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Received on: 14/11/2016
Accepted on: 23/02/2017

Electrical Laser Alarm System for Controlling the Buckling Failure of 304 Stainless Steel under Shot Peening Treatment

Abstract: *The purpose of this paper is to design and manufacture the electrical laser alarm system to assess the buckling failure of 304 stainless steel column and to estimate the critical buckling load (P_{cr}) under increasing compressive load without shot peening (WSP) and with shot peening (SP). The evaluation of the critical buckling load (P_{cr}) was done experimentally and theoretically for long and intermediate pinned – fixed columns. The experimental results revaled that 25 min. shot peening time (SPT) improved the critical buckling load (P_{cr}) by 13.3% - 15.39% improvement percentage (IP) for long columns while 18.51% - 23.07% for intermediates. Also it was observed that reducing the effective length (L_{eff}) resulting in increasing the effect of 25 min. shot peening time (SPT) and kept constant when effective length (L_{eff}) larger than 200mm. The difference percentage (DP) obtained from theoretically and experimentally comparison between the critical buckling load (P_{cr}) was 33.33 to 41.18 for without shot peening and 23.07 to 33.34 for 25 min. shot peening time (SPT) based on Euler and Johnson theories for both long and intermediate columns. Also it was revaled that increasing the slenderness ratio (S.R) reducing the critical buckling load (P_{cr}) for both columns and both conditions of testing without shot peening (WSP) and shot peening (SP).*

Keywords: *dynamic buckling , shot peening , Electrical laser alarm system , 304 stainless steel alloy .*

How to cite this article: H. J. M. Al – Alkawi, F. A. K. Fattah, and A. I. Hussain, , "Electrical Laser alarm system for controlling the buckling failure of 304 stainless steel under shot peening treatment," *Engineering & Technology Journal*, Vol. 35, Part A, No.5,pp. 516-524, 2017.

1. Introduction

Buckling is a broad term that describes a range of mechanical behaviors, it generally refers to an event where by 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 [1].

Buckling load is defined as the load at which a structural member becomes laterally unstable leading to collapse of it. It can be observed by sudden bending, warping, curling or crumpling of the elements or members under compressive stresses. The buckling of a beam – column depends upon flexural rigidity [2].

Columns are one of the most used basic structural elements, and there are extensive studies related to the elastic stability of columns with different properties in shape and of material and to their static and dynamic behaviors [3].

The elastic stability solutions normally account for critical buckling load of the beam or column under axial loading, where the application of the load is along the longitudinal axis of the structure [4].

M. Avcar. [5] studied the buckling behavior of the steel columns with different geometries and boundary conditions under axial compressive load. A comparison between boundary conditions, cross sections and slenderness ratio on the buckling load were investigated. Thomas. et . al [6] studied the buckling behavior of cold – formed steel columns in axial compression with pinned end connections and in two different orientations (Rectangular columns and I- shaped columns). Comparison between different buckling modes of cold – formed steel columns were investigated .M. Arif. et. al [7] studied the buckling loads of slender prismatic columns with a single non propagating open edge crack with various boundary conditions under axial compression. Al-Alkawi H. J. M. et. al [8]studied the influence of shot peening on the dynamic

https://doi.org/10.30684/etj.35.5A.11
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buckling properties of carbon steel columns under dynamic buckling with and without shot peening. The comparison involved initial imperfection, load duration and slenderness ratio of columns. R.Wathins. et. al [9] studied the buckling behavior of nickel titanium and 2024 aluminium columns (solid cylindrical rods) under clamped – clamped boundary conditions by using digital image correlation. The aim of present work to find the best behavior of buckling properties under different shot peening times (SPT). Also the determination of some aspects on buckling – shot peening interaction using 304 stainless steel alloy will be presented.

2. Theory

I. Long Columns

For long columns, Euler equation can be used to determine the critical load as

$$P_{cr} = \frac{\pi^2 E I}{{L_{eff}}^2} \qquad (1)$$

It is clear that the critical buckling load (Pcr) is not dependent on the mechanical properties of the material except the modulus of elasticity. But the critical load is directly depend on the dimensions of the column. The material strength is not involved in the above equation. For the above reasons, it is often of no benefit to specify a high strength material in a long column application [10].

