INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 10, Issue 4, 2019 pp.223-230
Journal homepage: www.IJEE.IEEFoundation.org

Influence of corrosion on buckling resistance of AISI 304 stainless steel columns

Ahmed A. Ibrahim[1], Al- Alkawi H. J[2], Al Nagshabandi A. M. Rachid[1], Samih K. Al-najjar[3]

[1] Sudan University of Science and Technology.
[2] University of Technology – Baghdad.
[3] State company for Automobile Industry and Equipment.

Received 9 May 2019; Received in revised form 3 Jul. 2019; Accepted 5 Jul. 2019; Available online 31 July 2019

Abstract
This paper investigates the dynamic behavior of buckling on AISI 304 stainless steel and AISI 304 corroded and as received were tested under dynamic compression buckling condition columns. Maximum reduction in buckling load was (28%) and (19.6%) for long and intermediate soil corroded columns respectively as compared with as received condition. Perry-Robertson equation was used to compare with the experimental results of buckling load.
Copyright © 2019 International Energy and Environment Foundation - All rights reserved.

Keywords: Soil; Buckling; Corrosion; Critical loads; Perry-Robertson equation.

1. Introduction

Material failures due to buckling are controlled by intrinsic factors, such as material property and extrinsic, such as environment and loading condition. For a given material, it is well known that corrosive media can accelerate buckling failure. It is noted that most of the corrosion is not a uniform corrosion but there is a random corrosion confined in a corner or central area which it is to be more critical [1].

Slater et al [1] investigated the corrosion of ship plates in which corrosion has reduced their thickness leading to accelerated failure buckling. They conclude that the corrosion plate have a significant effect on the buckling strength. Dolinsky [2] who first dealt with the strength of pipes subjected to continuous corrosion during working and stated that the main factor affect the strength of materials is the corrosion rate or corrosion speed. Paik [3] and Paik *et al* [4] investigated the ultimate tensile strength characteristics of plate elements with pit corrosion wastage under axial compressive. Paik *et al* [5] analyzed nonlinear finite element (ANSYS) package for steel plates under axial compressive and shear loads with varying the degree of pit corrosion intensity and plate geometric properties. It has been noticed that the smallest cross-sectional area is the dominant parameter to represent the ultimate strength reduction characteristics due to pitting corrosion. The ultimate strength of corroded plate with shear loads is governed by the degree of pit corrosion intensity.

Hussein [6] investigated the effect of rest period on buckling properties of (304 stainless steel) which used in drilling machine shaft and they concluded that the rest periods play an important factor for raising the critical buckling loads and thus increasing the factor of safety. There are not many works being reported on corrosion-buckling of stainless steel. Column fails by buckling when the axial compressive load exceeds some critical load [7]. The choice of which method to use depends on the value of slenderness ratio (S.R) or column constant (C_c). These factors can be defined as:

$$S.R = \frac{L_e}{r_{min}} = \frac{KL}{r_{min}} \tag{1}$$

And

$$r_{min} = \sqrt{\frac{I_{min}}{A}} \tag{2}$$

$$C_C = \sqrt{\frac{2\pi 2E}{\sigma_y}} \tag{3}$$

where; A: area of cross section (mm^2), r_{min}: Radius of gyration (mm), L: the length of the column (mm), L_e: Effect length of columns (mm), I_{min}: Moment of inertia (mm^4), σ_y: yield stress (MPa), E: modules of elasticity of materials used (MPa).

$$L_e = KL \tag{4}$$

where K: is constant dependant on the endurance fixity.
The purpose of this study is to investigate the buckling corrosion interaction behavior of columns made from (304 stainless steel) with a small diameter to column length.

