# The Cooling Rate Effect on the Buckling Strength and Elastic Properties of Heated Martensitic Stainless Steel Columns

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***Abstract:***

**The buckling strength of slender columns its important property especially for columns that subjected to axial compressive forces. In this paper, we study the effect of cooling rate after heating over ($Ac_3$) for martensitic stainless steel columns on the buckling strength and elastic properties for different type of fixing for column. The results show that the best buckling strength occurs when using very slow cooling rate (inside furnace), that the buckling strength increased about (31%) and elastic modulus increased about (25%) because the slow cooling increase the formation of pearlitetic microstructure that had high strength and good elastic properties . The very fast cooling rate (in salt water) decreased the buckling strength about (46%) and elastic modulus about (51%) because the fast cooling rate increase the formation of martensitic microstructure that had high hardness and low buckling strength and low elastic properties.**

**Key words: Buckling strength, elastic modulus, martensitic stainless steel, cooling rate.**

## 1. Introduction:-

**A long slender bar subject to axial compression is called (*Column*) and failure in column occurs by (*Buckling*).[1]**

**In science, buckling is a mathematical instability, leading to a failure mode. Theoretically buckling caused by a bifurcation in the solution to the equations of static equilibrium. At a certain stage under an increasing load, further load is able to be sustained in one of two states of equilibrium: an un-deformed state or a laterally deformed state. [1,2]**

**In practice, buckling characterized by a sudden failure of a structural member subjected to high compressive stress, where the actual compressive stress at the point of failure is less than the ultimate compressive stresses that the material is capable of withstanding. For example, during earthquakes, reinforced concrete members may experience lateral deformation of the longitudinal reinforcing bars. This mode of failure is also described as failure due to elastic instability. Mathematical analysis of buckling makes use of an axial load eccentricity that introduces a moment, which does not form part of the primary forces to which the member is subjected. When load is constantly being applied on a member, such as column, it will ultimately become large enough to cause the member to become unstable. Further load will cause significant and somewhat unpredictable deformations, possibly leading to complete loss of load-carrying capacity. The member is said to have buckled, to deform.[2,3]**

## 2. The Euler's Formula :-

**The critical load ($P_{cr}$) of slender bar subjected to axial compression is the value of axial force that is just sufficient to keep the column in slightly deflected configuration as shown in figure (1) .**

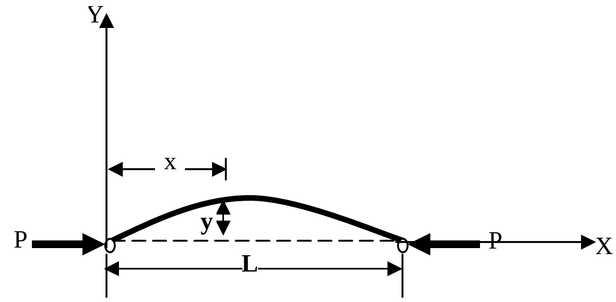


**Fig.-1- Deflected shape of column**

**The ratio of length of the column to the minimum radius of gyration of the cross-sectional area is termed (*Slenderness ratio*) of the column. This ratio is dimensionless and expressed as: [3,4]**

$$\text{Slenderness ratio} = \frac{L}{r_g} \qquad (1)$$

**where:**
**L ----- length of bar**
**$r_g$ ----- radius of gyration [is a parameter which quantifies the propensity of failure in a certain direction and can be expressed by the moment (I) of an area (A) then the radius of gyration is expressed as ] :**

$$r_g = \sqrt{\frac{I(m^4)}{A(m^2)}} \tag{2}$$

**Mathematical model for figure (1) are:**

$$EI\frac{d^2y}{dx^2} = M = -Py \tag{4}$$

**Let** $$\left(\frac{P}{EI} = k^2\right) \tag{5}$$

$$\Rightarrow \frac{d^2y}{dx^2} + ky = 0 \tag{6}$$

**This equation is readily solved by standard technique of differential equations as shown:**

$$Y = A\sin(kx) + B\cos(kx) \tag{7}$$

**From boundary condition of column:**
***Y*=0 at x=0 ▪▪▪▪➡ *B*=0**
**Y=0 at x=L ▪▪▪▪➡ kL=n $\pi$ where (n=1,2,3,4,……., )**

