Curved and Layer. Struct. 2022; 9:442–450 DE GRUYTER

Research Article

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Effect of shot peening on the critical buckling load of stainless steel 304 columns immersed in sea water

https://doi.org/10.1515/cls-2022-0181
Received Feb 10, 2022; accepted Aug 26, 2022

Abstract: A machine part subjected to an axial compressive load is called strut. But, a vertical strut is known as a column. The machine members that must be investigated for the column action are connecting rods, piston rods, screw jack, *etc*. When a column is subjected to a compressive load and this load is gradually increased, a stage will be reached when the column will be subjected to ultimate load. Beyond this, the column will fail by crushing, and the load will be known as crushing load. When the column is short or intermediate, sometimes this column fails by bending, i.e. buckling. When the column is long, the value of buckling load is low for long columns and is relatively high for intermediate columns. The present investigation focuses on the testing and evaluation of the mechanical end buckling columns (samples) using 304 stainless steel under dry, corrosion, and combined dry with shot peening (SP) process. The buckling behavior of the axial compressive load has been studied experimentally and theoretically using Euler and Rankin theories. The results obtained from the above study manifested that the column, whose slenderness ratio (SR) is more than 120, is denoted as the long column, and the Euler theory can be successfully used. But, when the SR is less than 120, the column is known as an intermediate one. The mechanical and buckling properties exhibited a reduction due to the corrosion media and a reasonable improvement when using SP.

Keywords: Stainless steel (304), buckling properties, prior seawater corrosion, shot peening treatment

1 Introduction

The computation of structure's buckling loads is crucial owing to the risk of the structure failing suddenly if the critical buckling load is achieved. When the buckling load is met, some buildings may lose all stability, putting people in danger. If a roof or other similar structures loses all stability, people may be at risk [1].

The present manufacturing industry puts a focus on the 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, the shell structures have a major advantage. When a load is applied to a shell, various internal forces are produced, which can result in bending, twisting, transverse shearing, and buckling [2]. The failure of structural elements through buckling has aroused, and still generates a vivid interest amongst researchers and engineers [3]. The critical buckling load is the upper limit of the allowed vertical frame loading. This load is defined by the frame configuration, cross-sections of the columns and horizontal beams as well as the configuration and stiffness of the connections between them. In the existing known nondestructive methods of determining the side sway frames critical load, an implementation of a vertical loading is technically difficult, and that is, especially essential at full-size tests [4]. Structures can fail due to a number of conditions, such as when the members or the complete structure reaches the yield or ultimate strength; override the maximum deflection, or when the fracture of members or collapse happens. Buckling is a broad term that describes several mechanical behaviors; it is generally referred to an event whereby a structural element in compression deviates from a behavior of elastic shortening within the original geometry and undergoes large deformations involving a change in member shape for a very small increase in load [5]. The bending of a structure under

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axial compressive load is referred to as buckling behavior. Columns, as one may know, are thin structural components that support axial compressive loads. A column may fail due to the structural instability known as buckling if the compressive load is too high. As a result, the subject of steel column buckling is a critical one. Underestimating this impact might result in severe outcomes or unwarranted safety factors [6].

2 Euler – Johnson formulas

When the column constant (Cc) is smaller than the slenderness ratio (S.R), the Euler equation may be used to calculate the critical load for long columns [7]:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \tag{1}$$

Where:
P_{cr} – The critical axial load that leads to buckling in column (N).
E – The modulus of elasticity of the column material (GPa).
I – The smallest moment of inertia of the column cross – section (mm^4).
L – The column length between the pinned ends (mm).
K – The constant of the end fixity of the theoretical and experimental values.

Except for the Young's modulus, the critical buckling load (Pcr) is not affected by material properties (mechanical). The critical load, on the other hand, is usually determined by the dimensions of the column. In the equation above, the material strength is ignored. As a result, specifying a high-strength material for a long column application is typically pointless [8].

When the Cc exceeds the S.R as depicted in Eq. (1), the column is deemed intermediate, and the Johnson formula can be utilized [9]:

$$P_{cr} A \sigma y \left[1 - \frac{\sigma_y (S.R)^2}{4\pi^2 E} \right] \tag{2}$$

The mechanical properties of the material as well as its modulus of elasticity have a serious influence on the Pcr in Eq. (2). When the Euler formula is applied, the mechanical characteristics are not a consideration for a long column [9].

3 Rankine or Rankine-Gordon formula

The Euler theory yields proper answers only for long columns, while this formula is applicable to the 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 [11]:

$$\frac{1}{P_R} = \frac{1}{P_e} + \frac{1}{P_c} \tag{3}$$

Where:
P_R – The Rankine load
P_c – The ultimate crushing load for the column
P_e – The Euler critical load.