2. Perry-Robertson equation
A component subject to compression is known as a strut if it is relatively long and prone to 'buckling'. A strut fails when a critical load called the 'buckling' or 'crippling' load causes sudden bending. The resistance to buckling is determined by the 'flexural rigidity' El or EAr_{min}^2, where r_{min} is the least radius of gyration and E is modules of elasticity of materials used. The important criterion is the 'slenderness ratio' L_e/r_{min}, where L_e is the effective length of the strut. The Euler theory is the simplest to use but the much more involved Perry-Robertson formula is regarded as the most reliable. This formula gives fairly correct results for all the types of columns ranging from short to long columns [8].

$$\text{Load} \quad P = A\left[\frac{\sigma_y+(\eta+1)\sigma_e}{2} - \sqrt{\left(\frac{\sigma_y+(\eta+1)\sigma_e}{2}\right)^2 - \sigma_y\sigma_e}\right] \tag{5}$$

where

$$\eta = 0.3\left(\frac{L_e}{100}\right)^2 \tag{6}$$

where L_e = actual length of pinned end strut.

$$\sigma_e = \text{Euler buckling stress} = \sigma_y\left[1 - \frac{\sigma_y\left(\frac{L_e}{r}\right)^2}{4\pi^2 \mathrm{E}}\right] \tag{7}$$

where σ_y = Yield stress in compression.

3. Experimental investigation
The samples used were AISI 304 stainless steel columns of 6mm diameter circular cross section area with different lengths (150 and 300) mm. Using rotating columns buckling test machine the samples were tested in two different conditions. First all test were run for new columns and studied the buckling resistance. Then the columns were subjected to corrosive media by burying it in the soil for 30 days to investigate the influence of corrosion on buckling resistance.

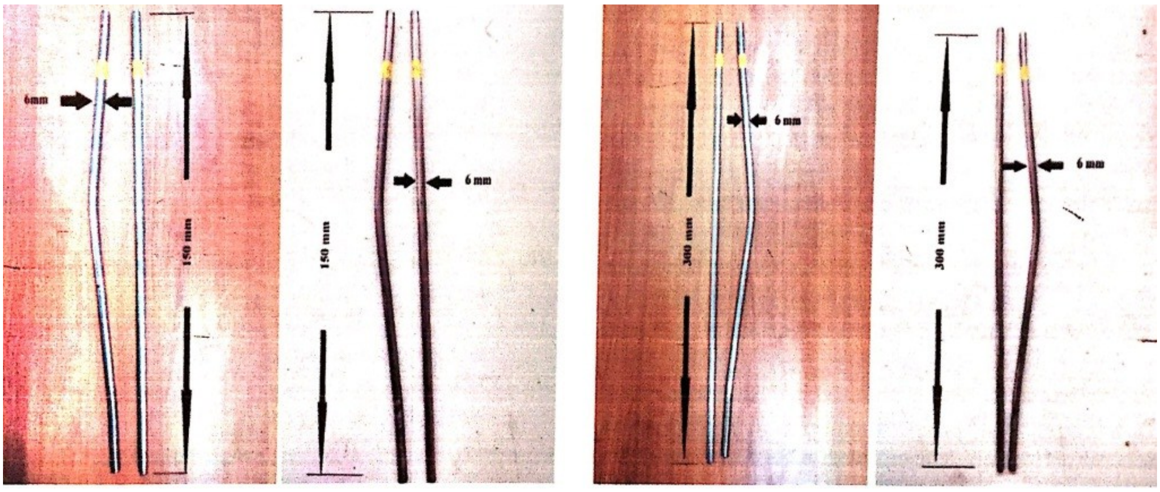
ISSN 2076-2895 (Print), ISSN 2076-2909 (Online) ©2019 International Energy & Environment Foundation. All rights reserved.

3.1 Chemical properties
This research starts firstly by analysis the chemical composition of the 304 stainless steel alloy composition and the results are compared with American standard ASTM A240, which are listed in Table 1.

Table 1. Chemical composition of 304 stainless steel (wt%).

