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An appraisal of Rankine and Perry-Robertson buckling formula under the combined effect of corrosion –shot peening interaction for 304 stainless steel alloy

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Abstract

Seawater has been used to immerse metals in several industrial applications. Axial loading is applied to these alloys. These alloys are prone to corrosion failures due to differences in environmental conditions. This research looked at the effect of submerged corrosion on the buckling behavior of 304 stainless steel long column type and intermediate alloy under increasing compressive dynamic stresses. Compressive buckling experiments were performed on twenty-four 304 stainless steel alloy columns, twelve of which were non-corroded, and the tests were performed under increasing axial dynamical compression loads. Before testing, the remaining columns were submerged for 90 days. For the subterranean columns, a maximum decrease of percent in critical buckling loading was obtained. This work uses the Rankine, and Perry-Robertson formulas to calculate the critical buckling stress of non-corroded and corroded 304 stainless steel alloys. The theoretical conclusions of the critical buckling stress were in good accord with experimental data....

Keywords: : Corrosion, column buckling, 304 stainless steel, Rankine formula, Johnson formula, shot peening interaction

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1.Introduction

Structural stability calculations have long been an important engineering discipline. Particularly, since Leonard Euler estimated the significant buckling load for a prominently supported column in 1744, the determination of a significant structure's buckling load has been investigated. When a structure quickly transitions from one equilibrium condition to another, it is said to buckle. The structure breaking risk quickly if the significant buckling load is approached necessitates the computation of a structure's buckling loads. a few structures may lose their solidity if the buckling load is approached, placing individuals in peril. People may be put at safety if a roof or other comparable structures lose their support. [1]

The present manufacturing business places a premium on structural parts that are low in weight yet strong enough to absorb a lot of energy and carry a lot of weight. Shell constructions and shallow trusses make up these components. In terms of weight bearing capability, shell structures offer a major advantage. When a load is given to a shell, it can bend, twist, transverse shear, and buckle as a result of various internal forces. [2]

On the other side one of most prominent considerations in the buildings construction and columns is to bear the highly load accounts endures structure or origin precisely approximating reality. The mathematical model employed in the analysis process determines the accuracy of the calculations, and when this model is reported in the case of litheness - plasticity, the accuracy in the analysis process is the highest. By applying proven numerical techniques to determine the effect of a signified plasticity, precision may be achieved in buildings subjected to a single pregnancy. In general, when the focus material is strained above to a utmost limit of submission of the material, the structure or column will fail. This is true for columns with a short length. The buckling generated by this force is known as critical load pregnancy, and it causes the columns with the longest lengths to break abruptly. A ruler made of wood, plastic, or a thin metal rod can be used to demonstrate the buckling phenomenon, with the shed force progressively accumulating and then transmitted to a erect column, causing it to bend. As long as the column has not reached the undergo phase, when

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this force is removed, it will resume to its natural condition. The column will bend and fail if the stress value is fewer than the yield stress of the same column. The main purpose of estimating the assessment of buckling is to figure out what force or stress will cause the column to become unstable and buckle. [3]

Small mechanical characteristics for 304 stainless steel, which is extensively used in profitable, manufacturing, and home applications because to its outstanding heat resistance and corrosion resistance, will be validated in this study. Tanks and containers are used for various a assortment of liquids and solids progression tools in the mining, cryogenic, chemical, food, dairy, and pharmaceutical sectors, as well as drilling operations.[4]

2. Theoretical

The kind of structure, the type of load, and the nature of the materials used all have a role in determining the failure of structures. For example, the refined loading cycles may cause an axle in an automobile to break down abruptly. As a result, the structure's capacity to perform its intended purpose is compromised. The simplest way to prevent these kinds of failures is to design structures that stay within the maximum stress that can be sustained. As a result, the design's strength and stiffness are important considerations. Buckling is another form of failure that occurs as a consequence of structural volatility caused through axial compression on the structural part.[5]

Buckling happens when a column is subjected to an axial load and deflects as a result of the high stress. Buckling can lead to failure if the compressive force is strong enough. Buckling failure is not caused by the material since, once the loads have been applied, the objects returns to its original form as long as the resilient limits have not been exceeded [6].