$$\therefore\ kL = n\pi \tag{8}$$

**Sub equ.(5) in equ.(8)**

$$\therefore \sqrt{\frac{P}{EI}}L = n\pi \tag{9}$$

$$\Rightarrow P = n^2\frac{\pi^2 EI}{L^2} \tag{10}$$

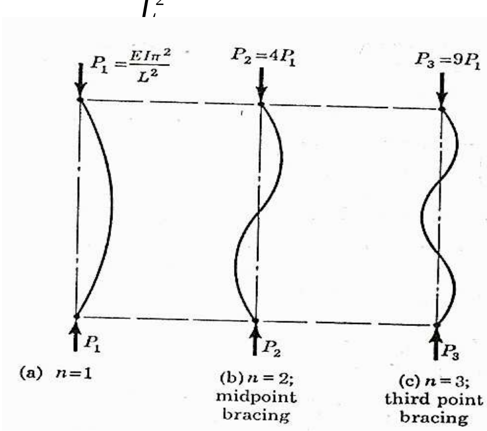


**Fig. 2. Effects of (n) on loads**

**when n= 1 (pin-pin ends) then :-**

$$P = \frac{\pi^2 EI}{L^2} \tag{11}$$

**and the Buckling Strength is define as:**

$$\sigma = \frac{\pi^2 EI}{A * L^2} \tag{12}$$

**This is called (Euler's buckling formula) for load and stress of pin-pin column.**
**The deflection shape as sine wave is:**

$$y = A\sin\left(\sqrt{\frac{P}{EI}}x\right) \tag{13}$$

**Sub equ. (9) in equ.(13) and we get :**

$$y = A\sin\left(\frac{\pi x}{L}\right) \tag{14}$$

**When n=1 (pin-pin end)**
**Equation (10) modified to the form:-**

$$P = \frac{\pi^2 EI}{(KL)^2} \tag{15}$$

**and to determine the value of elastic modulus can using the equ:**

$$E = \frac{\sigma(KL)^2}{\pi^2 * I} \tag{16}$$

**where (*KL*): is an effective length of column ($L_e$), and value of (*K*) depend on type of fixing for the column as shown in figure (3).[5,6]**

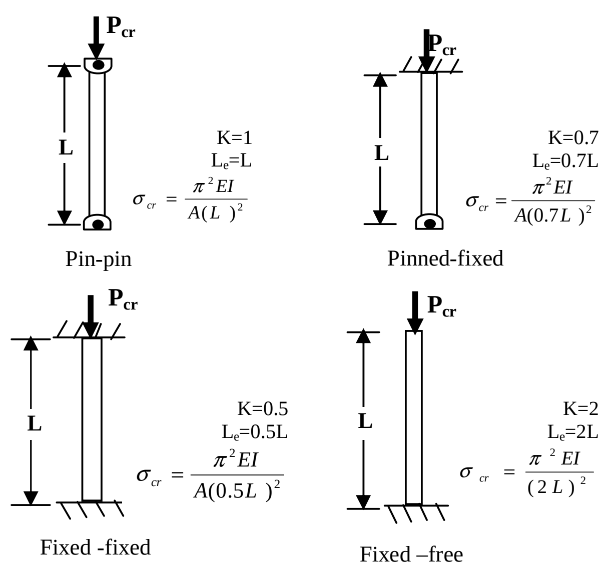


**Fig.3. Types of Column fixing**

## 4. Finite Element Model:-

**The linear or eigenvalue, buckling account for stress stiffness effects where compressive stresses tend to lessen a structure's ability to resist lateral loads. As the compressive stress increase, the resistance to lateral forces decreases. At some load level, this negative stress stiffening overcomes the linear structural stiffness, causing the structure to buckle.**