304 Stainless steel	C%	Mn%	P%	S%	Si%	Cr%	Ni%	N%
Standard ASTM A240 [9]	0.08 Max.	2 Max.	0.045 Max.	0.030 Max.	0.75 Max.	18-20	8-12	0.10 Max.
Experimental	0.03	1.82	0.015	0.027	0.61	18	9.8	0.07

3.2 Buckling specimens
Buckling specimens (columns) were designed to use different slenderness ratio (S.R) to distinguish between intermediate and long columns (150 and 300mm) respectively. The dimensions of the specimens used were detailed in Figure 1 and the main buckling specimen's parameters were illustrated in Table 2. After cutting operation of suitable length completed all the specimens were polished using different wet silicon carbide papers (260 to 1200 µm) for surface fine finishing.



Intermediate columns Long columns

Figure 1. Buckling column specimens of AISI 304 stainless steel.

Table 2. Buckling 304 stainless steel specimen's parameters.

No.	L_T (mm)	$L_{eff.}$ (mm)	D (mm)	A (mm^2)	I (mm4)	S.R	Type of column
1	300	210	6	28.27	63.6	140	Long
2	150	105	6	28.27	63.6	70	Intermediate

3.3 Electrical laser alarm system
The project security and safety assured that the Laser-ray must go through long distance without scattering effect and should be almost invisible except the radiation and incident points have to be visible [10]. Then an invisible boundary of a sensitive area was drawn and validated. There are two parts of the system transmitter (first part) built with a laser radiator, a pair of dry cell batteries, an on-off switch and a stand to hold on digital electronic caliper. The receiver has a focusing Light Depending Resistor (LDR) sensor to sense the laser continuously also was hold with a stand and it connected with the main driver circuit. The circuit has two parts consisting of discontinuity filters of ray and other is alarm circuit. When anybody crossover the invisible ray the main circuit senses the discontinuity by sensor and turn on the alarm circuit. If the alarm circuit is on it will still ringing but there are durations of ringing depends on reset timer. The laser alarm system has built with low cost and high performance. The power consumption of the system is very low. The schematic diagram of electrical laser alarm system in described as in Figure 2 and Table 3 shows the component list of circuit diagram. While the actual system coupled with the buckling test rig is shown in Figure 3.

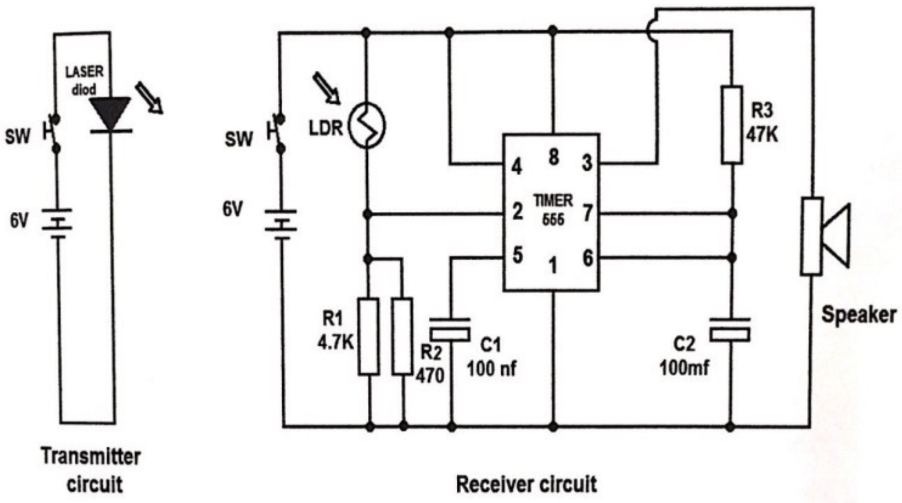


Figure 2. Circuit diagram of laser security system alarm.

Table 3. Laser alarm circuit diagram component.