3.Types of Columns

Columns are vertical components that are compressed axially. Short columns, long columns, and columns of intermediate length are the two, or rather three, types of columns. The slimness ratio of column the is the ratio of a column's length to its cross section's least radius of gyration (S.R). The slenderness ratio is included in all calculations used in the column analysis. The ratio decides whether the column is long, moderate, or short. The way the column is fixed, on the other hand, has an impact on its behavior. To establish the effective length, the long-term in the slenderness ratio must be modified. [7]

The effective slenderness ratio is when the effective column length equals the length of an corresponding pin-ended column with the similar load-carrying capability as the member in question, the effectual slenderness ratio is

S.R □KL/r□□□Le/r……………………………………………………(1)

Where

Le: effective length, taking into consideration how the ends are attached

r: the minimum radius of gyration, the gyration cross section, distinct as

$r = \sqrt{I/A}$ ……………………………………………………(2)

I: moment of inertia.

A: cross section area.

The thinness ratio is the primary predictor of the type of crash that can occur in a column under axial force. Lower slenderness ratios resulted in larger critical stresses, as seen in Figure (1) [8]..

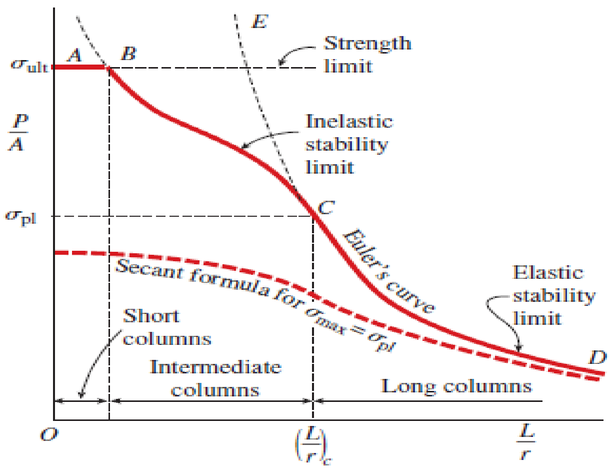

Fig (1): Compressing Stress and Slenderness Ratio [8].

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The amount of K is dictated by the column's end conditions, as indicated in Figure (2). It is important to note that the K values are depend on the projected profile of the mounted column when buckling occurs.

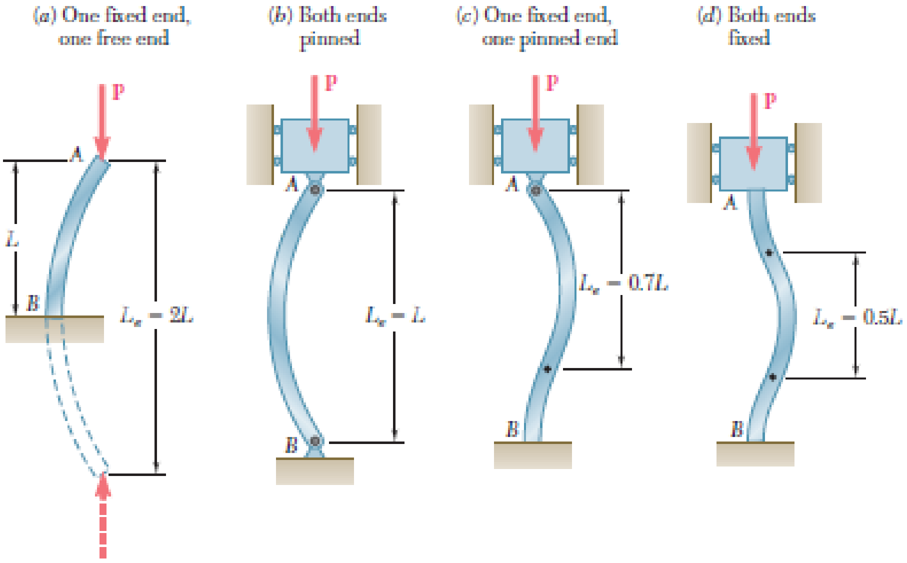

Figure (2): Effective length, Le=KL values for various connections. [9]

The transition slenderness ratio formula is used to calculate the value of (Le/r), which defines as the column is elongated or short (column constant formula) [10]

$$C_c = \sqrt{\frac{2\pi^2 E}{\sigma_y}} \qquad (3)$$

E: module elasticity.

