Studying the Effect of Cooling Rate on the Linear, Non-Linear Deflection and Elastic Properties of Stainless Steel (grade 410) Beams

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Abstract

In this paper, the non-linear analyses of beam deflection were used to calculate the modulus of elasticity of stainless steel (grade 410) beams that exposed to heating and then cooling with different rate. Several specimens of alloy steel were heated to temperature above critical temperature A_{C3} at iron-carbon diagram (about 920C^o) and then cooling with different cooling rate by using various cooling media. The cooling rates were (0.11, 1.2, 17, 77 and 150^{o}C/Sec). In order to measure the modulus of elasticity of these specimens, the linear and non-linear analysis (using ANSYS V.14 Software) for calculating the deflection of beam are used in additional to experimental results of maximum deflection of beam. From the theoretical and experimental results of maximum deflection of beam, the modulus of elasticity of the specimens were calculated using statistical method and then compared the results with the experimental results from tensile stress. For calculating the modulus of elasticity, the experimental results of maximum deflection of beam at different applied load were recorded and the modulus of elasticity calculated. A very good agreement between experimental and theoretical results and the maximum error was (8%).

Key words: stainless steel, Beam deflection, linear and non-linear deflection, cooling rate, modulus of elasticity, finite element.

1. Introduction

Deflection of beams depends on the stiffness of the material and the dimensions of the beams as well as the more obvious applied and supports. [1, 2, 3] At large deflections, the behavior of beam will change from bending to catenary action. Since the amount of catenary action is principally a function of the beams deflection, this can give the beam a very high load carrying capacity without beam collapse.[4]

Due to large deflection, the bending displacements are obtained from the (Euler-Bernoulli) beam theory taking into account the geometric non-linearity.[5]

A.Banerjee et al [5] proposed the non-linear shooting and adomian decomposition methods to determine the large deflection of cantilever beam under arbitrary loading condition. Li Chen[6] proposed a new integral approach to solve the Large deflection of cantilever beam by using the moment integral treatment. Carlos Vega et al [7] using the classical theory of the (Elastica) and the corresponding elliptical functions to large deflection analysis and post-buckling behavior of laterally braced or unbraced slender beam-columns of symmetrically cross-section subjected to end loads (forces and moments).T.S.Jang et al[8] developed new method of analyzing the non-linear deflection behavior of an infinite beam on the non-linear elastic foundation. Tzong Mou Wu [9] using an analysis program to obtain the accurate deflection and slopes of cantilever and simply supported beam. Kisso Kang et al [10] proposed an evaluation technique for the elastic modulus of cantilever beam by vibration analysis based on time average electronic speckle pattern interferometry (TA-ESPI)and Euler-Bernoulli equation. V.Azhmyakov and W.Schmidt [11] investigate the optimal dynamics of elastic beams with rectangular cross-section.

Raymond H.Plaut [12] determines the optimal distribution of material to minimize the vertical deflection of the free end of horizontal cantilever beam, and the beam is only subjected to its own weight. Large deflections are considered and the structure is modeled as an inextensible elastica. Sageev Oore [13] using the analysis for slender beams with varying cross-section under large non-linear elastic deformation. A thickness variation function is derived to achieve optimal-constant maximum bending stress distribution along the beam for inclined end load of arbitrary direction. Ang M.H [13] review several methods for completely solving the beam deflection curve of very flexible beams undergoing large deflections with the objective of compensating for these deflections. A simple numeric method is introduce and explore the feasibility of using neural network to perform the nonlinear mapping between the load and the resulting beam curve parameters.

