. See fig (5,6).

Application of Perry- Robertson formula

When comparing the berry-Robertson result with the value of the critical load experimental without corrosion , The prediction of Pcr due to Perry-Roberston (PR) is not satisfactory but if a factor of safety equal to 1.2 gave safety estimation for Pcr under dynamic loading. See table (5) **. Corroded** specimens contain localized pitting corrosion as shown in figure (7) .This means that the corroded cross-sectional area of column is always less than that of un corroded one. This reason leads to rise the stress concentration factor resulting in column resistance table(6).

Table (7) shows a comparison between non-corroded and 60 days corroded columns. This table indicates that increasing the experimental Pcr leading to increase the amount of the column resistance due to corrosion . Katalin and Dunai [9] found that the Pcr (60 days) / Pcr (dry) for some specimens taking the values of o.89 , o.98 , 0.93 ,0.98. These values represents the reduction in buckling resistance due to pitting corrosion . the results of the above table are well agreed with the findings of Ref [Katalin Oszvald and László Dunai , 2012].

CONCLUSIONS

1-The critical dynamic buckling loads of 27 dry and corroded columns were obtained experimentally under increasing loads.

2- The experimental data obtained above were compared to the Perry-Robertson theory prediction and it was found that good correlation has been observed for both dry and corroded columns with factor of safety equal 1.2

3- Increasing the corroded time reducing the critical buckling strength . The value of these buckling properties are reduced by of about 0.12 % to 2.5% and from 2.36% to 5.7% for 30 and 60 days for long corroded columns respectively and from 0.22% to 1.69% and from 1.81% to 4.2% for 30 and 60 days for the intermediate corroded columns.

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

6061-T4 Aluminum alloy	**Al%**	**C%**	**C%**	**F%**	**Mg%**	**Mn %**	**Si%**	**Ti%**	**Z%**
Standard	95.8-98.6	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
Experimental	balance	0.29	0.22	0.45	0.62	0.09	0.62	0.11	0.19

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	

Table (3) Tensile tests non-corroded and corroded specimens of 6061-T4 AL-alloy.

6061-T4 Aluminum alloy	**σ_u (Mpa)**	**σ_y (Mpa)**	**E (Gpa)**	**G (Gpa)**
Standard	252	145	68.9	26
AS reserved	241	149	71	27
30 days	238	147	71	27
60 days	237	143	70	28

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

Sp No	**AS received**			**30 day corrosion**			**60 day corrosion**			**Reduction in critical buckling load %**		**Type of column**
	P_{cr} (N)	δ_{IN} mm	δ_{cr} mm	P_{cr} (N)	δ_{IN} mm	δ_{cr} mm	P_{cr} (N)	δ_{IN} mm	δ_{cr} mm	30 day	60 day	
1	4592	0.52	4.3	4578	0.6	4.21	4512	0.52	4.3	0.3	1.77	**long**
2	1554	0.8	4.3	1542	0.85	4.14	1530	0.8	4.3	0.77	1.56	
3	2260	0.5	3.6	2247	0.51	3.6	2212	0.51	3.6	0.57	2.1	
4	494	1.3	4.2	479	1.31	4.2	473	1.31	4.2	3	4.25	
5	812	0.7	3.7	799	0.7	3.7	779	0.7	3.7	1.6	4	
6	5652	0.6	3.1	5644	0.62	3.1	5553	0.62	3.1	0.14	1.75	**intermediate**
7	8478	0.5	2.6	8471	0.5	2.62	8316	0.5	2.62	0.08	1.9	
8	3532	0.3	2.3	3530	0.3	2.3	3413	0.3	2.3	0.05	3.3	
9	1659	0.6	2.4	1655	0.6	2.4	1636	0.6	2.4	0.24	1.38	

Table(5) : Comparison between Perry-Robertson result with experimental critical load value without corrosion