σ_y: yield strength.

If the slenderness ratio (Le/r) is larger than (Cc), the column is lengthy and should be resolved using the Euler formula (described in the following section). The column is short or intermediate when the slenderness ratio (Le/ r) is smaller than (Cc). The Johnson equation must be employed in these instances [11].

The kind of column (long, intermediate, or short) may also be decided using the table below (1)

Table (1): Slenderness ratio for columns of different materials (S.R= Le/r) [11]

Material	Short column (strength limit)	Intermediate column (Inelastic stability limit)	Long column (Elastic stability limit)
Structural steel	S.R.<40	40< S.R.< 150	S.R.>150
Aluminum Alloy AA6061-T6	S.R. <9.5	9.5 < S.R.< 66	S.R. > 66
Aluminum Alloy	S.R.<12	12< S.R.<55	S.R. > 55
Wood	S.R.<11	11 < S.R. < (18-30)	(18-30) <S.R.< 50

Rankine or Rankine-Gordon Formula

The Euler theory yields proper answers only for long columns, while this formula is applicable to columns of all lengths, from extremely long to intermediate, and it yields unreliable results [10].

For a strut, the Rankine formula combines the Euler and crushing loads [12]:

$$\frac{1}{P_R} = \frac{1}{P_e} + \frac{1}{P_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (4)$$

Where

PR: is the Rankine load

Pc: is the ultimate crushing load for the column

Pe: is the Euler critical load

Because Pe is relatively big for very short struts, 1/Pe may be ignored and PR = Pc. Pe is very small for very long columns, and 1/Pe is quite large, hence l/Pc can be ignored. As a result, PR = Pe For extreme levels of L/k, the Rankine formula holds true. For the intermediate values in the range under consideration, it is also determined to be fairly accurate. The final formula is as follows:

$$PR = \frac{\sigma_y A}{1+a(\frac{L}{K})^2} \quad (5)$$

Where

σy: is the yield stress in compression

a: Rankine's constant = $\sigma y/\pi 2E$

Therefore the main goal of current research is to evaluate the significant buckling load for 304 stainless steel column under prior seawater corrosion state. To improve buckling characteristics before corrosion and buckling test, shot penning (SP) treatment was used.

Perry Robertson formula

The equation of Perry-Robertson was updated to description for the inadequacies of both the Euler and Johnson equations for long and intermediate columns. This formula was created on the basis of the idea that all realistic failure can be reported through a hypothetical beginning column crvature. The equation of Perry-Robertson is based on the idea that by presenting the strut of an initial curve, any failure in the column, whether due to incorrect industry, eccentricity, or loading material, may be accommodated. This is meant to be a cosine curve for mathematical purposes, despite the fact that the actual form is expected to have only a little impact on the outcome. As a result, the ends of strut AB in Fig. (3) show L are pin-connected. specifies the starting curvature Y_0 at each separated X from the centre. [12]

$$y_0 = C_0 \cos\frac{\pi X}{L} \quad (6)$$

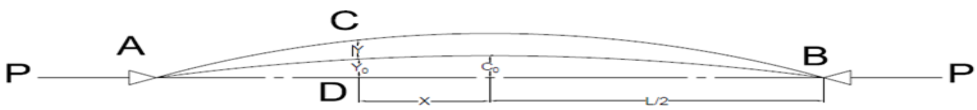

Figure (3): Column with initial bending [8]

$$P = A\left[\frac{\sigma_y+(1+\eta)\sigma_e}{2} - \sqrt{\left(\frac{\sigma_y+(1+\eta)\sigma_e}{2}\right)^2 - \sigma_y\sigma_e}\right] \quad (7)$$

Here constant η is a depending on the proposed material.
The value of η for a brittle proposed material, η= 0.015 L/k
The value of η for a for ductile proposed material, $\eta=0.3\left(\frac{L_e}{100r}\right)^2$
Le= length effect of pinned end strut
=0.7 L of fixed ends strut
= 2.0 L of strut with one end fixed,
r = gyration radius
σ_y= stress yield
σ_e= Euler stress
A= cross section area of column.