Symbol	Component	Rating
SPK	speaker	5 watt, 8Ω
C1	Capacitor	100nF
C2	Capacitor	100µF
R1	Resistor	4.7K Ω
R2	Resistor	470 Ω
R3	Resistor	47 Ω

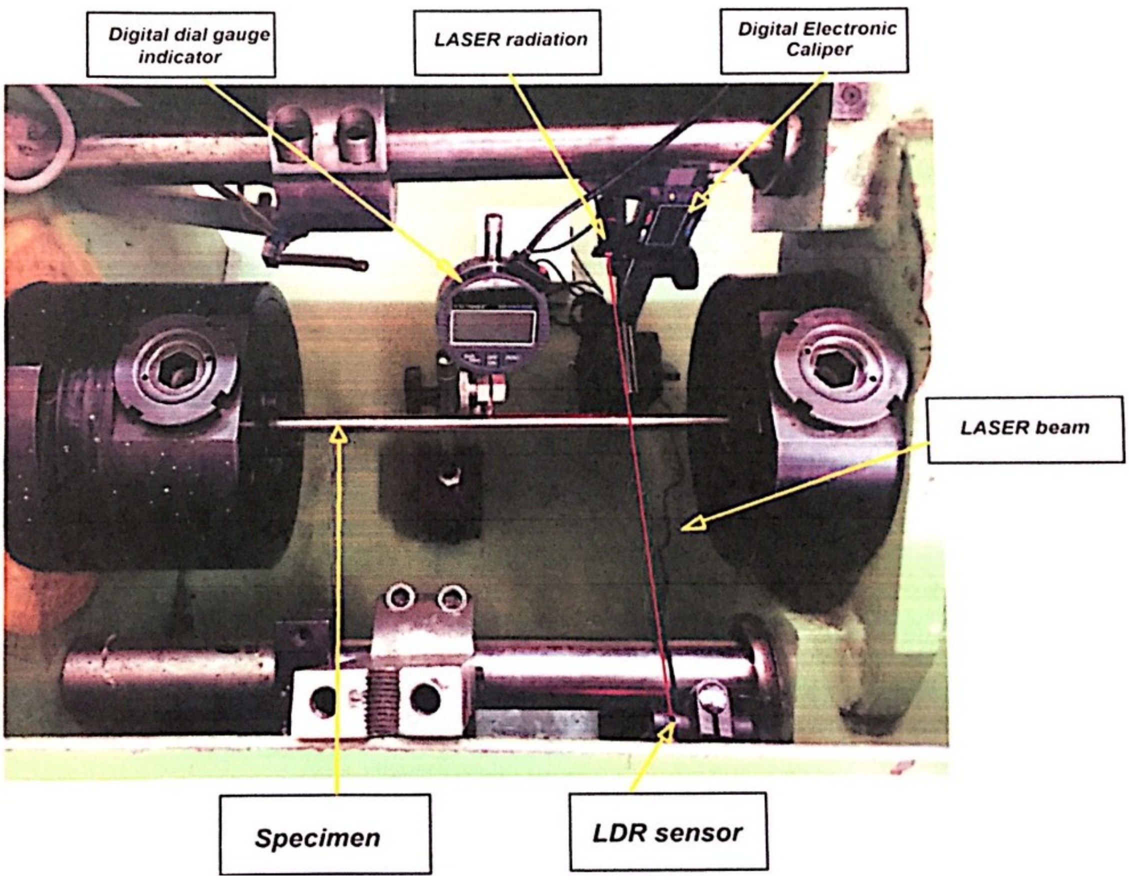


Figure 3. Actual electrical laser alarm system coupled with buckling test rig machine.

 ©2019 International Energy & Environment Foundation. All rights reserved.

Buckling of a column is the change of its equilibrium state at a critical compressive axial load applied. If a column has high bending stiffness, its buckling resistance is high. Failure column was described as elastic instability and the value of E of the materials is a key property [7].
Figure 4 shows the buckling test-rig machine. The rig consists of the following systems:

- Torsion systems.
- Compression system.

The torsion system consists of an electrical motor of (0.5kw), which operates at two different speeds, high speed (34 r.p.m) and low speed (17 r.p.m). When the motor starts, it gives motion in two different directions, clockwise and counterclockwise. Acyclic counter (indicating total number) is fixed on the control plate front. The recording digits are (99999.9) which refer to the number of cycles during test.