The deflection of a cantilever beam under loading is known to be describes by relationship between the curvature at any point on the beam and the applied moment at the point under assumption that the material of beam linearly elastic. This relationship is:

$$\therefore \delta y = \frac{p * l^3}{3E * I} \qquad (1)$$

Equation (1) used for determine the maximum deflection for cantilever beam when subjected to concentrated load at free end. and equation (1), can used to find the elastic modulus after cooling as :

$$E = \frac{p * l^3}{3 * \delta y * I} \qquad (2)$$

Where:

P=concentrated load at the free end of beam (N)

l=beam length (m)

δy=beam deflection before and after cooling (m)

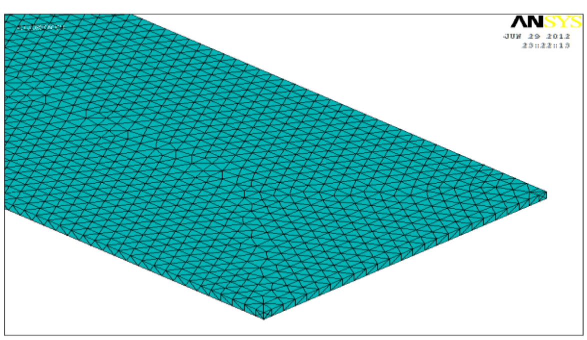
I=second moment of area for beam (m)

The aim of this work is study the effect of different cooling rate on the elastic properties, linear and non-linear deflection of stainless steel (grade 410) beam.

2. Finite Elements Models

In this paper, two finite elements models made using ANSYS software version 14. The first model deals with linear deflection of the cantilever beam under concentrated load. While the second model deals with non - linear deflection of the cantilever beam under concentrated load. In these models, the three dimension element(Solid 92) used as shown in Figure (1), (see Help of ANSYS [15]). The number of elements in these models was (40,000) and the number of nodes was (80,000). The cases, which were studied, can be listed in table (1).

Fig. 1. Three Dimensions Elements Mesh.



Table(1): ANSYS Software Cases			
No.	Case Details	Type of Analysis	Applied Load (N).
1.	Deflection of beam without thermal cycle.	Linear and Nonlinear	0.0981-0.6867 step 0.0981
2.	Deflection of beam with thermal cycle (heating to 920C^0 with cooling rate 0.011 C^o/sec)	Linear and Nonlinear	0.0981-0.6867 step 0.0981
3.	Deflection of beam with thermal cycle (heating to 920C^0 with cooling rate 1.2 C^o /sec)	Linear and Nonlinear	0.0981-0.6867 step 0.0981
4.	Deflection of beam with thermal cycle (heating to 920C^0 with cooling rate 17 C^o/sec)	Linear and Nonlinear	0.0981-0.6867 step 0.0981
5.	Deflection of beam with thermal cycle (heating to 920C^0 with cooling rate 77 C^o/sec)	Linear and Nonlinear	0.0981-0.6867 step 0.0981
6.	Deflection of beam with thermal cycle (heating to 920C^0 with cooling rate 150 C^o/sec)	Linear and Nonlinear	0.0981-0.6867 step 0.0981
7.	Deflection of beam of several modulus of elasticity (80, 85, 90, 275, 300, 325 and 350 GPa.)	Linear and Nonlinear	0.0981-0.6867 step 0.0981

3. Experimental Work

3.1 Sample preparation

The chemical composition of the alloy used can be seen in table (2) by x-ray analysis:

Table (2): Chemical composition stainless steel beam.

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

The applications of this type of 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.[16,17]

3.2 Tensile Test Steps:

1. The tensile test done according to American standard (ASTM D683) by using universal test machine (Inestron wdw100-E) to determine the properties like (elastic modulus , yield strength ,and ultimate strength for sample).
2. Fixing the sample between the machine grips.
3. Applied the load at strain rate of (0.5 mm/min).
4. Record the results of test and the stress-strain diagram.

figure (2) show the dimensions of tested stainless steel sample .

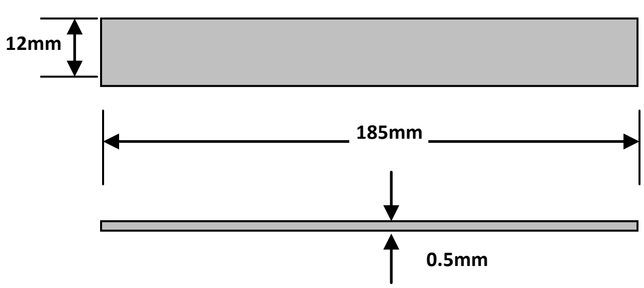


Fig.2.The dimensions of stainless steel sample.