Shot Peening Treatment

Shot peening is a cold working technique that involves firing spherical rounds into the treated material in order to introduce compressive residual stresses for work hardening or to remove surface layers. Shot peening improves mechanical characteristics such as stress corrosion cracking. Shot peening is therefore frequently used in a range of industries, including vehicles, aircraft, and machinery [13].

Shot peening is a technique for establishing residual compressive stresses on the surface of materials that stay in the material whether or not the member is loaded. The mechanical and material factors of the shot peening process affect the residual tension that is created. Shot peening is the process of hitting the surface of a material with enough force to create plastic deformation (metallic cast steel balls, ceramic particles, and glass). It functions according to the plasticity principle, with each particle acting as a ball-peen hammer. The peening intensity determines the depth of the generated layer and the degree of residual compressive stress caused. Peening intensity describes the kinetic energy contained inside a stream of peening medium (shot). The strength of the peening depends on the type of peening (shot size, shot speed, shot hardness, impact angle, shot flow rate, coverage, etc.). Axles, drive shafts, gears, turbine blades, aerospace industries, heavy load applications, and components sensitive to cyclic stress are all subject to shot peening. [14].

Shot peening is done with a centrifugal wheel mechanism. The working speed is 1435 revolutions per minute, and the wheel diameter is 590 mm. The shot flow rate is modified to create varied shot peening intensities. A shot blasting machine (model STB-OB) will be utilized in this project, as shown in Figure (4), using the settings listed in Table (2):

Fig (4): Shot peening machine

Table (2): Specifications of shot peening Machin Items

Item	Quant.	Unit	Remark
Ball size	0.6	mm	
Sphere material			Cast Steel
Rockwell hardness	(48 – 50)	HRC	
Pressure	12	bar	
Speed	40	m/sec	
Distance from nozzle to specimen	10	cm	

The shot peening is carried out on 24 sample with different lengths. Each group exposed to the shot peening separately for 15 minutes.

Experimental work

This section covers the mechanical characteristics of 304 stainless steel as well as the specifics of the specimens utilized. Table (3) lists the mechanical characteristics.

Table (3) the experimental and the standard mechanical properties of stainless steel 304.

304 stainless Steel	***UTS*** (MP_a)	***Ys*** (MP_a) 0.2% Proof Stress	*E*	*G*	µ Poi.ratio	ϵ% Elongation
Standard ASTM A370 [61]	621	290	193-200	74-77	0.30	55
Experimental	625	305	198	76	0.33	50

Dry						
Experimental Dry+sp	679	328	200	74	0.3	47
Experimental WC	612	287	188	70	0.3	58
Experimental SP+WC	622	300	200	73	0.3	52

304 stainless steel now offers better mechanical properties thanks to shot peening. The improvement is caused by the creation of a highly deformed surface layer and compressive residual stresses on the sample's surface. The ultimate strength (UTS) and yield stress (Ys) valves are created using the residual stress level. Table 1 shows the results (5-1). The improvement percentage in (UTS) in(Dry) medium owing to 15 minutes of shot peening is 7.95, whereas it is 1.6 in (WC). It is obvious that shot peening has only a little influence on improving mechanical characteristics. The conclusions of Arker and Sovitec [15] are supported by the results in table (3), which may be displayed as shown in fig (5).