**The ANSYS program uses an eigenvalue formulation to perform linear buckling analysis. This formulation determines the scaling factors (eigenvalues) for the stress stiffness matrix that offset the structural stiffness matrix. The governing equation for linear buckling is :-**

$$([K] - l[S])\{u\} = 0 \qquad (17)$$

**where:**

**[K]…… structural stiffness matrix**

**[S]……. stress stiffness matrix**

***l*……..eigenvalue representing the scale factors**

**$\{u\}$……..eigenvector representing the buckled shape.**

**The point at which buckling occurs is called the bifurcation point, because of the two paths the force-deflection curve can take after reaching that point. After exceeding the bifurcation point, the structure will either buckle or continue to take on load in unstable state.**

**It is important to realize that linear buckling cannot account for any nonlinearities or structural imperfections. These factors, if present in an actual structure would cause the buckling load to be lower than the analysis results. However, linear buckling is very efficient and therefore requires relatively little computer time compared to nonlinear buckling analysis. It is useful for studying the general behavior of a structure before performing a nonlinear stability analysis, or for academic engineering studies.[7]**

**The linear buckling model by ANSYS V.11 shown in figure (4), when using element of type (3-D 10-Node Tetrahedral Structural Solid) , and using properties of experimental work with type of fixing for each samples to comparing with experimental work results.**

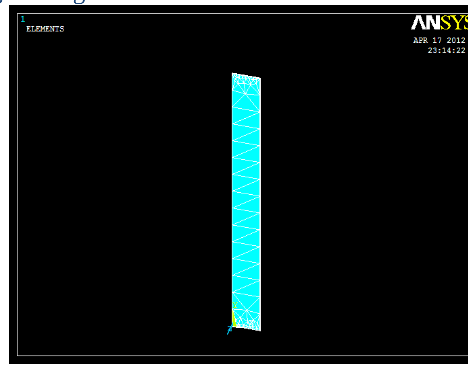


**Fig.4. 3-D Finite Element Model for buckling samples**

## 5. Experimental Work:-

**In the experimental, work the stainless steel grade (410) that ferro-magnetic type with chemical composition that shown in table (1) and microstructure shown in figure (5).**

**Table.1. Chemical composition of martensitic stainless steel grade (410).**

| Composition | C | Cr | Ni | Mn | Si | P | S | Fe |
|---|---|---|---|---|---|---|---|---|
| % | 0.15 | 12.5 | 1 | 1 | 1 | 0.04 | 0.03 | Balance |

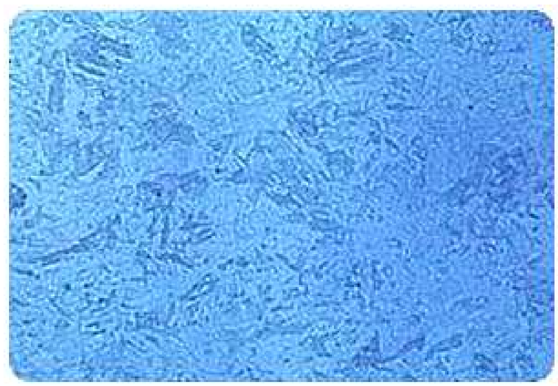

**Fig.5.Microstructure of martensitic stainless steel .[8]**

**The application of this type of stainless steel are : aerospace, automotive, hydroelectric engines, cutlery, defense, power hand tools, pump parts, valve seats, chisels, bushings, ball bearings, sporting equipment industry, surgical instruments etc.[8,9]**

**The samples dimensions shown in figure (6), show that the samples are slender columns.**

**The sample tested according to standard (ASTM D683) by using universal test machine (Inestron wdw100-E) to find the mechanical properties of stainless steel samples as shown in figure (7).**

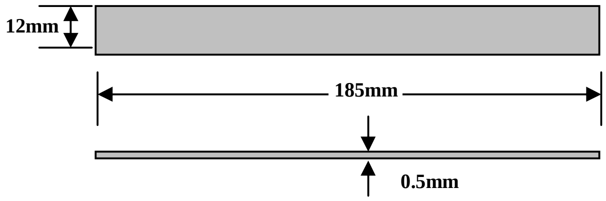


**Fig.6.The dimensions of experimental samples.**

**Fig.7. Universal test machine**

**The column samples heated inside electrical furnace above the upper critical temperature ($A_{C3}$) by ($60C^o$) that chooses according to:[10]**