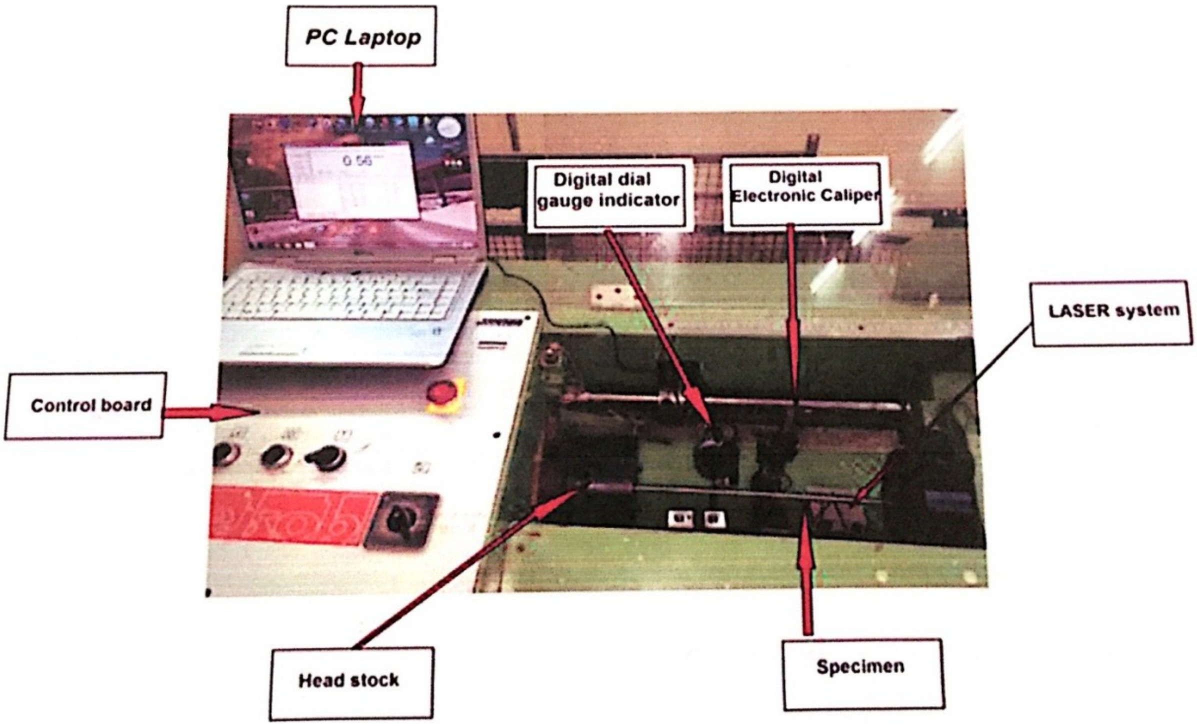


Figure 4. The test rig for dynamic buckling rests with the control panel.

The compression system includes a manual hydraulic pump with a maximum pressure up to (315 bar). A screwed shaft is used to transfer the pressure from the hydraulic pump to the jaw which supports the specimen. A digital dial gauge indicator is used to measure the specimen deflection. In the present study, under compression load control buckling failure is defined when the lateral deflection (total deflection) reach to (1%) of column length. Gradually increase the load and observe the behavior of the column until it begins to bend noticeably in the middle. This level of laterally bend is approximately 1% of the total length of column [3, 6].

4. Experimental results and discussion

4.1 Mechanical properties test

The tensile tests are done in the University of Technology – material engineering department. The results shown in Table 4 represent the tensile and mechanical properties of 304 stainless steel column.

Table 4. Tensile and mechanical properties test results of 304 column.