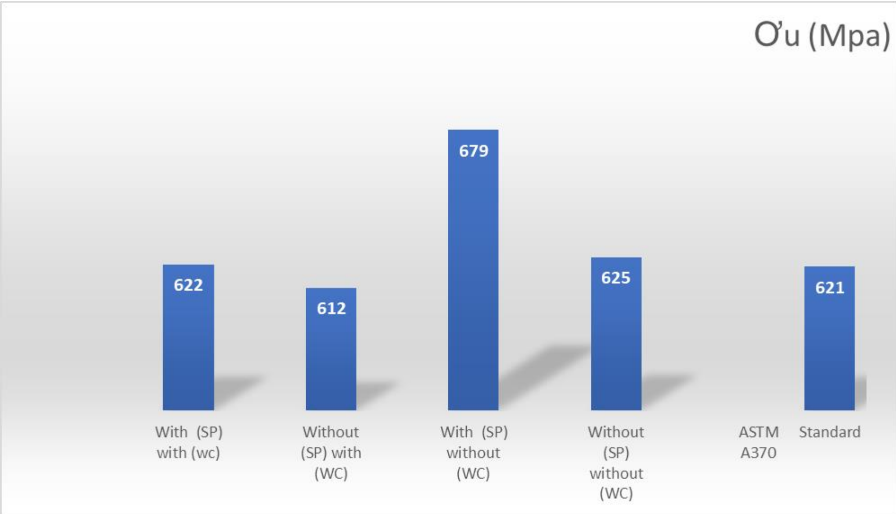

Figure (5): the mechanical characteristics of stainless steel 304, both experimental and standard

Seawater properties

The city of Al-Faw in the Basra Governorate provided a sample of sea water (Arabian Gulf). The Environmental Analysis Division of the Ministry of Health and Environment's Diyala Environment Directorate evaluated the sample's features and chemical components. The results were as follows in table (4):

Table (4) : Seawater properties.

seawater	***PH*** ---	***E.C*** us	T.D.S Mg/l	Turb NTU	T.H Mg/l	DO NTU	COD Mg/l
Experimental	6.8	12240	7965	43.79	2815	6.4	67

Results of buckling tests

Buckling results included experimental data on buckling alone and buckling with shot peening interaction. To conduct the buckling test experimentally, 24 samples (columns) columns long and intermediate with a diameter of 5mm, an area of 19.634mm2, and a duration of 15 minutes (SP).were mounted in buckling test equipment, and all tests were performed at room temperature (RT). The findings are given in the form of tables or graphs. Tables (5) and show the findings of dynamic compression buckling of columns .

Table (5) : demonstrates the results of 24 columns under buckling

NO.	L (mm)	L_e (mm)	S.R	P_{cr} (N)	C_c	Ơin (mm)	Ơcr (mm)	SP (min)	WC (Day)	TYPE OF COLUMN
1	500	400	160	198	115	0.31	4.8	-	-	long
2	500	400	160	202	115	0.26	4.31	-	-	long
3	500	400	160	196	115	0.27	4.6	-	-	long
4	500	400	160	282	112	0.19	4.52	15	-	long
5	500	400	160	280	112	0.16	4.33	15	-	long
6	500	400	160	286	112	0.22	4.45	15	-	long
7	500	400	160	180	120	0.21	4.37	-	90	long
8	500	400	160	182	120	0.16	4.4	-	90	long
9	500	400	160	174	120	0.24	4.17	-	90	long
10	500	400	160	239	114	0.33	4.54	15	90	long
11	500	400	160	245	114	0.29	4.71	15	90	long
12	500	400	160	249	114	0.45	4.83	15	90	long
13	400	300	110	455	115	0.23	3.39	-	-	intermediate
14	400	300	110	466	115	0.29	3.41	-	-	intermediate
15	400	300	110	469	115	0.16	3.25	-	-	intermediate
16	400	300	110	477	112	0.19	3.61	15	-	intermediate
17	400	300	110	488	112	0.16	3.53	15	-	intermediate
18	400	300	110	482	112	0.25	3.72	15	-	intermediate
19	400	300	110	418	120	0.34	3.51	-	90	intermediate
20	400	300	110	428	120	0.27	3.45	-	90	intermediate
21	400	300	110	426	120	0.29	3.73	-	90	intermediate
22	400	300	110	447	114	0.17	22.8	15	90	intermediate
23	400	300	110	443	114	0.30	22.6	15	90	intermediate
24	400	300	110	453	114	0.24	23.1	15	90	intermediate

