The Effect of Heat Treatment on Elastic-Plastic Behavior and Absorbing Energy for L-shaped Mild Steel Under Compressive Axial Load

Ayad Arab Ghaidan
Petroleum Eng. Department/ College of Eng./ University of Kirkuk

Abstract

The paper deals with the experimental investigation to crushing collapse behaviour of thin-walled mild steel L-shaped structural under compressive axial load. The aim of this paper is to show that the increase of plastic region will be on the account of elastic region for L-steel plates under compressive axial load by using heat treatment (Tempering). The result has shown a decrease in elastic region with an increase in plastic region during crushing L- steel plates which caused an increase in absorbing energy. Details of the deformation processes were examined by using theoretical, experimental and three-dimensional finite element models. The effect of heat treatment processes were presented to increase plastic region with absorbing energy during crushing plates, Heat treatment is a very useful process to improve absorbing energy with decreasing size of plates. Static load-deformation curves were compared with those obtained from theoretical model based on perfect plasticity and finite element simulations using nonlinear ANSYS program and obtained by quasi-static tests. Conclusions have been given concerning the agreement between the results of finite element simulations and the static once.

Keywords: **Heat treatment processes, Axial crushing, ANSYS, L-shape plate, Finite element.**

تأثير المعاملة الحرارية على سلوك المرونة- اللدونة و امتصاص الطاقة لصفائح الفولاذ على شكل L تحت قوى انضغاطية محورية

أياد عرب غيدان
قسم هندسة النفط / كلية الهندسة / جامعة كركوك

الخلاصة

يتعامل هذا البحث مع التجارب العملية لسلوك انهيار فولاذ على شكل حرف (L) تحت قوة انظغاطية محورية. تم مناقشة النتائج باستخدام نماذجَ عناصرِ محددة ثلاثية الأبعادِ وتجريبيةِ ونظريةِ. تم دراسة تأثير معاملة الحرارة على منطقة اللدونة و تاثيرها على امتصاص الطاقة اثناء السحق لصفائح ألفولاذ و تبين ان المعاملة الحرارية مفيدة جدا لتحسين الطاقة الممتصة عند تقليل ابعاد النموذج. تم مقارنة منحنيات القوى و التشويه اثناء السحق للنتائج المستحصلة من التجارب العملية و النظرية و العناصر المحددة من برنامج انسس حيث بينت الاستنتاجات ان هنالك تقارب بين النتائج العملية و النتائج التي تم الحصول عليها من استخدام العناصر المحددة.

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Notation:

E: young modulus (N/m^2)
HD: hardens
l: length of plate (mm)
Mp: plastic bending moment per unit length (N.m/m)
P: applied load (N.m)
Pc: initial plastic collapse (N)
R: half-Radial length (mm)
t: thickness (mm)
W: energy absorbing (J)
Y: yield strength (N/m^2)
Δ: deflection (axial deformation) (mm)

1. Introduction:

Increasing the number of impact events in many types of accidents such as traffic accidents, collisions of ships either with an iceberg or ship grounding on a narrow rock,... etc. induced the rapid development of crashworthiness impact dealing with research into the impact of engineering problems particularly in the field of dynamic response of structures in the plastic range and the design of energy absorbers. A new challenge appeared to design special structural members which would dissipate the impact of energy in order to limit the deceleration and finally to stop a moveable mass (e.g. vehicle) in a controlled manner. Such a structural member termed as Energy Absorber Converts totally or partially i.e. to convert the kinetic energy into another form of energy. One of the possible design solutions is the conversion of the kinetic energy of the impact into the energy of plastic deformation of a thin-walled metallic structural member[1].
Thus, the evaluation of the collapse (crushing) behaviour of thin-walled elements becomes an important problem of the modern engineering analysis and concerns particularly dynamic crushing of thin-walled structures.

Wierzbicki and Huang [2] studied the post buckling and post failure responses of a thin–walled prismatic column under axial compressive loading. They developed a simple mode of an imperfect column to describe the transition of deformation from post buckling to post failure stage.

A.A.A. Alghamdi [3] reviewed the common shapes of collapsible energy absorbers and the different modes of deformation of the most common ones. Common shapes include circular tubes, square tubes, frusta, struts, honeycombs, and sandwich plates. Common modes of deformation for circular tubes include axial crushing, lateral indentation, lateral flattening, inversion, and splitting.