Euler's Formula limitations

It is known that the crippling stress for column can not be more than crushing stress of the column material. Thus, Euler's Formula gives the crippling stress of column equal to the crushing stress of column material. From the experimental compression test, the crushing stress for the mild steel is 324 MPa and the modulus of elasticity is equal to 210 GPa [11]. It can be equated crushing stress to crippling stress

$$\sigma_y = 324 = \frac{\pi^2 E}{S.R^2} = \frac{\pi^2\, 210 * 10^3}{S.R^2} \qquad (2)$$

Slenderness ratio (S.R)= 79.981 ≈ 80, Hence if S.R is less than 80, Euler's equation can applied for mild steel column. Sometimes, when S.R is larger than 80 for mild steel, the columns are called long columns, and those S.R less than 80 are known as intermediate or short columns. It is thus obvious that the Euler's theory holds good only for long columns. The vertical column have two second moment of area (moment of inertia), Ixx and Iyy. Since the column tend to buckle in the least moment of inertia direction. Therefore the least valve of the above two moments of inertia is to be used in the Euler's equation.

II. Intermediate Columns

For intermediate column, when the slenderness ratio (S.R) is less than the column constant(C_c), then the column is intermediate and Johnson formula can be applied. Then the Johnson Formula may be written as:

$$P_{cr} = A\, \sigma_y \left[1 - \frac{\sigma_y\, (S.R)^2}{4\pi^2 E}\right] \qquad (3)$$

The critical load (Pcr) in equation (2) is directiy affected by material strength in addition to its modulus of elasticity. While strength is not a factor for a long column when Euler formula is used. Johson [1] presented a straight line theory for intermediate and short columns and it may .written in the form

$$P_{cr} = A\,[\sigma_y - C_c\,(S.R)] \qquad (4)$$

Where:

A is the cross – sectional area of the column.

σ y is the yield stress of column material.

Cc is the column constant $=\sqrt{\frac{\pi^2\, 2E}{\sigma_y}}$., it's valve depends on the material and the type of ends condition. After application of equation (4), Johson found that results of this equation are very approximate and then a new proposed formula was presented in the form of Parabolic shape as given in equation (3). The experiment results and analysis revaled that the results of equation (2) are very approximate and the difference between the experimental and the above equation is slilitly high. Thus, Johnson proposed another formula in the form of parabolic as given in equation (3).

It is obvious that Euler's Formula gives valid results only for long and very long columns .

3. Experimental Work

I. Material selection

Stainless steel 304 is selected because it is widely used in many applications. All the materials were received from the state company of mechanical Industries Al – Ascandaryah and tested to obtain its chemical composition and mechanical properties. The results are listed in table (1), the chemical analysis which was done in Engineering center for testing and recondition. While the relevant mechanical properties are shown in table (2). This tables exhibits the average of three readings of mechanical properties.

Table (1) Chemical composition of 304 stainlesssteel (wt%)

304 stainless steel	C %	Mn %	P %	S %	Si %	Cr %	Ni %	N %	Fe %
Standard ASTM A240	0.08 max	2.00 max	0.045 max	0.030 max	0.75 max	18.o-20.0	8.0-12.0	0.10 max	Balance
Experimental	0.026	1.75	0.016	0.021	0.66	18.9	9.6	0.07	Balance

Table (2) Mechanical properties of stainless steel 304

304 stainless steel	σ_u (MP_a)	σy (MP_a) 0.2% proof stress	E (GP_a)	G (GP_a)	μ Poi.ratio	Ɛ %Elongation
Standard ASTM A370 [12]	621	290	193-200	74-77	0.30	55
Experimental	630	300 tension compression 450	200	77	0.31	52

II. Buckling specimens

Specimens used in buckling test were received in the form of rolled rods of stainless steel 304. An axial compression is subjected to the specimen without shot peening. The deflection of the specimen length is measured by the dial gauge depend on buckling failure definition which is defined here when the column buckle 1% of original length then the testing be automatically stopped and failure is occurred [13]. The untreated buckling specimens with treated by shot peening are shown in figure (1).