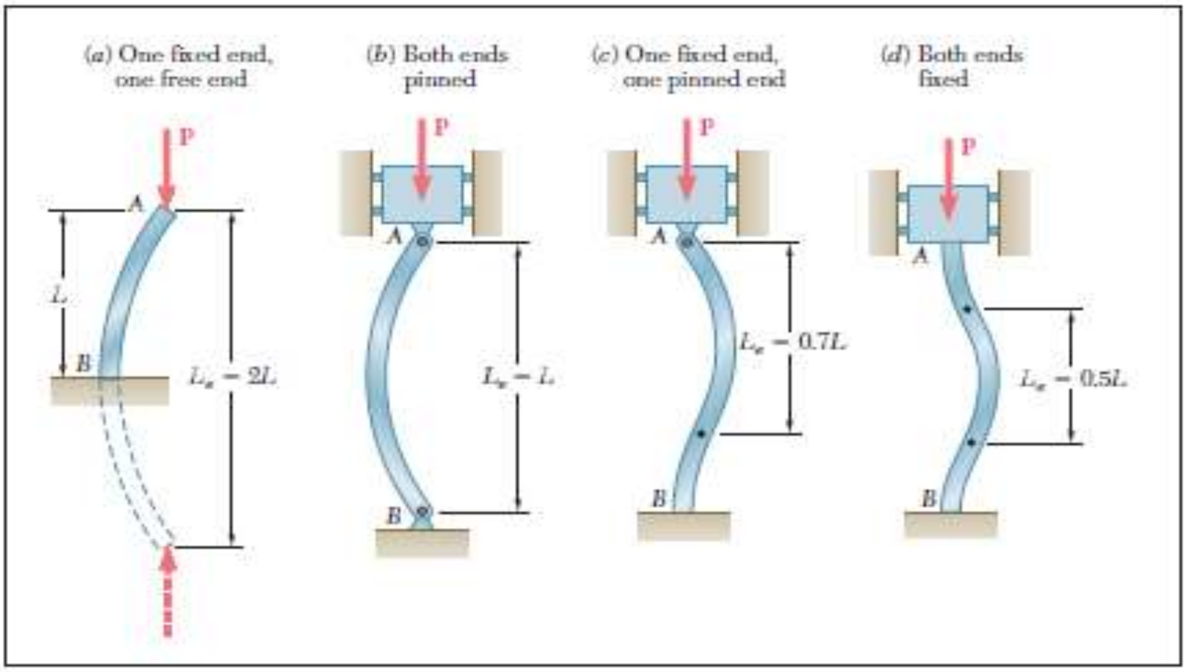
Specimen No	**P_{cr} Exp (N)**	**P_{cr} (Perry-Robertson) (N)**	**P_{cr} (Perry-Robertson) (N) with S.F**	**Type of column**
1	4592	3641	3034	**long**
2	1554	1526	1271	
3	2260	2625	2187	
4	494	492	410	
5	812	858	715	
6	5652	6042	5053	**intermediate**
7	8478	9638	8031	
8	3532	5025	4187	
9	1659	1821	1517	

Table (6) result of corroded-buckling specimens for long and intermediate columns

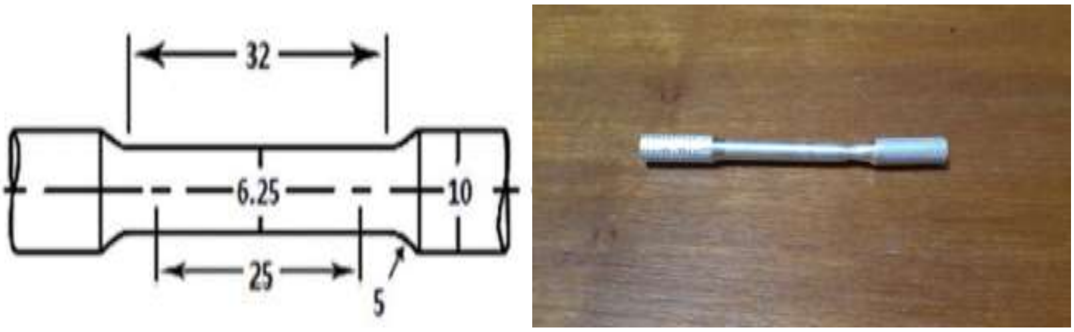
Specimen No	Pcr Exp(N)		Pcr (Perry-Robertson) (N)		Pcr (Perry-Robertson) (N) with S.F		Corrosion Time
	30 day	60 day	30 day	60 day	30 day	60 day	
1	4578	4512	3629	3567	3024	2972	**long**
2	1542	1530	1522	1500	1268	1250	
3	2247	2212	2616	2570	2180	2141	
4	479	473	489	481	407	400	
5	799	779	856	842	713	701	
6	5644	5553	6007	5892	5005	4910	**intermediate**
7	8471	8316	9566	9327	7971	7772	
8	3530	3413	4989	4811	5157	4009	
9	1655	1636	1814	1780	1511	1483	

Table (7) : comparison between dry and 60 days corroded columns

SP NO	Pcr (n) dry	Pcr 60days corrosion	Reduction in Pcr due to 60 day corrosion	Pcr (60 days)/ Pcr (dry)
1	4592	4512	80	0.982
2	1554	1530	24	0.984
3	2260	2212	48	0.978
4	494	473	21	0.957
5	812	779	33	0.959
6	5652	5553	99	0.982
7	8478	8316	162	0.980
8	3532	3413	119	0.966
9	1659	1636	23	0.986



Fig(1): The types of end fixity [Fadhil ,2014]



Figure(2) Tensile test specimen (all dimensions in mm) accorded to ASTM A370 specification