The samples heated inside electrical furnace above the upper critical temperature (AC_3) by (60C^o) that chooses according to:[18]

$[Ac_3 = 910 - 203\sqrt{\%C} - 15.2(\%Ni) + 44.7(\%Si) + 104(\%V) + 31.5(\%Mo)]$
Standard deviation= $\pm$ 16.7C^o.

So that the samples heated to (920C^o) with soaking time inside furnace for (2hr) to ensure the all structure been as austenite structure and then the samples cooled with different cooling rate as: [19, 20]

1) Very slow cooling (inside furnace 0.011C^o/sec):- 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 1.2C^o/sec):- 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 17C^o/sec):- When slower cooling rate is desired oil quenches can be employed. The slower cooling through the (ms) to (mf) 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 77C^o/sec):- 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 150C^o/sec):- 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.

3.3 Beam Deflection Determination

The experimental procedure for calculating beam deflection that was used in this paper is the same procedure used by Belendez et.al[21], Figure.(3) shows a photograph of a system made up of a flexible steel beam of rectangular cross-section built-in at one end and loaded at the free end with a mass. The beam is fixed to a vertical stand rod by means of a multi-clamp using two small metallic pieces, which provide a better support .The load at the end of the beam was varied from (0.0981-0.6867N) by step (0.0981 N). The cases which were studied can be listed in Table (3) .

Fig. 3. Photograph of a cantilever beam loaded with an external vertical concentrated load at the free end.

Table (3): Experimental Cases.		
No.	Case Details	Applied Load (N).
1.	Deflection of beam without thermal cycle.	0.0981-0.6867 (step 0.0981)
2.	Deflection of beam with thermal cycle (heating to 920C^0 with cooling rate 0.011 C^o/sec)	0.0981-0.6867 (step 0.0981)
3.	Deflection of beam with thermal cycle (heating to 920C^0 with cooling rate 1.2 C^o /sec)	0.0981-0.6867 (step 0.0981)
4.	Deflection of beam with thermal cycle (heating to 920C^0 with cooling rate 17 C^o/sec)	0.0981-0.6867 (step 0.0981)
5.	Deflection of beam with thermal cycle (heating to 920C^0 with cooling rate 77 C^o/sec)	0.0981-0.6867 (step 0.0981)
6.	Deflection of beam with thermal cycle (heating to 920C^0 with cooling rate 150 C^o/sec)	0.0981-0.6867 (step 0.0981)

3.4 Theoretical Calculation of Elastic Modulus

The moduli of elasticity of beams determined by using two methods. The first method was statistically method .This method depends on the experimental results of deflection in additional to the theoretical result of non-linear and linear analysis in order to calculate the sum of the mean square root (χ^2) . The sum of the mean square root (χ^2) was minimum as possible, where (χ^2) is given by the following equation: [21]

$$\chi^2(E)=\sum_{j=1}^{J}\left[\delta y(E,F_j)-\delta y,\exp(F_j)\right]^2 \qquad (3)$$

Where:

$\delta y(E,F_j)$ is the theoretical deflection in y-direction for modulus of elasticity (E) and for concentrated load (F_j), and,

$\delta y,\exp(F_j)$ is the experimental deflection in y-direction for concentrated load (F_j).

The second method used the equation of deflection for cantilever beam which derived in section (equ.9) to calculate the modulus of elasticity of beam at each value of concentrated load and then calculate the average value of modulus of elasticity.

4. The results and discussions

5.1 Tensile Test Results

Table (4) show the mechanical properties of material of stainless steel (grade 410).

Table (4): Physical and Mechanical properties of stainless steel beam.