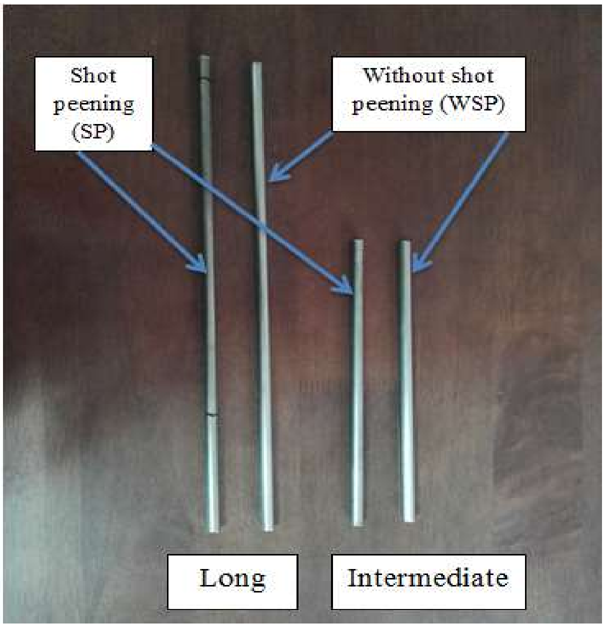

Figure (1) Columns used in the present work.

III. Shot peening process

Shot peening treatment was performed using centrifugal wheel system. Diameter of wheel 590mm, operating speed 1435 rpm. Shot flow rate was varied to obtain various shot peening intensities. But for the present work , the following specifications of shot peening can be illustrated below using Machine No. 03008 Tumblast Control Panel device Model STB-OB .

average ball size = 0.6 mm .
ball material = Cast Steel .
rockwell hardness = (48 - 50)HRC .
pressure = 12 bar.
velocity = 40 m/sec .
distance from nozzle to specimen = 10 cm

The shot peening procedure was carried out on 12 specimen with different diameters and lengths. This is done by placing all the 12 specimens inside the shot peening device as shown in figure (2) time reaches 25 min. For the steel alloy used previous work was obtained that 25 min is the optimum time for improve the mechanical and buckling properties [10].

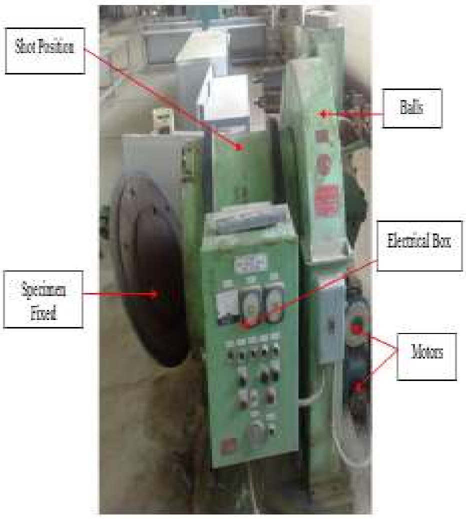

Figure (2)The shot peening device .

IV. Buckling test machine

The buckling test machine is used to implement the buckling test for variable amplitude and deflection measurement for dynamic loads. In figure (3) the specimen is subjected for variable load and deflection. The value of load (P) is measured in (KN) deflection in (mm).

Figure (3) Machine of buckling test .

4. Electrical laser alarm system has two main electrical circuits transmitter and receiver

I .Transmitter circuit

The laser diode transmitter which is a beam generator. The transmitter part is built with a laser diode radiator, with one dry cell battery, it should be powered with 9 volt DC supply, an ON – OFF switch and fixed on one side stand to hold on digital electronic caliper frame [14].

II. Receiver circuit

The receiver has a photocell sensor at the front end. The photocell sensor also holds with a stand and it connected with the main driver circuit. The receiver should be fixed on the opposite frame and should be properly aligned to the laser beam. Normally the laser beam illuminates the face of photocell and it conducts [15].

Figure (4) Shows the actual electrical laser alarm system coupled with buckling test rig machine.