Figure (3) specimens in soil

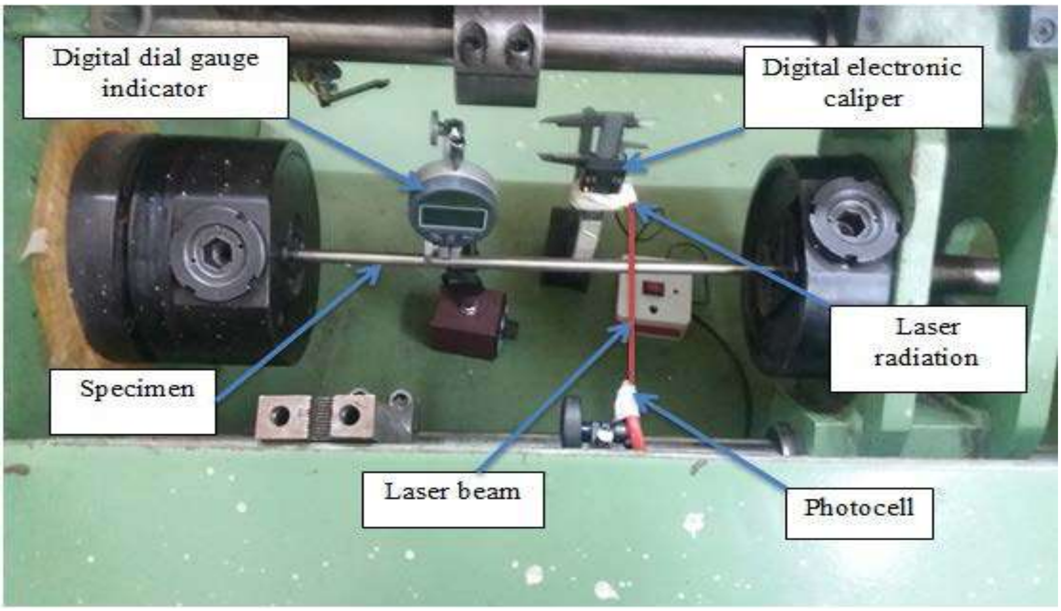
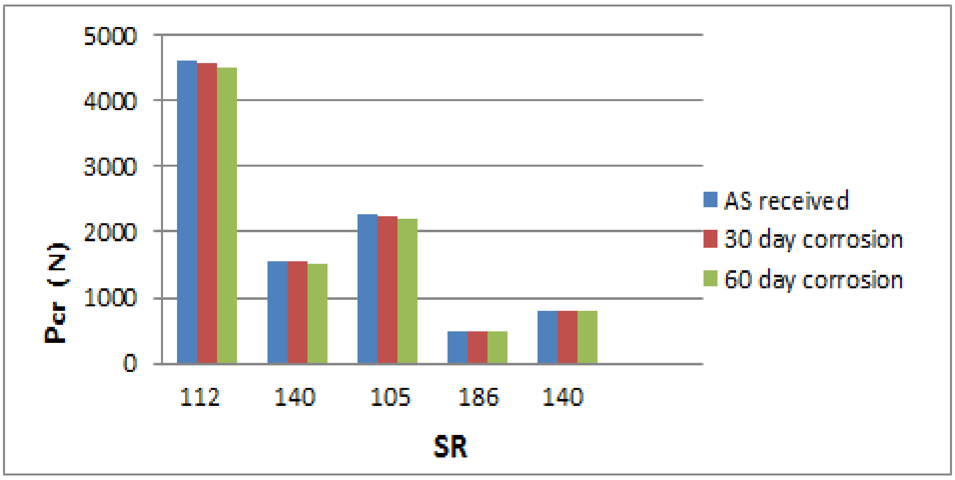


Figure (4) failure system with laser cell circuit



Figure(5): corrosion-buckling interaction for long columns

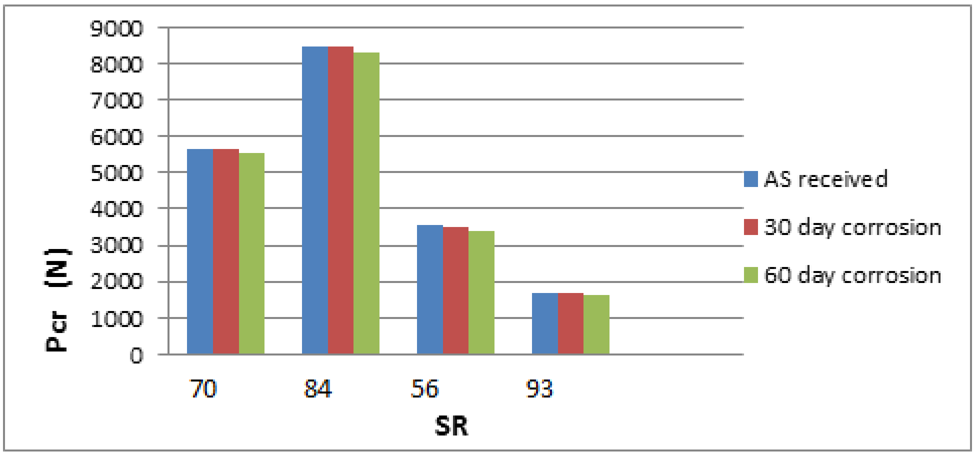


Figure (6): corrosion-buckling interaction for intermediate columns

Figure:(7) the specimens with pitting corrosion

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