Elastic modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Maximum Strain(%)
202	560	1040	0.75

In this paper, four analyses methods were made. The first method was Non-linear analysis of cantilever beam. The variation of deflection of beam (using non-linear analysis) due to vary of concentrated load can be shown in figure (4). The effect of thermal cycle (heating + cooling) with different cooling rate can be illustrated in this paper. When the cooling rate was increased, the maximum deflection increased too at the same concentrated load. The increasing of cooling rate of thermal cycle leads to decreasing the modulus of elasticity of the beam and then the increasing in maximum deflection of beam. In Figure (5), the linear analysis of beam deflection can shown and the maximum deflection of beam will changed with varying the concentrated load, but the curve in linear analysis is more linearity than that in the non-linear analysis for the same cooling rate. By Theoretical linear analysis (equation Method) the maximum deflection will be increase when the concentrated load increased and when the cooling rate increase as shown in Figure (6) . Experimentally, the same phenomenon shown in Figure (7) where the maximum deflection will be increase when the concentrated load and cooling rate increase.

Figures from (8) to (13) show the comparison between the four analyzing methods for each cooling rate and the effect of nonlinearity can be appear sharply when the concentrated load was at maximum value. For any cooling rate, a very good agreement between the experimental results and non-linear analysis results was found and this agreement appear sharply when the cooling rate increase.

The theoretical and experimental methods for calculating the modulus of elasticity of beams were used. Figure (14) shows the values of modulus of elasticity calculating by these methods. When the cooling rate of thermal cycle was increased, the modulus of elasticity decreased. The maximum error percentage between the first theoretical results (statistical method) and experimental results was about (-0.6%) to (7.8%).

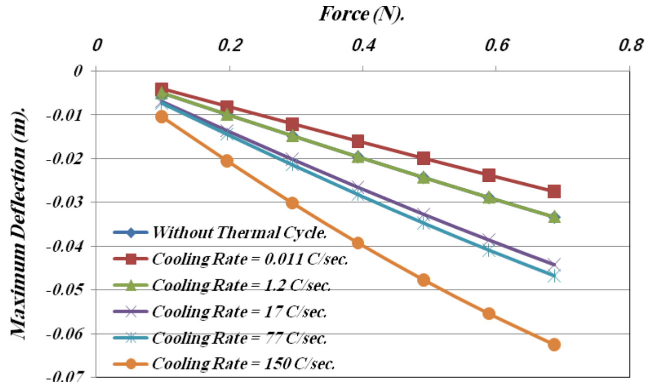


Fig.(4): Variation of Max. Deflection due to Applied Force for Different Cooling Rates Using Non-Linear Analyzing by ANSYS Software.

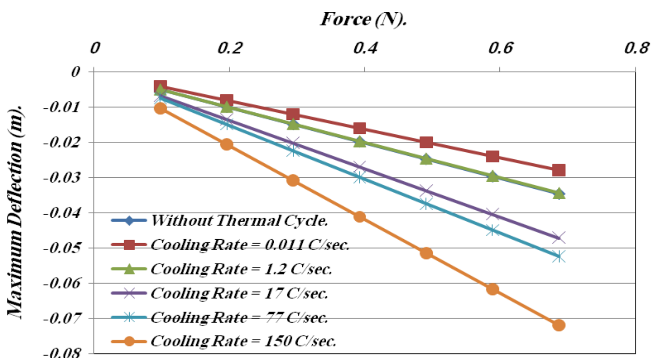


Fig.(5): Variation of Max. Deflection due to Applied Force for Different Cooling Rates Using Linear Analyzing by ANSYS Software.

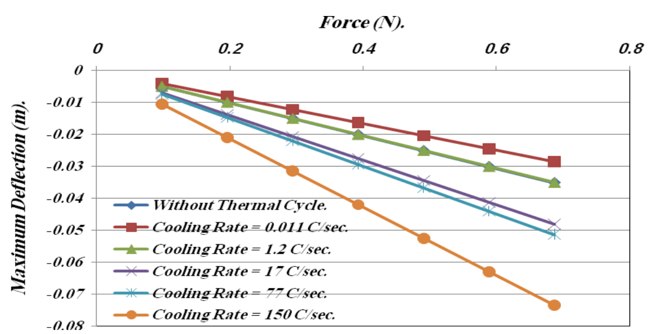


Fig.(6): Variation of Max. Deflection due to Applied Force for Different Cooling Rates Using Linear Analyzing.