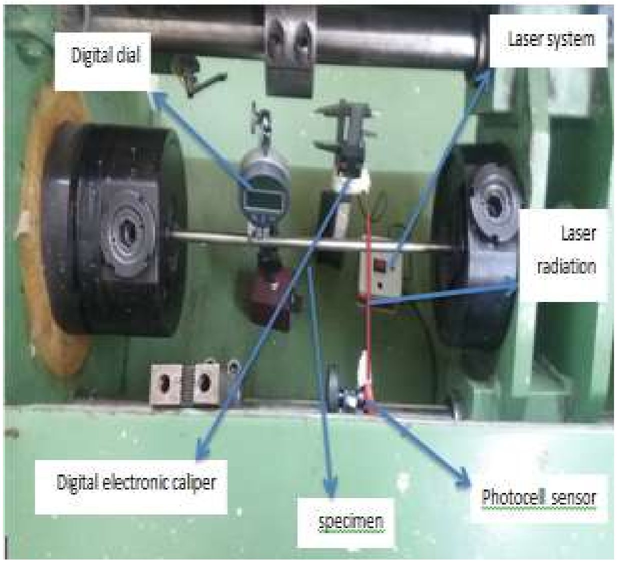

Figure (4) Electrical laser alarm system coupled with buckling test rig machine .

III. General operation

The laser alarm circuit has two sections. The transmitter is a laser diode and should be fixed on one side of the circuit. The receiver is a photocell and should be fixed on the opposite a laser diode and should be properly aligned to the laser beam. When laser diode is interrupted to get a continuous in a buzzer while a buzzer remains off in the state laser diode conducts light to a photocell acts as an open circuit.

The complete circuit schematic diagram of the alarm system is shown in figure (5).

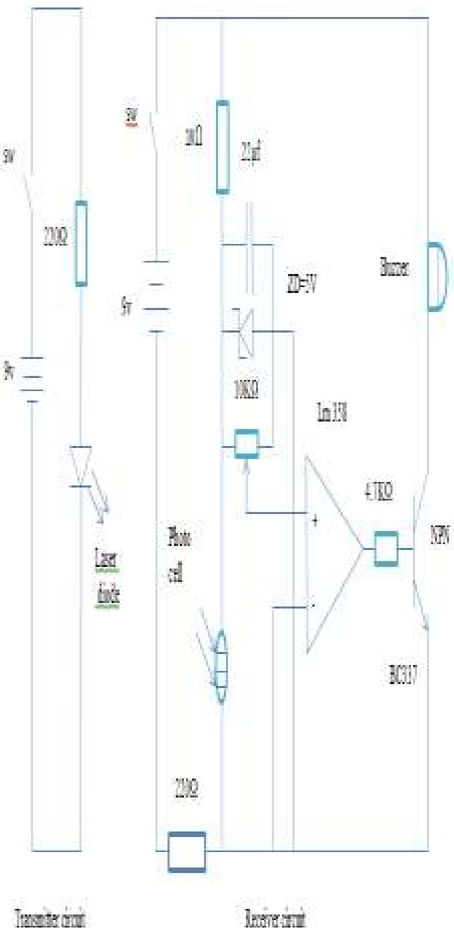

Figure (5) circuit diagram of laser security alarm system .

5. Results and Discussions:

I. Buckling test results

The experimental results obtained for buckling testing and the theortical ressults used the famous buckling theories are listed and discussed in details through this paper. The buckling results included experimental data of buckling with and without shot peening interaction. To achieve the buckling test experimentally, (24) samples (columns) have been installed in buckling test appratus and all the tests have been done at room temperature (RT). Table (3) gives the results of dynamic compression buckling of columns.

Table (3) Experimental results of columns under buckling with and without shot peening interaction.