S. S. Hsu& N Jones [4] presented Quasi-static and dynamic axial crushing tests which have been performed on thin-walled sections made of mild steel. The tests were arranged to investigate the mode transitions during the impact crushing of thin-walled tubes and materials were chosen for their distinctive individual characteristics such as strain rate sensitive properties and pronounced strain hardening, etc. Standard collapse modes developed in the tubes and the associated energy absorbing characteristics have been examined and compared with previous studies on mild steel.

Static or quasi-static numerical analysis gives an approximate answer about a quantitative character of the failure dynamic loading path of a thin-walled structure [5]. Response of the structure to the dynamic load is of similar character as to the static one.

Steel is the common name for a large family of iron alloys. Steels can either be cast directly to shape, or into ingots which are reheated and hot worked into a wrought shape by forging, extrusion, rolling, and other processes. Wrought steels are the most common engineering materials used, and come in a variety of forms with different finishes and properties. Alloy steels are steels that exceed the element limits for Carbon steels. However, steels containing more than 3.99% chromium are classified differently as stainless and tool steels. Alloy steels also include steels that contain elements not found in carbon steels such as nickel, chromium (up to 3.99%), cobalt...etc.[6]

The main purpose of heat treating to low carbon steels is to increase their plastic region, absorbing energy under static load, harden, and the subsequent wear resistance in the steel. The process involves heating a metal into above its austenite transformation temperature (typically 800–900°C), which dissolves precipitated carbides in the lattice structure to form a homogenous austenite structure[6].

Sample of steel was purchased from local market and the spectrometry analysis was carried out (D. A. Fadare, T. G. Fadara and O. Y. Akanbi) [7]. The steel samples were heat treated at different temperature levels and holding times; and then cooled in different media The mechanical properties were determined using standard methods Results showed that the mechanical properties of steel can be changed and improved by various heat treatments for a particular application. It was also found that the annealed samples with mainly ferrite structure gave the lowest tensile strength and hardness value and highest ductility and toughness value while hardened sample which comprise martensite gave the highest tensile strength and hardness value and lowest ductility and toughness value.

Mechanical properties depend largely on the various forms of heat treatment operations and cooling rate (T. Senthilkumar & T. K. Ajiboye)[8]. Hence, depending on the properties and the applications that may be required for any design purpose a suitable form of heat treatment should be adopted. For high ductile, minimum toughness, and annealing the medium carbon steel will give satisfactory results. Thus, it is important to clearly specify the condition of the carbon steel as purchased so that tests can be conducted to ensure the material compositions before they are put to final use.

The present study is deals with the effect of heat treatment on the elastic-plastic region, energy absorbing during collapse or crashing, and the failure of the low carbon (L-shape plates) steel under static compressive load. Experimental, numerical, and theoretical (based on perfect plastic) studies are performed in order to exam the effect of heat treatment on the elastic plastic region, energy absorbing, and yield strength. Three dimension non-linear finite element analysis including the effect of heat treatment on the yield point is performed using ANSYS commercial software.

2. Theory:

An L-structural plate is neither too thin nor too flexible of length L when subjected to loads P can only collapse plastically when one hinge has been formed to permit it to behave as a mechanism, figure (1). The plastic hinge is assumed to arise at the location where maximum elastic bending moment occur it is easy to see it, if the centre of the plate, O, remains stationary, Figure (2). Then, at the collapse of the one rigid portions of the plate between the hinge rotate with angular speed, Ω, about instantaneous centre, I, and the force P,

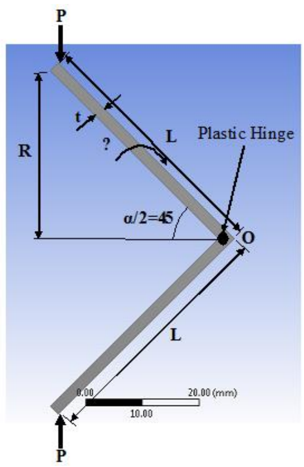

Figure (1)) Shows Plastic Hinges

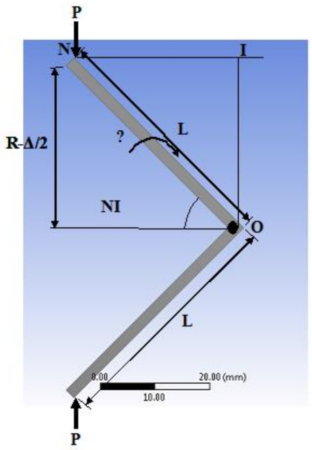

Figure (2) Clarifies Deformation Procedure

move toward the centre of the L-plate with speed R.Ω. The work input rate is therefore 2P.R.Ω and the plastic work dissipation rate is 2MP.Ω. thus:

$2P.2R.\Omega=2M_P.\Omega$ ..………………………………………………..………..(1)

from which,

$P=M_p/2R$ …....………………………………………….……………………(2)

$P.NI.\Omega=M_P.\Omega$

Or

$P=M_p/NI$ …..………………………………………..…………………...(3)

If Δ denotes the total plate deflection

$NI^2 = L^2 - (R - \Delta/2)^2$ ……………………………………………………(4)

Where $D=2R$

$\frac{P}{2M_p} = \frac{1}{\left[L^2-\left(R-\frac{\Delta}{2}\right)^2\right]^{1/2}}$ ……………......…………………………….……………(5)

Or

$\frac{P}{2M_p/R} = \frac{1}{[(L/R)^2-(1-\Delta/R)^2]^{1/2}}$ …..……………………………………………….…….(6)

where t is the plate thickness and M_p denotes the fully plastic bending moment and can be calculated as:

$M_p = \frac{1}{4}Yt^2$ ……….......……………………………………………………..(7)

Where:

Y is the yield strength of the plate. so the initial plastic collapse load Pc is equal to:

$P_c = M_{p.}l/2R$ ……………………………....…………………..…………….(8)

Where:

l is the length of the plates, and R is the distance .

3. Finite Element Simulation:

Finite element simulation was performed and took Approximately 45 min. The modeling consists of the following phases [9].

3.1 Model Discretization:

A mapped mesh consisting of brick elements (ANSYS element type SOLID45) are used for the three-dimensional modeling of solid structures Figure (3). The nodes having three degrees of freedom at each node define the element: translations in the nodal x, y, and z directions. The element has plasticity, stress stiffening, large deflection, and large strain capabilities. Table (1) shows dimension and size of the plate.

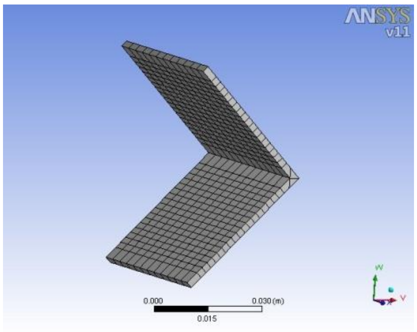

Figure (3) Ansys Model

Table (1) Describes Size and Dimension of Plate

t (mm)	L (mm)	R (mm)	l (mm)
2	44	31	50

3.2 Material Properties:

For the modeling as received steel (AISI 8620) with Tempering heat treatment (heated to 700 deg Celsius for the same time interval 2 hours) has been chosen. Yield strength of the material was measured as 210MPa from a simple tension test. In the modeling elastic modulus and Poisson's ratio were taken as 200 GPa and 0.3, respectively.

3.3 Boundary Conditions:

The "Rigid" material was used to define the boundary conditions, because the plates are crashed between two rigid flat materials. The "Rigid" material offers the option to define rotational and transnational boundary conditions for all parts that are meshed with the material "Rigid". Because we created two material models using the "Rigid" material (bottom and top) we can easily define different boundary conditions for the two parts. For the bottom material, we prohibit displacement in all translational directions and around every rotational axis. The top material is supposed to move in the negative Y-direction.

3.4 Loading History:

One-step displacement, which is 62 mm radial compression, is given to the rigid flat material at the top of the plate. Deformed mesh is shown in Figures (4) for lengths (50mm) respectively, which shows the deformation distribution. Loads deformation curves are shown in Figures (3).

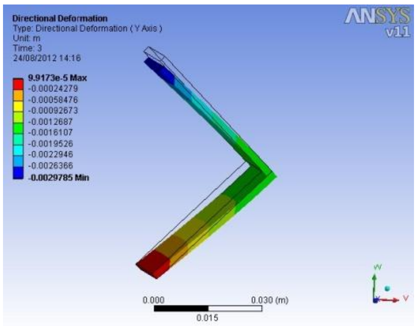

Figure (4) Indicates Deformation element tube l=50mm

4. Experimental Setup:

The effect of heat treatment of mild steel AISI 8620 by using four process ANNEALING, NORMALIZING, QUENCHING and TEMPERING on its absorbing energy is investigated. This study was conducted using a furnace. AISI 8620 is a Standard grade Alloy Steel, its mechanical properties and Composition are shown in tables (2) and (3) respectively. The specimen size is shown in Figure (5).