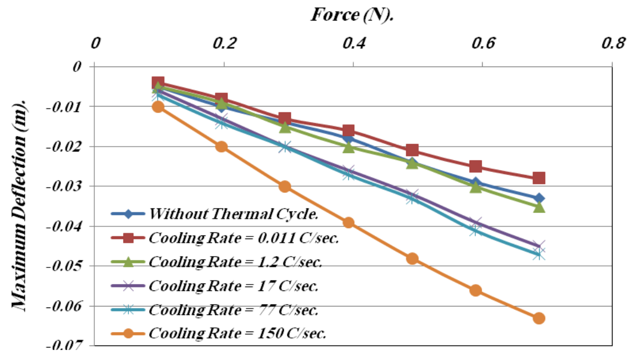


Fig.(7): Experimental Results of Variation of Max. Deflection due to Applied Force for Different Cooling Rates.

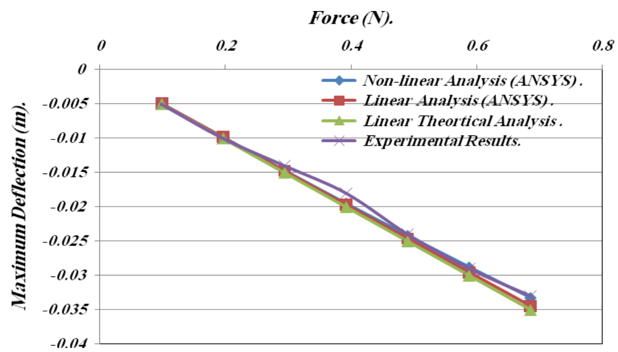


Fig.(8). Comparison Between Different Techniques to calculate Max. Deflection due to Applied Force for Beam Without Thermal Cycle.

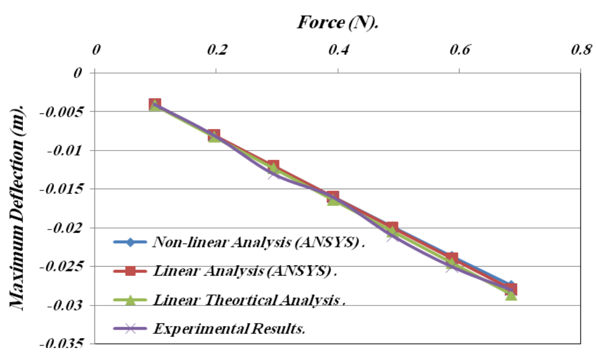


Fig.(9). Comparison Between Different Techniques to calculate Max. Deflection due to Applied Force for Cooling Rates= 0.011 C°/Sec.

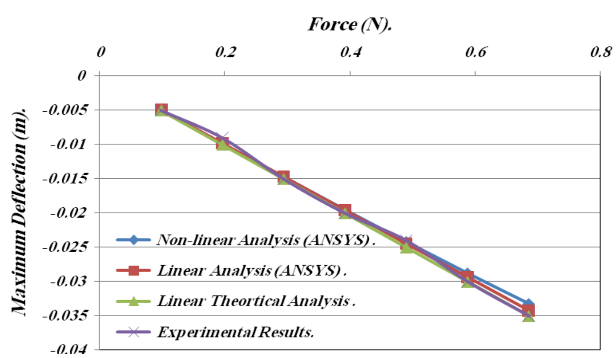


Fig.(10). Comparison Between Different Techniques to calculate Max. Deflection due to Applied Force for Cooling Rates= 1.2 C°/Sec.