Because P_e is relatively big for very short struts, $1/P_e$ may be ignored and $P_R = P_c$. P_e is very small for very long columns, and $1/P_e$ is quite large; hence l/P_c can be ignored, as a result, $P_R = P_e$. For the 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:

$$P_R = \frac{\sigma_y A}{1 + a\left(\frac{L}{K}\right)^2} \tag{4}$$

Where:
σ_y – The yield stress in compression
a – Rankine's constant = $\sigma y/\pi 2E$.

Therefore, the main goal of this work is to evaluate the critical buckling load for 304 stainless steel column under prior the sea water corrosion state. To improve the buckling characteristics before corrosion and buckling test, a SP treatment was used.

4 Shot peening treatment

Shot peening is a cold working procedure in which spherical rounds are fired into the worked material to impart compressive residual stresses for work hardening, or to remove surface layers. Mechanical properties like as stress corrosion cracking are improved by shot peening. As a result, shot peening is widely employed in a variety of sectors, including automobiles, planes, and equipment [12]. Shot peening is a method of creating residual compressive stresses on the surface of materials, which remain in the material regardless of whether the member is loaded or not. Material and mechanical factors influence the residual stress created by the shot peening process. Shot peening is the technique of striking a material's surface with enough force to cause plastic deformation with shot (metallic cast steel balls, ceramic particles, and glass). It works using the plasticity approach, with each particle acting as a ball-peen hammer. The depth of the induced layer and the degree of the residual compressive stress created are highly dependent on the peening intensity. The kinetic energy within a stream of peening medium is characterized as a peening intensity (shot). The intensity of peening is determined by the type of peening (shot size, shot speed, shot hardness, impact angle, shot flow rate, coverage, *etc*.). Axles, drive shafts, gears, turbine blades, aerospace industry, heavy load applications, and components subjected to cyclic stress are examples of shot peening uses [13]. The centrifugal wheel system is used to do shot peening. The wheel diameter is 590 mm, and the operating speed is 1435 revolutions per minute. To achieve different shot peening intensities, the shot flow rate is changed. In this project, a shot blasting machine (model STB-OB) was used, as illustrated in Figure 1, with its specifications shown in Table 1.

Figure 1: Shot peening machine

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

5 Experimental work

This section covers the mechanical characteristics of the used 304 stainless steel as well as the specifications of the specimens utilized. Table 2 lists the mechanical characteristics.

The mechanical characteristics of 304 stainless steel have been improved by shot peening. The improvement is related to the creation of a severely deformed surface layer and the generation of compressive residual stresses on the sample's surface. The residual stress level is used to create the ultimate strength (UTS) and yield stress (Ys) valves as shown in Table 3. The improvement percentage in (UTS) in (Dry) media due to 15 min shot peened is 7.95 while at (WC) is 1.6. It is clear that the shot peening treatment has a little effect on the improvement the mechanical properties. The results in Table 2 can be plotted as shown in Figure 2 and in conclusion, these results are in agreement with Arker and Sovitec [14].

Table 1: Specifications of shot peening machine

Items	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	

Table 2: The experimental and standard mechanical properties of stainless steel 304

304 stainless steel	*UTS* (MPa)	Y_S (MPa) 0.2% Proof Stress	*E*	*G*	μ Poi. Ratio	ε% Elongation
Standard ASTM A370 [**?**]	621	290	193-200	74-77	0.30	55
Experimental Dry	625	305	198	76	0.33	50
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

The effect of SP treatment on the tensile behavior shows an improved percentage (IP) due to SP process. The corrosion weakens the surface and decreases its mechanical properties and hence causing a significant reduction in the strength of 304 stainless steel, as given in Table 3.

It can be seen that corrosion, in general, has the overall effect on the surface quality of a structure and reduces the strength of 304 stainless steel. The reason for this reduction is due to the disability of samples surface to withstand the applied load [12]. But, SP is considered as cold working. The surface grains are in residual compressive stress, while the inner layer is in tension, thus providing conditions that will curtail the growth of surface cracks [13].