For annealing, the specimen was heated to a temperature of 900 deg. Celsius. At that temperature, the specimen was held for 2 hours. The furnace was switched off and the

Table (2) Demonstrates Mechanical Properties

Density (×1000 kg/m3)	7.7-8.03
Poisson's Ratio	0.27-0.30
Elastic Modulus (GPa)	190-210
Tensile Strength (Mpa)	536.4
Yield Strength (Mpa)	385.4
Elongation (%)	31.3
Reduction in Area (%)	62.1
Hardness (HB)	149
Impact Strength (J) (Izod)	112.2

Table (3) Point out Chemical Composition

Element	Weight %
C	0.18-0.23
Mn	0.70-0.90
P	0.035 (max)
S	0.04 (max)
Si	0.15-0.30
Cr	0.40-0.60
Ni	0.40-0.70
Mo	0.15-0.25

specimen temperature decreased with the same rate as that of the furnace so that the specimen at that temperature gets sufficient time to get properly homogenized. When the furnace temperature has already reached the room temperature, the specimen was taken out of the furnace.


Figure (5) Shows up Experimental Specimen

For Normalizing, the specimen was heated to a temperature up to 900 deg. Celsius. The specimen was kept for 2 hours. The furnace was switched off and the specimen was taken out. The specimen was allowed to cool normally to the ordinary environment. The specimen was cooled to room temperature.

For Quenching, The specimen was heated to the temperature of around 900 deg. Celsius and was allowed at that temperature for 2 hours. An oil bath was maintained at a constant temperature in which the specimen had to be put. After 2 hours, the specimen was taken out of the furnace and quenched in to the oil bath directly. After around half an hour the specimen was taken out of the bath and cleaned properly. The rate of cooling is very fast because the liquid does not release heat readily.

Finally, Tempering was used, the specimens were heated to 900 deg. Celsius for 2 hours and then quenched in to the oil bath maintained at room temp. The five specimens were heated to 250 deg. Celsius for different periods of 1 hour, and 2 hours respectively. Five specimens were heated to 500 deg. Celsius for different periods of 1 hour, and 2 hours respectively. The remaining five specimens were heated to 700 deg. Celsius for same time intervals of 1 hour and 2 hours respectively.

After the specimens got heated to a particular temperature for a particular period, the specimens were cooled at room temperature. The heat treatment of tempering at different temperature and different periods, developing a variety of properties to the specimen crushed load of 10 ton had applied on the specimens that had gotten heat treatment are shown in figure (6) to investigate its ability on absorbing energy and its elastic-plastic region


Figure (6) Illustrates Specimen Under Loads


Figure (7) Proposes Deformation Plate

during collapse. Plates crashing under static load are Figure (5) Shows up Experimental Specimen shown in Figure (7). The load- deflection diagrams for the compressive test are shown in figures (8-16), Figure (5) Shows up Experimental Specimen) respectively.

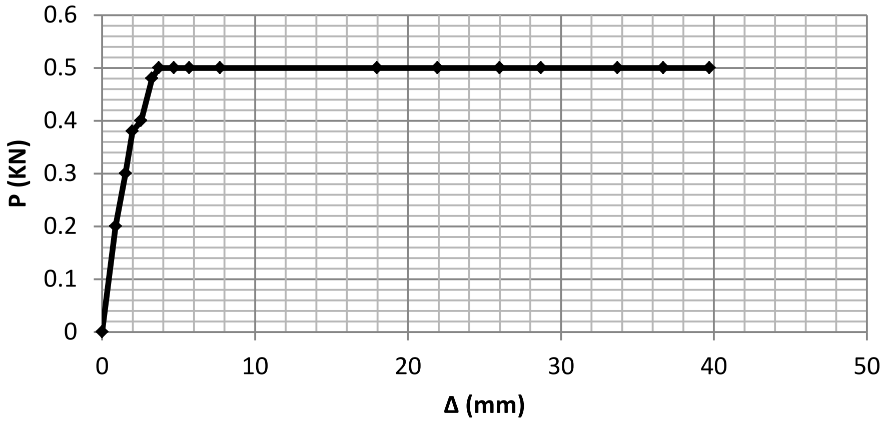

Figure (8) Records the relationship between slope &load length =50mm (Full annealing)