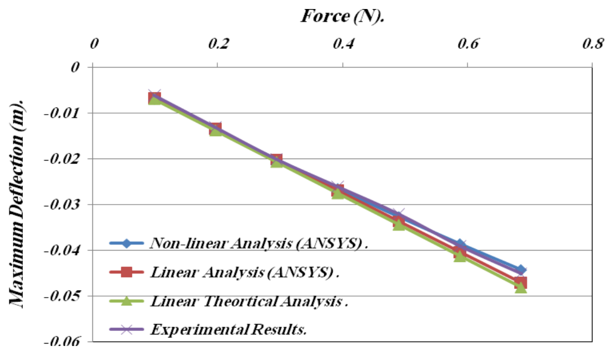


Fig.(11). Comparison Between Different Techniques to calculate Max. Deflection due to Applied Force for Cooling Rates= 17 C^o/Sec.

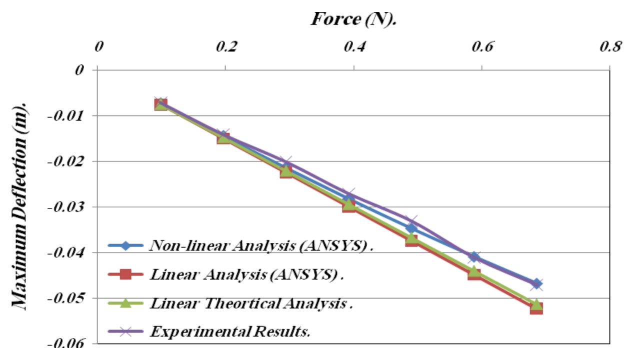


Fig.(12). Comparison Between Different Techniques to calculate Max. Deflection due to Applied Force for Cooling Rates= 77 C^o/Sec.

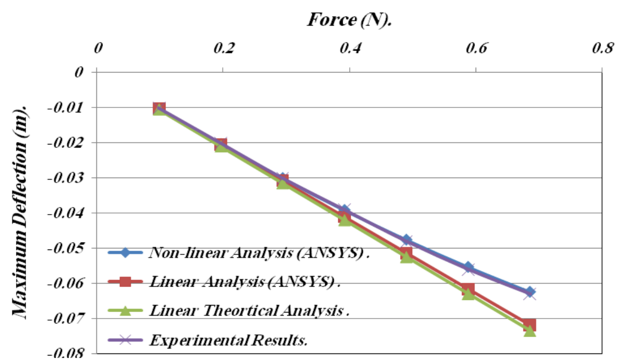


Fig.(13). Comparison Between Different Techniques to calculate Max. Deflection due to Applied Force for Cooling Rates= 150C^o/Sec.

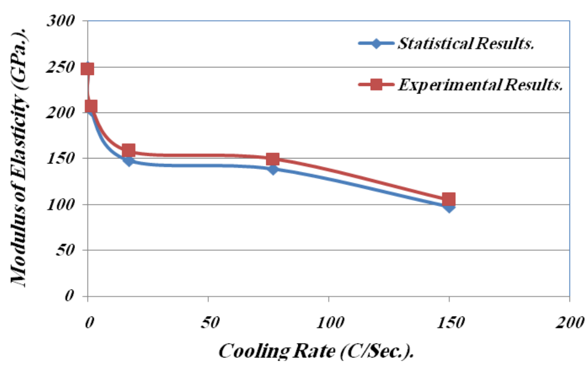


Fig.(14):Comparison Between Experimental and Statistical Results of Modulus of Elasticity When the Cooling Rate Changes.

5. Acknowledgment

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6. Conclusion

From the above results, the following remarks can be concluded:

1- The deflection of beam is effected by the rate of cooling for alloy steel beam and this deflection increased when using the high cooling rate.
2- The modulus of elasticity of stainless steel (grade410) samples effected by the cooling rate after heated over (A_{c3}), and this modulus increased when the cooling is so slow and vice versa.
3- The non-linearity of cantilever beam increased when the concentrated load increased.
4- The cooling rate affects on the non-linear deflection by varying the modulus of elasticity.
5- Good agreement between the experimental and theoretical results with divergence of (8%).

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