Table 3: Reduction percentage (RP) due to corrosion

Reduction percentage (RP) due to corrosion	
Dry	
UTS	YS
2.08	5.9

Table 4: Properties and chemical compounds of sea water

Sea water	PH	$E.C$	T.D.S	Turb	T.H	DO	COD
	–	us	Mg/l	NTU	Mg/l	NTU	Mg/l
Experimental	6.8	12240	7965	43.79	2815	6.4	67

Table 5: The results of 24 columns under buckling only and buckling shot peening interaction for both columns long and intermediate for 5 mm diameter and area 19.634 mm^2 and 15 min. SP time

NO.	L (mm)	L_e (mm)	S.R	P_{cr} (N)	C_c	C_{in} (mm)	C_{cr} (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

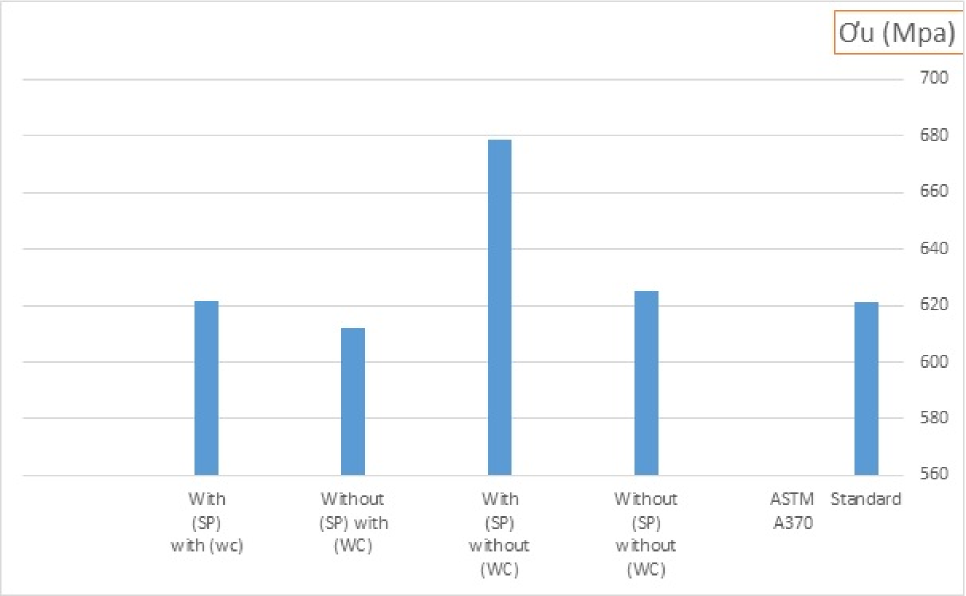

Figure 2: Experimental and the standard mechanical properties of stainless steel 304

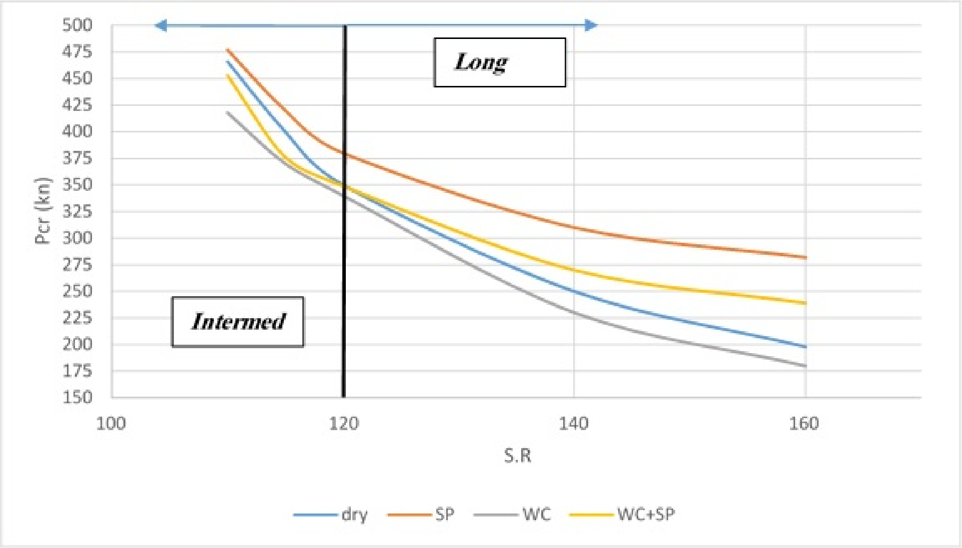

Figure 3: The P_{cr} (dry), (WC), (SP) and (SP+WC) for long and intermediate columns

5.1 Sea water properties

A sample of sea water (Arabian Gulf) was taken from the city of Al-Faw in the Basra Governorate. The sample's characteristics and chemical components were investigated in the Ministry of Health and Environment's Diyala Environment Directorate's Environmental Analysis Division's laboratories. The outcomes are given Table 4.