**[$Ac_3 = 910 - 203\sqrt{\%C} - 15.2(\%Ni) + 44.7(\%Si) + 104(\%V) + 31.5(\%Mo)$]**

**Standard deviation=$\pm 16.7C^o$.**

**So that the samples will heated to ($920C^o$) with soaking time inside for (2hr) to ensure the all structure been as austenite structure and then the samples cooled with different cooling rate as :[ 11,12]**

1) **Very slow cooling (inside furnace):- The very slow cooling will provide the time to austenite microstructure to transform to pearlite structure that had good strength but low less hardness .**
2) **Slow cooling (still air):- The advantages of using air are that distortion is negligible and that the steel can easily straightened during cooling process. One drawback here is that the surface may be oxidized the cooling**
3) **Medium cooling (by oil):- When slower cooling rate is desired oil quenches can be employed. The slower cooling through the ($m_s$) to ($m_f$) temperature range leads to a milder temperature gradient and a reduced likelihood of cracking. Problems associated with quenchants include water contamination, smoke and fire hazards. In addition, quench oils tend to be somewhat expensive.**
4) **Fast cooling (by water):- water is good quenching medium. It is cheap, readily available, easily stored nontoxic nonflammable smokeless and easy to filer and pump but with water quench the formation of bubbles may cause soft spots in the metal. Agitation is recommended with use of water quench. Still other problems with water quench include its oxidizing nature, its corrosivity and the tendency to excessive distortion and cracking**
5) **High speed cooling by brine (salt water):- Brine is a more severe quench medium than water. Unfortunately, it tends to accelerate corrosion problems unless completely removed. Sodium or potassium hydroxide can be used when very severe quenching is desired and one wishes to obtain good hardness**

**The samples tested to find the critical load and critical buckling stress according to standard (DIN1025) by using Euler buckling tester with types of fixing as:-.[13]**

1) **Pin-pin column**
2) **Pin-fixed column**
3) **Fixed-fixed column**
4) **Fixed- free column**

**The applying load will increased until sample start buckle and record the value of load that causes it for different types of fixing and for each sample that cooled with different cooling rate.**

## 6. The results and discussions:-

**The figure (8) show the stress-strain diagram for martensitic stainless steel grade (410), and from these results can find the mechanical properties of material as shown in table (2).**

**From this figure can notice that the martinsitic stainless steel had high strength, good hardenability with low ductility and toughness.**

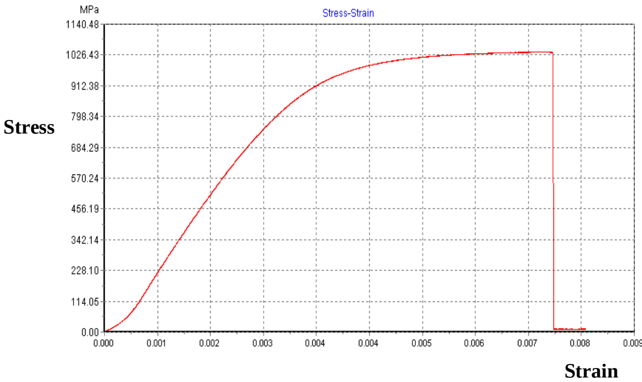


**Fig.8. Stress-strain diagram for stain for martensitic stainless steel sample.**

**Table.2. Physical and Mechanical properties of martensitic stainless steel.**

| Density (kg/m3) | Elastic modulus (GPa) | Yield Strength (MPa) | Tensile Strength (MPa) | Maximum Strain (%) |
|---|---|---|---|---|
| 7800 | 202 | 560 | 1040 | 0.75 |

**Figures (9, 10, 11, and 12), show the relation between the cooling rate and the buckling strength of martinsitic stainless steel at experimentally and ANSYS for various type of fixing :-**