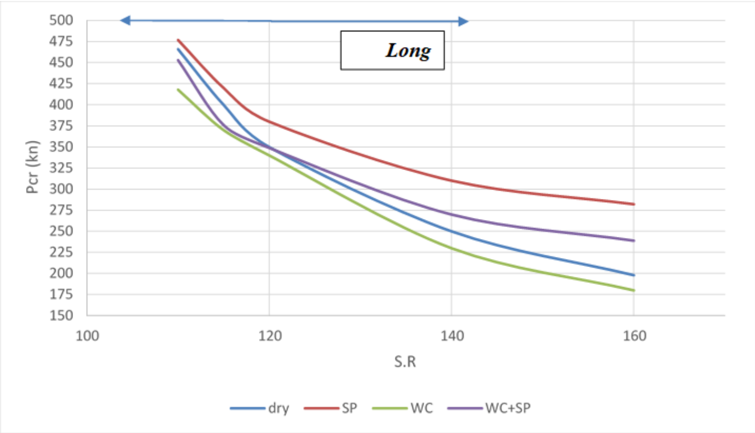

Figure (6): Pcr (dry), (WC),(SP) and (SP+WC) for long and intermediate columns

Application of Rankine-Gordon Formula

For both long and intermediate columns, the Rankine-Gordon formula is an empirical formula that takes into account both yield stress in compression and buckling stresses. The Rankine-Gordon formula is utilized because Euler's formula only applies to long struts, and many struts in machines have proportions that render Euler's theory inapplicable. The Rankine formula is a good approach to handle all kinds of columns (long and intermediate). Table (6) shows that when comparing experimental and Rankine predictions, adequate results may be obtained without the use of a factor of safety .

Table (6): Comparison1between Rankine-Gordon formula results with experimental results

NO.	P_{cr} Experimental (N)	P_{cr} rankine (N)	S.F	S.F 2.5 long	S.F 2 intermediate
1	198	408.85	2.06	163	---
2	202	408.85	2.02	163	---
3	196	408.85	2.08	163	---
4	282	439.6	1.55	175	---
5	280	439.6	1.57	175	---
6	286	439.6	1.53	175	---
7	180	384.72	2.13	153	---
8	182	384.72	2.11	153	---
9	174	384.72	2.21	153	---
10	239	402.15	1.68	160	---
11	245	402.15	1.64	160	---
12	249	402.15	1.61	160	---
13	455	690.22	1.51	---	345
14	466	690.22	1.48	---	345
15	469	690.22	1.47	---	345

16	477	742.27	1.55	---	371
17	488	742.27	1.52	---	371
18	482	742.27	1.53	---	371
19	418	649.48	1.55	---	324
20	428	649.48	1.51	---	324
21	426	649.48	1.52	---	324
22	447	678.9	1.51	---	339
23	443	678.9	1.53	---	339
24	453	678.9	1.49	---	339