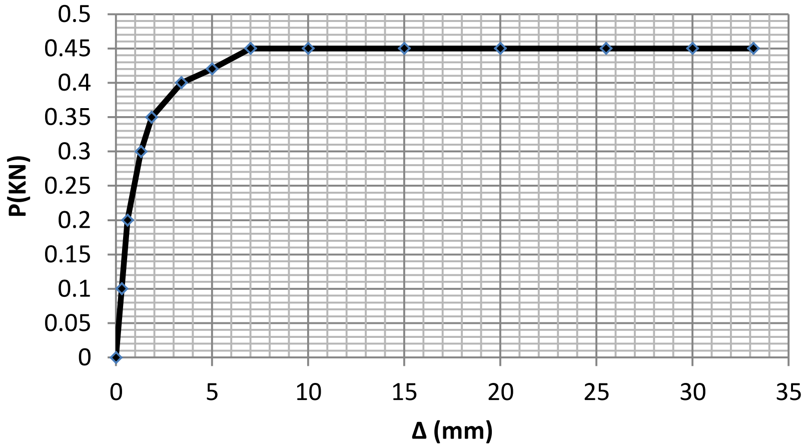

Figure (9) Records the relationship between slope &load length =50mm (Normalizing)

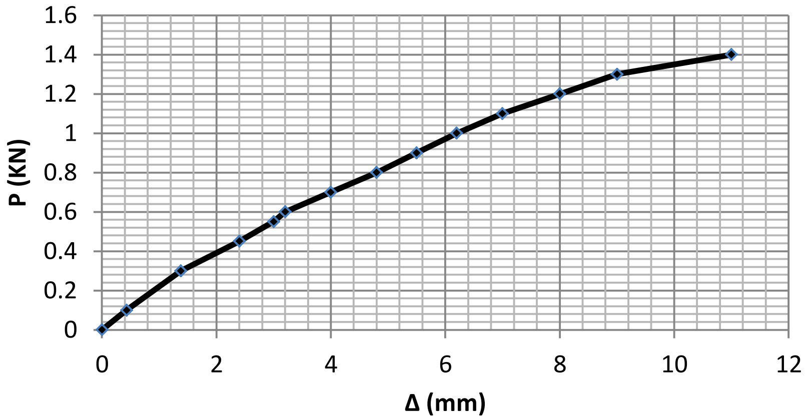

Figure (10) Records the relationship between slope &load length =50mm (Quenching)

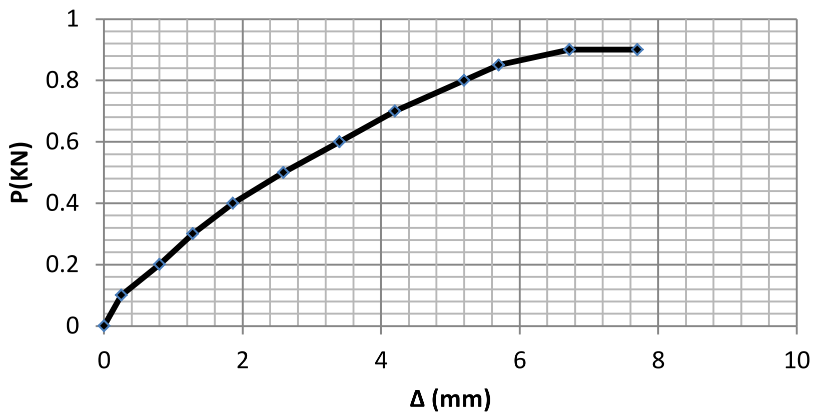

Figure (11) Records the relationship between slope &load length =50mm (Tempering 250C^o 1 Hour)