No.	L (mm)	L_{eff} (mm)	D (mm)	S. R	P_{cr} (N)	Shot peening time (min)	Type of column
1	400	280	6	186.66	1066	0	long
2	300	210	6	140	1895	0	long
3	400	280	7	160	1975	0	long
4	300	210	7	120	3398	0	long
5	400	280	8	140	3303	0	long
6	300	210	8	105	5285	0	long
7	190	133	6	88.66	4434	0	intermediate
8	170	119	6	79.33	5276	0	intermediate
9	190	133	7	76	7560	0	intermediate
10	170	119	7	68	8403	0	intermediate
11	190	133	8	66.5	11168	0	intermediate
12	170	119	8	59.5	12011	0	intermediate
13	400	280	6	186.66	1230	25	long
14	300	210	6	140	2186	25	long
15	400	280	7	160	2279	25	long
16	300	210	7	120	3901	25	long
17	400	280	8	140	3800	25	long
18	300	210	8	105	5990	25	long
19	190	133	6	88.66	5255	25	intermediate
20	170	119	6	79.33	6254	25	intermediate
21	190	133	7	76	9095	25	intermediate
22	170	119	7	68	10185	25	intermediate
23	190	133	8	66.5	13641	25	intermediate
24	170	119	8	59.5	14783	25	intermediate

II. Buckling loads against length

Table (4) shows the variations of experimental compressive buckling loads against the length (L) or effect length (L_{eff}) for three cross – sectional area of column i.e , 28.274 , 38.484 and 50.265 mm^2 crossponding to 6 , 7 and 8 in diameter respectively. The difference between P_{cr} (wsp), without shot peening and P_{cr} (sp), with shot peening for Pinned – Fixed (P –F) is given in table (4) using the improvement percentages equation as [5] :

Improvement percentage , (IP) due to

$$IP = \left[\frac{P_{cr\,(sp)} - P_{cr\,(wsp)}}{P_{cr\,(wsp)}}\right] \times 100 \qquad (5)$$

Table (4) improvement percentage (IP) in critical buckling loads due to shot peening treatment .

Type of column	L (mm)	L_{eff} (mm)	D (mm)	A (mm^2)	IP %
Long	400	280	6	28.274	15.38
Long	300	210	6	28.274	15.35
Long	400	280	7	38.484	15.39
Long	300	210	7	38.484	14.80
Long	400	280	8	50.265	15.04
Long	300	210	8	50.265	13.33
Intermediate	190	133	6	28.274	18.51
Intermediate	170	119	6	28.274	18.73
Intermediate	190	133	7	38.484	20.30
Intermediate	170	119	7	38.484	21.20
Intermediate	190	133	8	50.265	22.14
Intermediate	170	119	8	50.265	23.07

It is clear from results, the largest improvement occur in the intermediate columns and the lowest improvement occur in the long columns. Consequently, it is revealed that, the most efficient type of column against buckling is the intermediate column. The lowest improvement percentage(IP) due to shot peening (SP) is 13.33% for long column while the best improvement percentage(IP) is 23.07% for intermediate column. The highest improvement in critical dynamic buckling due to shot peening(SP) occur in intermediate columns of 8 mm in diameter and at 81 slenderness ratio(S.R) . Figure (6), increasing the effective length (Leff) reducing the critical buckling load (P_{cr}) for all the slenderness ratios taken. The shot peening at 25 min. raising the curves and improved the critical buckling load (P_{cr}) for all the selected slenderness ratio. This improvement is coming from the presence of compressive residual stresses at the surface and sub surface of columns. This results is agreed with Ref[16].