5.2 Buckling test results

Experimental data on buckling alone and buckling with shot peening interaction were included in the buckling results. 24 Samples (columns) were mounted in a buckling test device to perform the buckling test experimentally, and all tests were performed at the room temperature (RT). Tables or graphs are used to present the findings. The findings of the dynamic compression buckling of columns are depicted in Table 5 and Figure 3.

Within the inelastic zone, intermediate columns require more stress to fail. It has also been discovered that

Table 6: The improvement percentage (IP) in the critical buckling loads due to 15 min. shot peening treatment

Type of Column	L (mm)	L_e (mm)	P_{cr} (N)	P_{cr} (N) with SP	IP %
Long (SP)	500	400	198	282	29
	500	400	202	280	27
	500	400	196	286	31
Long (SP+WC)	500	400	180	239	24
	500	400	182	245	25
	500	400	174	249	30
Intermediate (SP)	400	350	455	477	4
	400	350	466	488	4
	400	350	469	482	2
Intermediate (SP+WC)	400	350	418	447	6
	400	350	428	443	3
	400	350	426	453	5

Table 7: Comparison between the experimental results and the Euler results for long specimens

No.	P_{cr} Experimental (N)	P_{cr} Euler (N)	S.F	S.F 3
1	198	489.4	2.44	193
2	202	489.4	2.39	193
3	196	489.4	2.46	193
4	282	494.35	1.75	164
5	280	494.35	1.76	164
6	286	494.35	1.72	164
7	180	464.68	2.58	154
8	182	464.68	2.55	154
9	174	464.68	2.67	154
10	239	494.35	2.06	164
11	245	494.35	2	164
12	249	494.35	1.98	164

the specimen's initial deflection has a significant impact on the critical buckling load. Because of water corrosion, the fraction of critical buckling loads in intermediate columns has decreased. If the load is steadily increased, the column will begin to buckle at a certain point.

A buckling load, also known as a critical load, is the load that causes the column to buckle. The critical buckling load for intermediate columns is greater than the critical buckling load for long columns [14].

6 Application of Euler formula

To calculate the critical load or stress, Euler formulas might be used. It is beneficial in the early stages of the design process. According to the SR and Cc, the specimens were sorted into two groups: Long and intermediate columns. The Euler formula is valid for long columns. Table 7 compares the experimental results before SP and the Euler's results for the critical buckling load with and without corrosion.

The critical buckling load in all long columns appears to be greatly reduced by the corrosion environment. This reduction is due to material removal from the column's surface, which results in a stress concentration factor, which lowers the critical buckling load. The corrosion buckling interaction behavior of 304 stainless steel with water corrosion (WC) is manifested in Table 7. The reduction in the critical buckling load for specimens without SP is (1.1%) and for specimens with SP is (1.18%).

For both dry and WC instances, the Euler formula produces inflated predictions in a receiving condition. This is because Euler's equation assumes that the column is 100% straight, and this cannot be achieved in practical applications, where the primary deformation is observed in the samples, as evinced in the Table 5. Euler theory can be applied with a (3) safety factor. At critical load, the column should just begin to buckle if there is no safety factor (3). To compute the acceptable load, a safe load would be a decreased value found by applying the deviation factor to the critical load.

Table 8: Comparison between the Rankine-Gordon formula results and the 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