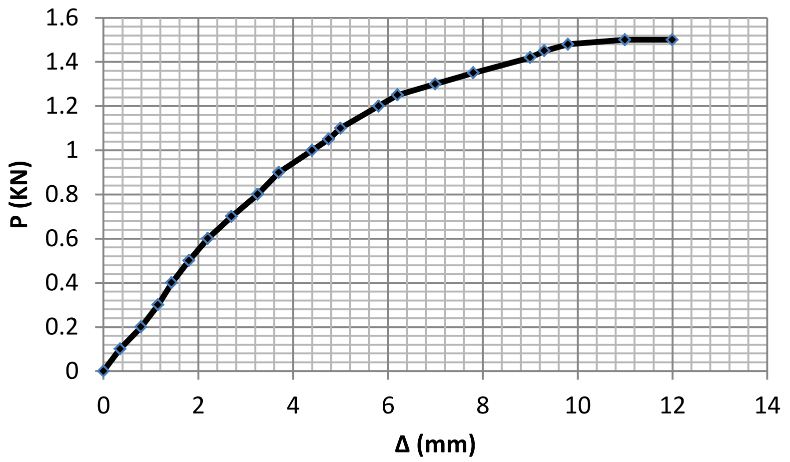

Figure (12) Records the relationship between slope &load length =50mm (Tempering 250C^o 2 Hour)

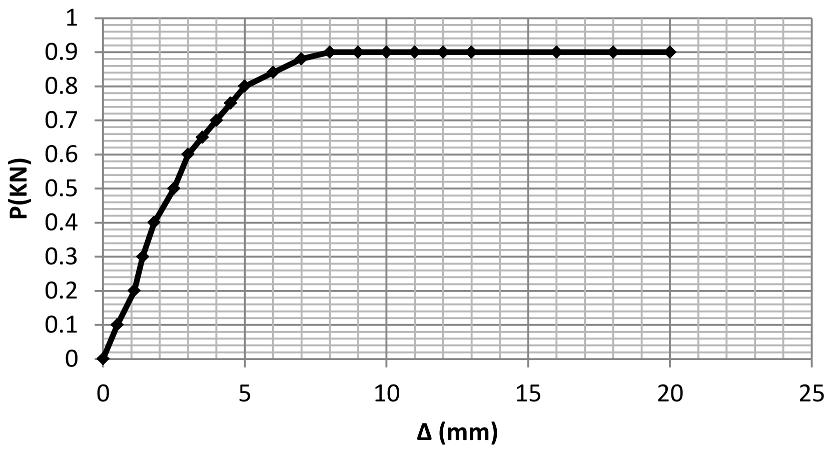

Figure (13) Records the relationship between slope &load length =50mm (Tempering 500C^o 1 Hour)

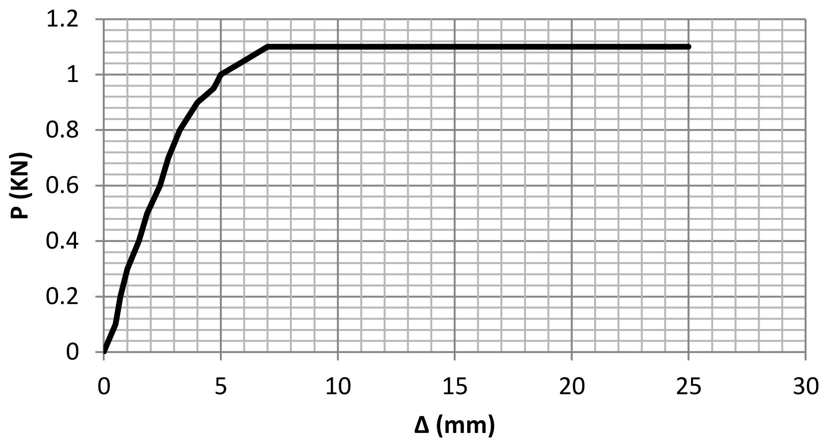

Figure (14) Records the relationship between slope &load length =50mm (Tempering 500C° 2 Hour)