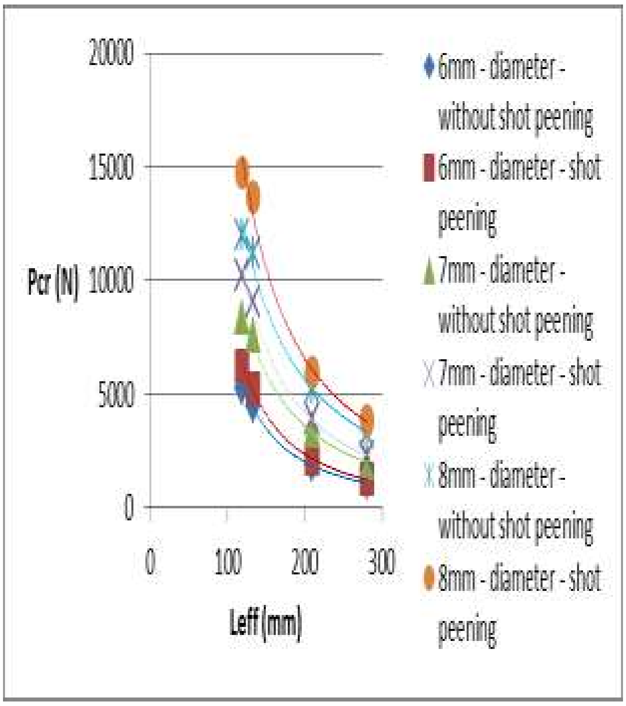

Figure (6) the critical buckling load (P_{cr}) without shot peening (WSP) and shot peening (SP) against the effective length (L_{eff}) for long and intermediate columns.

The influence of shot peening (SP) on the critical buckling load(P_{cr}) for long columns are 15.38%, 15.35% , 15.39% , 14.80% , 15.04% and 13.33% while for intermediate column , 18.51% , 18.73% , 20.30% , 21.20% , 22.14% and 23.07%. It is observed that the effect of 25 min shot peening(SP) treatment on critical dynamic buckling loads increase with reducing the effective length and remains almost constant when the effective length(L_{eff}) larger than 200mm as given in table (5). This results is agreement with ref. [8].

Table (5) Critical buckling load (P_{cr}) verses the effective length (L_{eff}).

L (mm)	L_{eff} (mm)	D (mm)	A mm^2	P_{cr} (WSP)	P_{cr} (SP) (N)
400	280	6	28.274	1066	1230
300	210	6	28.274	1895	2186
400	280	7	38.484	1975	2279
300	210	7	38.484	3398	3901
400	280	8	50.265	3303	3800
300	210	8	50.265	5285	5990
190	133	6	28.274	4434	5255
170	119	6	28.274	5276	6254
190	133	7	38.484	7560	9095
170	119	7	38.484	8403	10185
190	133	8	50.265	11168	13641
170	119	8	50.265	12011	14783

Table (6) Results of P_{cr} comparison under SP and WSP.

Without shot peening (WSP)

L_{eff}(mm)	D (mm)	P_{cr} exp (N)	P_{cr} Euler or John (N)	DP due to Eul or Joh%
280	6	1066	1599	33.33
210	6	1895	2843	33.34
280	7	1975	2963	33.34
210	7	3398	5267	35.48
280	8	3303	5054	34.64
210	8	5285	8986	41.18
133	6	4434	7095	37.5
119	6	5276	8443	37.6
133	7	7560	12097	37.5
119	7	8403	13445	37.5
133	8	11168	17870	37.5
119	8	12011	19218	37.5

Shot peening (SP)

L_{eff}(mm)	D (mm)	P_{cr} exp (N)	P_{cr} Euler or John (N)	DP due to Eul or Joh%
280	6	1230	1599	23.07
210	6	2186	2843	23.10
280	7	2279	2963	23.08
210	7	3901	5267	25.93
280	8	3800	5054	24.81
210	8	5990	8986	33.34
133	6	5255	7095	25.93
119	6	6254	8443	25.92
133	7	9095	12097	24.81
119	7	10185	13445	24.24
133	8	13641	17870	23.66
119	8	14783	19218	23.07

III. Comparison of P_{cr} due to Euler or Johnson with the experimental for both cases WSP and SP.

The variation of critical dynamic buckling loads of P-F 304 stainless steel columns with three different diameters i – e different cross sectional area can be seen in table (6) with the difference between the P_{cr} loads**.** This difference in percentage is calculated based on the expersion [5]**.**

Difference percentage

$$(DP) = \left[\frac{P_{cr}\ (Euler\ or\ John) - P_{cr}\ (exp)}{P_{cr}\ (Euler\ or\ John)}\right] \times 100 \qquad (6)$$

It is clear that, DP for unpeened is greater than peened specimens and the reasons may be coming from the followings.

1- The peened columns having mechanical and buckling loads greater than the unpeened columns.