**1-pin-pin column**

**2- pin-fixed column**

**3-fixed-fixed column**

**4-fixed-free column**

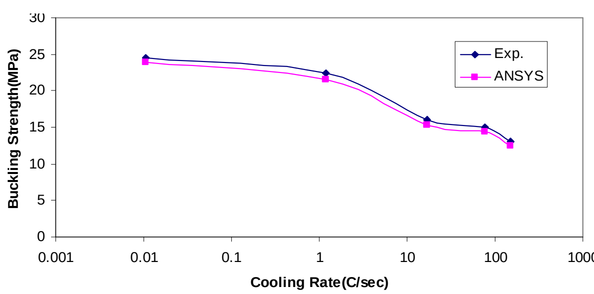


**Fig.10.The relation between cooling rate and buckling strength for pin-fixed ends column.**

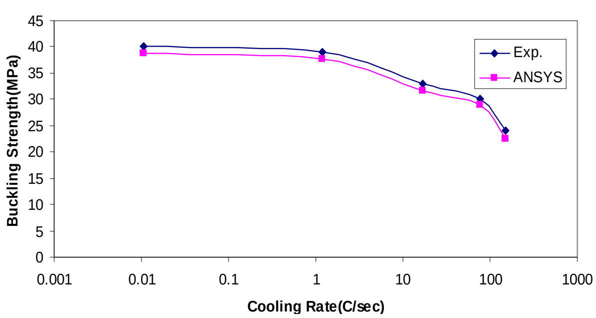


**Fig.11.The relation between cooling rate and buckling strength for fixed-fixed ends column**

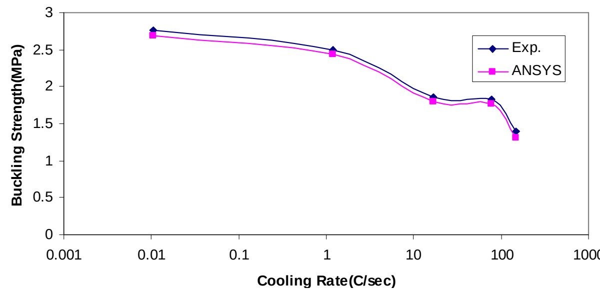


**Fig.12.The relation between cooling rate and buckling strength for fixed-free ends column**

**From these figures we can notice that the samples that cooling by very slow cooling rate (inside furnace) will had better buckling strength than the samples that cooling with slow cooling rate (still air) , medium cooling rate (by oil) ,quenching (by water) , and high quenching (salt water). This occur due to the very slow cooling inside furnace after heating over (920C$^{o}$) will be as annealing process, and this heat treatment make the stainless steel more soft but increased tensile strength because the fine pearlitic structure will appear clearly and its causes the increasing in tensile strength , while the fast cooling (quenching) will give the sample high hardness and reduces the tensile strength because during fast cooling austenite cannot transform to ferrite and pearlite by atomic diffusion. With the quenching-hardening process, the speed of quenching can affect the amount of martenisite formed. This severe cooling rate will be affected by the component size and quenching medium type (water, salt water).**

**The critical cooling rate is the slowest speed of quenching that will ensure maximum hardness (full martensitic structure) .[14,15]**

**Figures (13, 14, 15, and 16) show the relation between the cooling rate and Elastic modulus (E) for martensitic stainless steel experimentally only.**