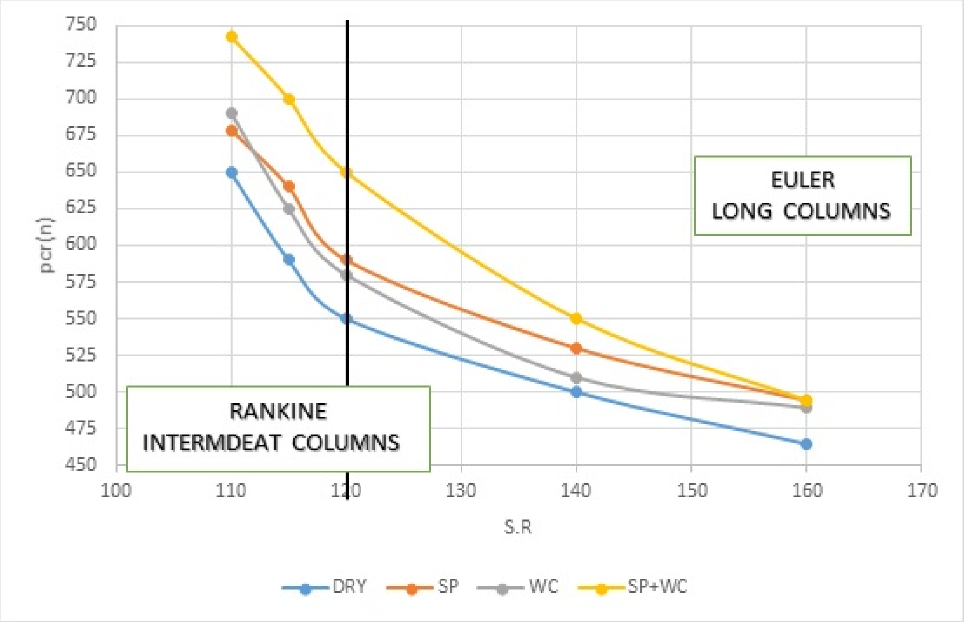

Figure 4: Euler and Rankine buckling results for long and intermediate samples

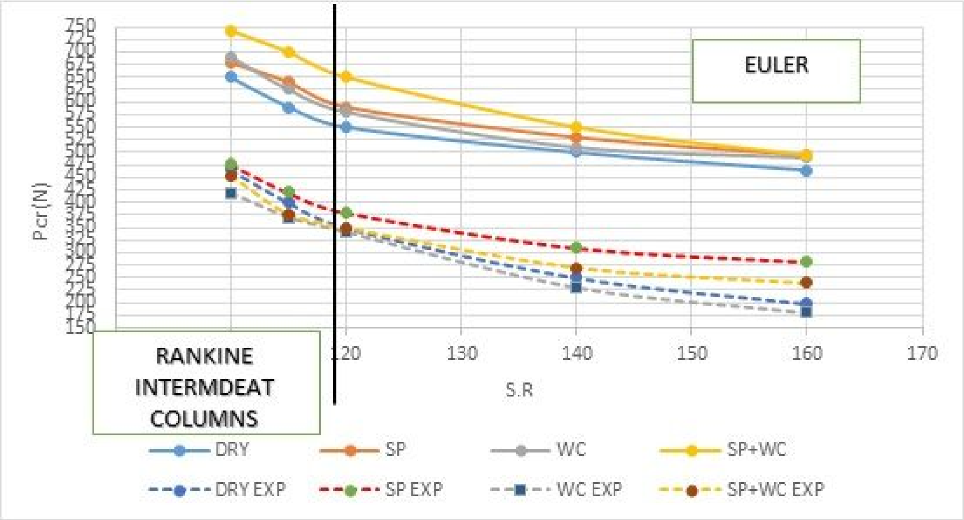

Figure 5: Comparison of the Euler and Rankine buckling results for long and intermediate samples with the experimental results

7 Application of Rankine-Gordon formula

The Rankine-Gordon formula is an empirical formula that considers both yield stress in compression and buckling stresses for both long and intermediate columns. Because Euler's formula only applies to lengthy struts, and many struts in machines have proportions that make Euler's theory inapplicable, the Rankine-Gordon formula is used. A valid way to cover all sorts of columns is the Rankine formula (long and intermediate). When comparing between the experimental and the Rankine predictions, satisfactory values are obtained without the use of a factor of safety, as displayed in Table 8.

Figure 4 elucidates the Euler and Rankine buckling results for long and intermediate samples, while Figure 5 illustrates the comparison of the Euler and Rankine buckling results for long and intermediate samples with the experimental results

8 Conclusions

For 304 stainless steel columns, the influence of corrosion on the buckling behavior was explored. The following are some of the inferences that can be drawn:

- Experimental results of mechanical and buckling properties with corrosion showed a significant reduction in the valves of UTS, YS, E and P_{cr}.
- The columns, whose C_c is less than 120, are denoted intermediate column, while the larger than 120 are known long columns.
- When using Euler's formula, the P_{cr} for a long column is unaffected by the material's strength (i.e. strength is not a factor), but the stiffness (E) of material is a crucial factor in determining the P_{cr}. When using the Rankine formula, the P_{cr} for intermediate columns is affected by strength as well as E.
- It was discovered that the effect of SP on the samples not submerged in sea water, as well as on the samples immersed in sea water, increases the mechanical characteristics, and that this increase is proportionate to the decrease caused by corrosion.
- In both situations (dry) and (corrosion), the Euler and Rankine formulas manifested a good agreement in compression with experimental results with a factor of safety 3 and 2.5, respectively.

Acknowledgement: One of the authors, Al-Alkawi, H. J. M., expresses his thanks to Bilaid Al-rafidain University College for their support and encouragement during this research work.

Funding information: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author contributions: Amjed M. Bader was the student made the measurements and experimental work, Dhia A. Alazawi made the formulas, Hussain J. M. Al_Alkawi the

supervisor checked the results and Saad T. Faris made the shot peening treatment.

Conflict of interest: The authors have no conflict of interest.

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