2- The treated columns by shot peening carried out higher buckling life and higher residual stresses.

$$S.F = \frac{P_{cr}\ (Euler\ or\ Johnson)}{P_{cr}\ (Experimental)} \qquad (7)$$

The above equation gives, max S.F of 1.7 for unpeened and 1.5 for peened specimens. In order to use the Euler or Johnson formula it is recomoded to take factor of safety not less than 2.

Abdul aziz et al [16] concluded that a factor of safety of 3 should be taken when use the Euler and Johnson formulas.
It is observed from the above results that the highest DP between P_{cr} Euler or Johnson and P_{cr} exp.occured at 210mm L_{eff} with 41.18% for unpeened column.

IV. Buckling loads against slenderness ratio
The slenderness ratio of 304 stainless steel column are calculated for circle cross – section using the equation

$$S.R = \frac{L_{eff}}{r} \quad (8)$$

Where R is the radius of gyration and can be defined by the equation.

$$r = \sqrt{\frac{I_{min}}{A}} \quad (9)$$

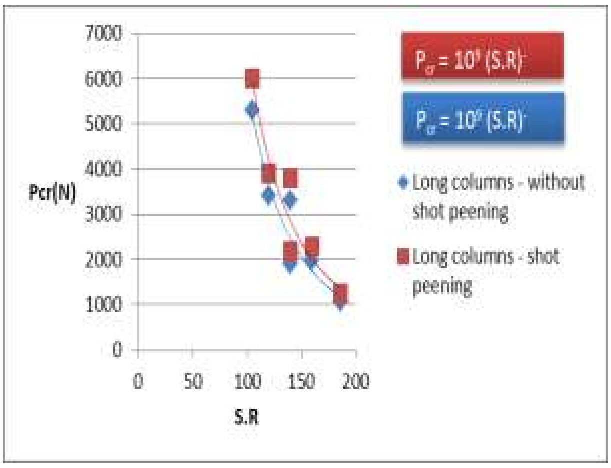

Figure (7) experimental P_{cr} against slenderness ratio (S.R) for long columns and two cases of testing.

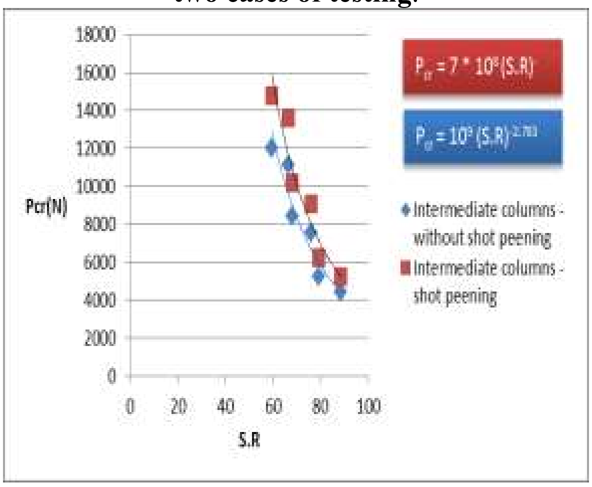

Figure (8) experimental P_{cr} against slenderness ratio (S.R) for intermediate columns and buckling without SP and with 25 min SPT .

The effects of S.R of column on critical dynamic buckling is expected, increasing S.R, which is illustrated in figures (7) (8), reducing the critical dynamic load for both columns, long and intermediate, and for both cases without SP and with SP. These results are in good correlation with Refs [9] [10].

6. Conclusions

In this work, the influence of shot peening on the critical buckling load performance was investigated on 304 stainless steel alloy and the following conclusions can be drawn.

1. Design and manufacture the electrical laser alarm system to assess the buckling failure of 304 stainless steel column and to estimate the critical buckling load under increasing the compressive load without shot peening(WSP) and with shot peening(SP) .
2. The experimental results revealed that the 25 minute shot peening time improved the critical buckling load by 13.3% - 15.39% improvement percentage for long columns while 18.51% - 23.07% improvement percentage for intermediate columns.
3. Difference percentage obtained from comparison between the critical buckling load theoretical and the critical buckling load experimental 33.33 to 41.18 for without shot peening and 23.07 to 33.34 for 25 minute shot peening time based on Euler and Johnson theories for both long and intermediate columns.

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