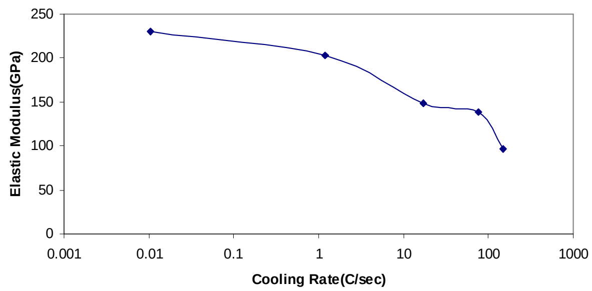


**Fig.13.The relation between cooling rate and Elastic modulus of pin-pin ends column.**

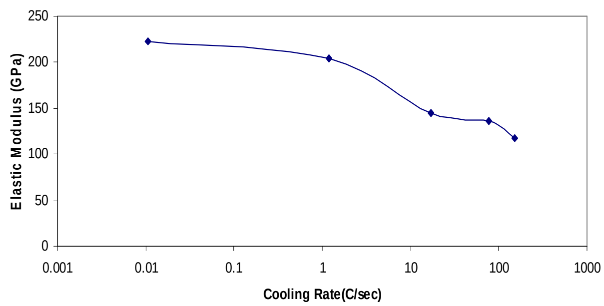


**Fig.14.The relation between cooling rate and Elastic modulus of pin-fixed ends column.**

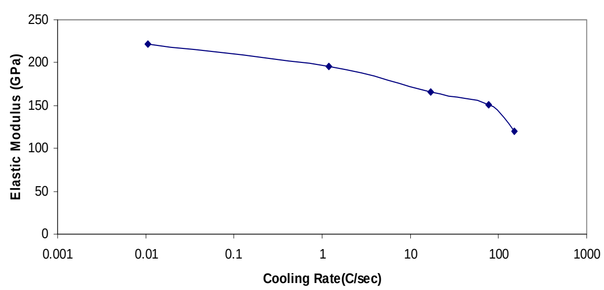


**Fig.15.The relation between cooling rate and Elastic modulus of fixed-fixed ends column.**

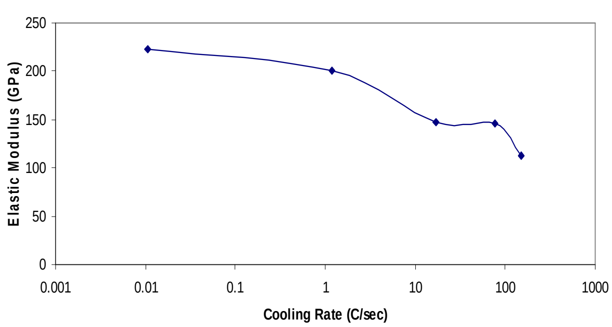


**Fig.16.The relation between cooling rate and Elastic modulus of fixed-free ends column.**

**From these figures can notice the elastic modulus will effected by cooling rate and that due to the microstructure that produce after cooling.The very slow cooling (inside furnace) will make most microstructure been as pearlite phase and that had high strength, high elastic modulus , and good toughness .**

**Figure (17) show the comparison between the elastic modulus at different cooling rate for various type of fixing , and can show the highly increasing in elastic modulus when using very slow cooling(inside furnace) and decreasing in its value at very fast cooling(by salt water) for different type of column fixity.**

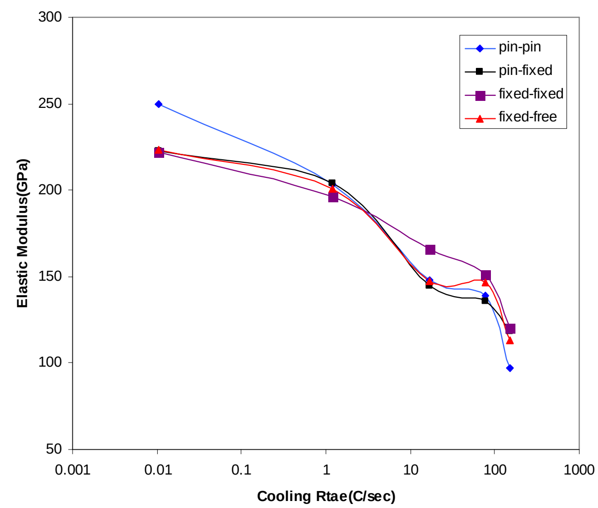


**Fig.17.The relation between cooling rate and Elastic modulus for various type of beam fixing**

## 7. The Conclusions:-

**The buckling strength of materials affected by the tensile properties and that appear so clear for martensitic stainless steel slender column that had good strength but low ductility and toughness. The heating of martensitic stainless steel slender columns over the upper critical temperature then cooling them with different cooling rate. The results show that the very slow cooling (inside furnace) will provide the increasing in buckling strength (about 31%) and increase in elastic properties (about 25%) because the slow cooling will provide the enough time to transformation of microstructure from austenite to pearlite that had high strength and high elastic modulus. With very fast cooling(with salt water), the buckling strength will reduces (about 27%) when cooling by water and (46%) by salt water cooling, and reducing the elastic properties about (30%) for water cooling, and (51%) for salt water cooling.**

**For future work, we recommend studying the effect of cooling rate on buckling strength of other types of materials and study the effect**

**of cooling rate on mechanical properties of martinsitic stainless steel like tensile strength, impact strength, and hardness.**

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