304 Stainless steel	σu (Mpa)	σy (Mpa)	E (Gpa)	G (Gpa)	μ poi. ratio	ϵ% Elongation
Standard ASTM A370 [9]	621	290	193-200	74-77	0.3	55
Experimental	628	311	200	75	0.3	51

 ©2019 International Energy & Environment Foundation. All rights reserved.

4.2 Buckling test results

The specimen was fixed horizontally and the initial deflection can be measured by digital dial gauge. Laser radiation is located in perpendicular position on the specimen and raising a level of laser radiation by moving digital electronic caliper to the initial deflection plus 1% of an actual length of the specimen. After complete adjustment of a specimen, the electrical motor was rotated at (17 r.p.m) and a compression load was increment by a hydraulic pump. The deflection of the specimen is recorded to the computer via dial gauge. When the deflection reached 1% of specimen length, the laser radiation will cut off and the alarm sound work. Then the test is completed, the machine shut down and the number of cycles and pressure value were recorded.

Table 5 illustrated experimental results of the critical buckling loads for 12 columns tested under compression loading without corrosion (as received material). Intermediate columns are defined by the minimum slenderness ratio, and for 304 stainless steel, the value was equal to S.R=70. For larger than 90 the column may change to become long column. It is clear that failure stress value as a result of applied buckling load decrease whenever slenderness ratio increases.

Table 5. Experimental results of 304 stainless steel without corrosion.

Long columns					Intermediate columns				
L_{total} (mm)	L_{eff} (mm)	S_{in} (mm)	P_{cr} (N)	N cycle	L_{total} (mm)	L_{eff} (mm)	S_{in} (mm)	P_{cr} (N)	N cycle
300	210	0.5	2500	18	150	105	0.6	3100	44
300	210	0.6	2650	22	150	105	0.8	3000	38
300	210	0.5	2700	26	150	105	1.1	2890	36
300	210	0.7	2675	20	150	105	0.7	3215	45
300	210	0.65	2780	27	150	105	0.85	3080	51
300	210	0.55	2690	29	150	105	0.9	3020	56

It can be seen from the Table 5 that the intermediate columns have more resistance to buckling load than long columns. This is clear from the loads values and the number of high cycles compared to long columns. Table 6 shows the experimental results of corroded columns buried in the soil for 30 days.

Table 6. Experimental results of 304 stainless steel with corrosion.

Long columns					Intermediate columns				
L_{total} (mm)	L_{eff} (mm)	S_{in} (mm)	P_{cr} (N)	N cycle	L_{total} (mm)	L_{eff} (mm)	S_{in} (mm)	P_{cr} (N)	N cycle
300	210	0.8	1980	16	150	105	0.7	2600	32
300	210	0.9	2000	20	150	105	1.0	2450	30
300	210	1.1	1850	19	150	105	0.9	2320	29
300	210	1.2	1790	17	150	105	0.8	2480	35
300	210	1.3	2010	15	150	105	0.75	2510	38
300	210	0.85	1880	18	150	105	0.92	2340	37

Corrosion in metal structures seems most important degradation mechanism in determining the remaining life of these structures. Deterioration of a steel structure due to corrosion can change its stiffness and behavior. The difference in the results that have been obtained from the buckling tests of columns before and after the burial process was a reduction of the load carrying capacity as shown in table (6), and consequently a reduction of the structural reliability. The reason for the decline in the strength may come back to several possibilities: Corrosion causes irregularity in diameter of the column which leads to the occurrence of the stress concentration areas lead to a decrease in the column resistance to withstand the stresses applied to it. As well as the column specimen suffers from low cycle fatigue resulted from cyclic load lead to reduction in strength and its life as in Table 6. The reduction, based on the average value of critical buckling load, is as (28%) and (19,6%) for long and intermediate corroded columns respectively, compared with as received material columns.

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online) ©2019 International Energy & Environment Foundation. All rights reserved.

Theoretical buckling load resulted from Perry-Robertson Equation were illustrated in Table 7. Comparing these results with the experimental critical buckling load results (average of six readings) for each column length. The difference between real (experimental) results and theoretical results of Perry-Robertson comes back to the accuracy of buckling machine construction, initial alignment of column specimen.
Where S.F is a safety of factor according to Perry-Roberston theory.