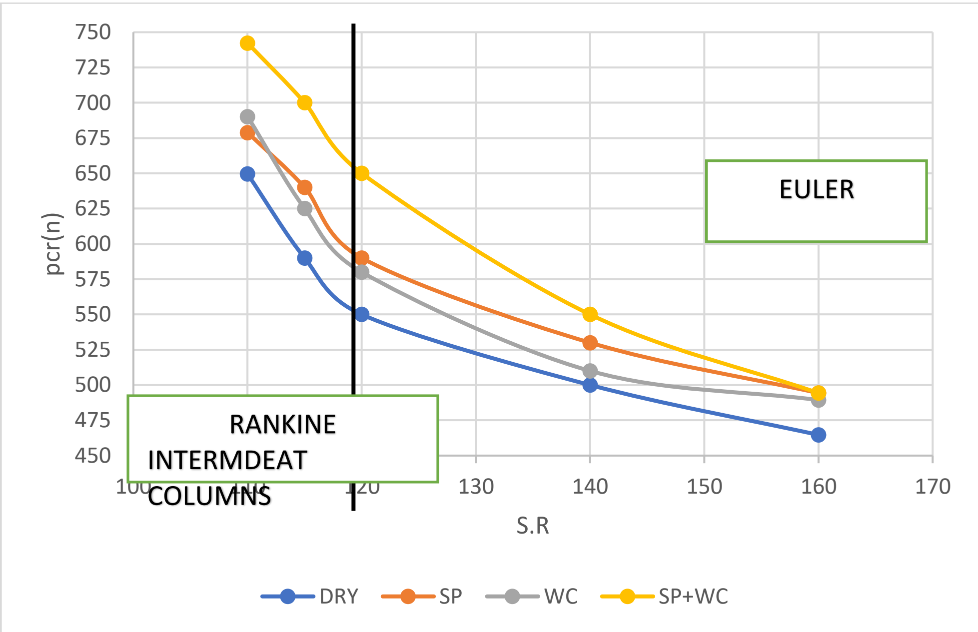

Figure (7): Euler and Rankine buckling results for long and intermediate sample

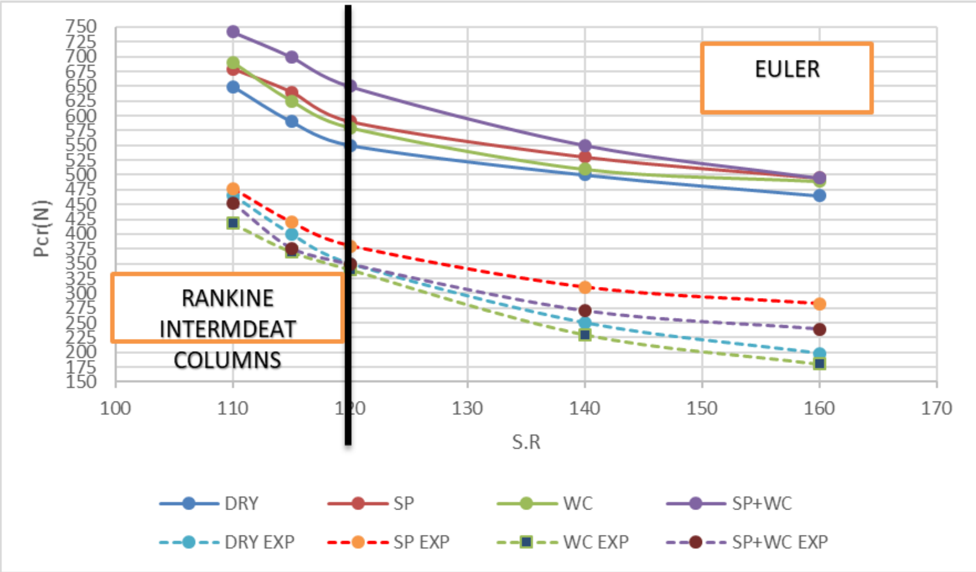

Figure (8): Euler and Rankine buckling results for long and intermediate sample with the experimental results

Application of Perry Robertson formula

When the Perry-Robertson results in Table (7) are compared to the experimental value of the critical The Perry-Robertson (PR) forecast of Pcr under a load without corrosion is unsatisfactory, but if a factor of safety equal to (2.5) is employed, this will provide an estimate of Pcr's safety under dynamic loading.

Table (7): Comparison1between Perry Robertson formula results with experimental results

NO.	P_{cr} Experimental (N)	P_{cr} Perry- Robertson (N)	S.F	S.F 2.5 long
1	198	475	2.4	190
2	202	475	2.35	190
3	196	475	2.42	190
4	282	473.9	1.6	189.5
5	280	473.9	1.69	189.5
6	286	473.9	1.65	189.5
7	180	446.1	2.47	178.44
8	182	446.1	2.45	178.44
9	174	446.1	2.56	178.44
10	239	474.6	1.98	189.84
11	245	474.6	1.93	189.84
12	249	474.6	1.9	189.84

Conclusion

For the experimental analysis of corrosion buckling indication of 304 stainless steel alloy. It is concluded that a correlation between the direct result obtained from the test rig and the theoretical results predicted by Rankine and Perry- Robertson. The major conclusion can be drawn from this work may be recorded as:

1- The Rankine and Perry- Robertson theories are able to estimate the buckling behaviour after taking a suitable factor of safety.
2- Corrosion media reduces the buckling strength for long and intermediate columns of 304 stainless steel alloy. This need higher factor of safety am pared to dry buckling.

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