Table 7. Theoretical and experimental buckling load values.

Long columns				Intermediate columns			
$L_{eff.}$ (mm)	$P_{cr.}$ (N) exp.	$P_{cr.}$ (N) Perry-Robertson	S.F	$L_{eff.}$ (mm)	$P_{cr.}$ (N) exp.	$P_{cr.}$ (N) Perry-Roberson	S.F
In case of not corroded new columns							
210	2666	5517	2.06	105	3051	7659	2.51
In case of corroded columns							
210	1918	5517	2.87	105	2450	7659	3.1

5. Conclusions

In this paper, the Followings are the major conclusions of the present investigation can be drawn:

1. Intermediate columns are higher in buckling load and number of cycles to failure than long columns.
2. According to Perry-Robertson theory the factor of safety should be more than 2.5 for uncorroded columns and more than 3 for corroded columns.
3. Maximum columns length reduction because of buckling load in both long and intermediate was (28 %) and (19.6%) respectively compared with as received condition.
4. Critical buckling load using Perry-Robertson formula in both columns length gives a higher value than experimental results.
5. No. of cycles to reach the critical laterial deflection in long columns was higher for intermediate columns compared to long columns for both cases corroded and not corroded.

Abbreviations list

Symbol	*Diffinition*	*Unit*
σ_y	Yield stress	MPa
σ_u	Ultimate stress	MPa
$L_{eff.}$	Effective column length	mm
L_T	Total column length	mm
μm	Micron meter	
D	Diameter of column	mm
E	Modulus of elasticity	GPa
G	Modulus of rigidity	Gpa
AISI	American Iron & Steel Institute	
δ_{in}	Initial column deflection	mm
$\delta_{cr.}$	Critical deflection	mm
P_{cr}	Critical buckling load	N
N_f	Number of machine cycle	Cycle

References

[1] Slater, P.A., Pandey, M.D. and Sherbourne, A.N., 2000. Finite element analysis of buckling of corroded ship plates. Canadian Journal of Civil Engineering, 27(3), pp. 463-474.
[2] Dolinsky, V. M., 1967. Analysis of loaded tubas subjected to corrosion. khim, Nef,.Mashino-stroyenye, 2, pp: 21-30.
[3] Paik, J.K., 2003. Time-dependent risk assessment of aging ships accounting for general/pit corrosion, fatigue cracking and local dent damage. SNAME Trans, 111.
[4] Paik, J.K., Lee, J.M. and Ko, M.J., 2003. Ultimate compressive strength of plate elements with pit corrosion wastage. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 217(4), pp.185-200.

 ©2019 International Energy & Environment Foundation. All rights reserved.

[5] Paik, J.K., Lee, J.M. and Ko, M.J., 2004. Ultimate shear strength of plate elements with pit corrosion wastage. Thin-Walled Structures, 42(8), pp.1161-1176.
[6] Hussein, H.A., 2010. Buckling of square columns under cycling loads for nitriding steel din (ck45, ck67, ck101) (Doctoral dissertation, PhD. Thesis, University of Technology, Department of Mechanical Engineering).
[7] Alwan, M.K., 2014. Experimental And Numerical Study Of Buckling For Carburized Low Carbon Steel Columns. Journal of Engineering and Sustainable Development, 18(2), pp.133-145.
[8] Carvill, J., 1994. Mechanical engineer's data handbook. Butterworth-Heinemann.
[9] 304/ 304L stainless, UNS S30400 / UNS S30403, 2007. AK Steel Corporation, 9227 center pointe drive, West Chester, OH45069, available: WWW.aksteel.com.
[10] Paul, D., Rana, M.S. and Hossain, M.M., 2012. A preview on experimentation on Laser security system. Engineering Science and Technology: An International Journal, 2(2).

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online) ©2019 International Energy & Environment Foundation. All rights reserved.