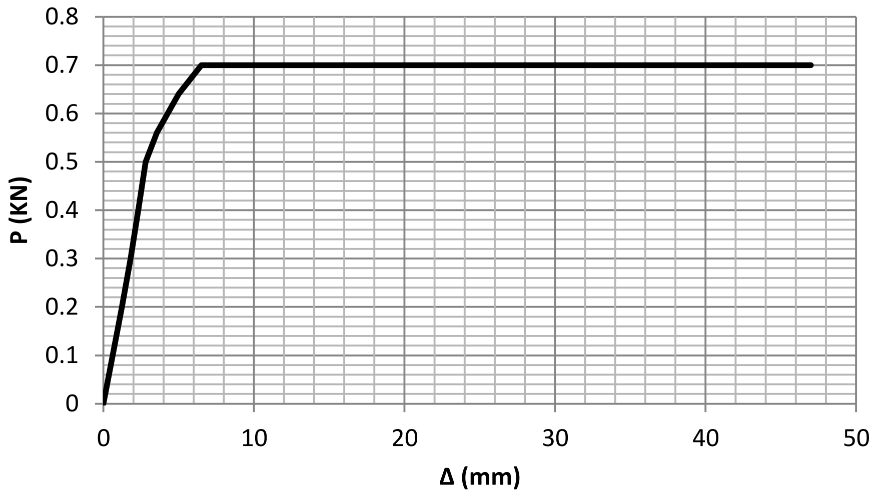

Figure (15) Records the relationship between slope &load length =50mm (Tempering 700C° 1 Hour)

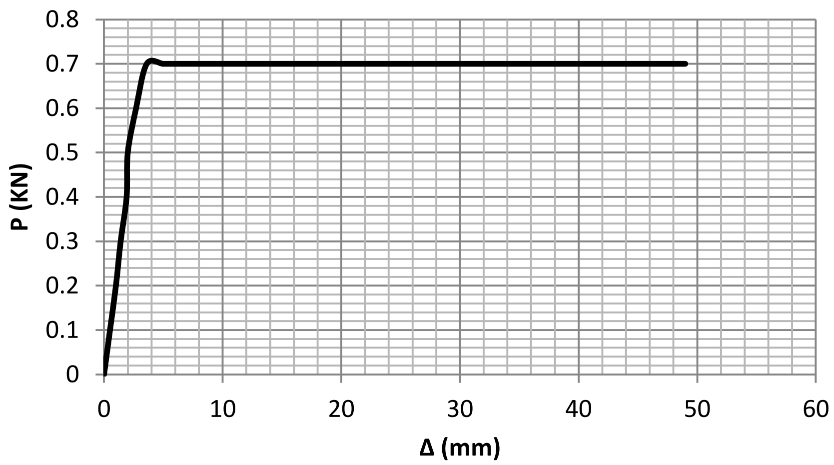

Figure (16) Records the relationship between slope &load length =50mm (Tempering 700C° 2 Hour)

4. Discussion:

The deformation behavior of Mild steel (AISI 8620) specimens in the size range from two length 50mm and 100 mm under compressive load was investigated using static hydraulic machine load. Experimental investigation, theoretical modal based on full plastic theory, and Finite element by using ANSYS nonlinear programmer was used to find the slope of the load–displace during plates crushing. Heat treatment has a strong influence on mild steel behavior that effects are shown in Figures (8-16). The specimens became more brittle when cooling it by oil bath but can improve its plasticity region when Tempering was used. Table (4) shows the effect of heat treatment on the behavior of plate elastic-plastic (ratio=plastic region/elastic region) and absorbing energy during crushing. When specimens were cooled by oil bath (Quenching), plastic region was equal to zero with an increase elastic region, and specimens were unuseful for absorbing energy. By crushing, however; plastic region of specimens can be increased by Tempering with increasing temperature of heating and the time of heating, Figures (10 to 16) show the effect of Tempering on the elastic-plastic region for specimens and better plastic region with energy absorbed results can be found when specimen Tempering at 700 ^{o}C in 2 hours.

Table (4) Represent the Effect Tampering Heat Treatment on Plate Behaviour

	Elastic region (mm	Plastic region (mm)	ratio	W(J)	HD
Tempering 250 ^{o}C for 1hour	7.7	0	0.00	4.5	54
without Tempering	11	0	0.00	9.35	52
Tempering 250 ^{o}C for 2hour	9.8	2	0.20	10.736	52
Tempering 500 ^{o}C for 1hour	7	13	1.86	15.58	52
Tempering 500 ^{o}C for 2hour	7	28	4.00	24.8	50
Tempering 700 ^{o}C for 1hour	5	42	8.40	30	52
Tempering 700 ^{o}C for 2hour	2.7	46.3	17.15	31.8	47

Figure (17) shows a comparison between Finite element analysis by Ansys programmer results which were very close to Experimental results (Tempering at 700 ^{o}C in 2 hours) than theoretical (equation 6) because the perfect plasticity materials were suggested in theoretical models .

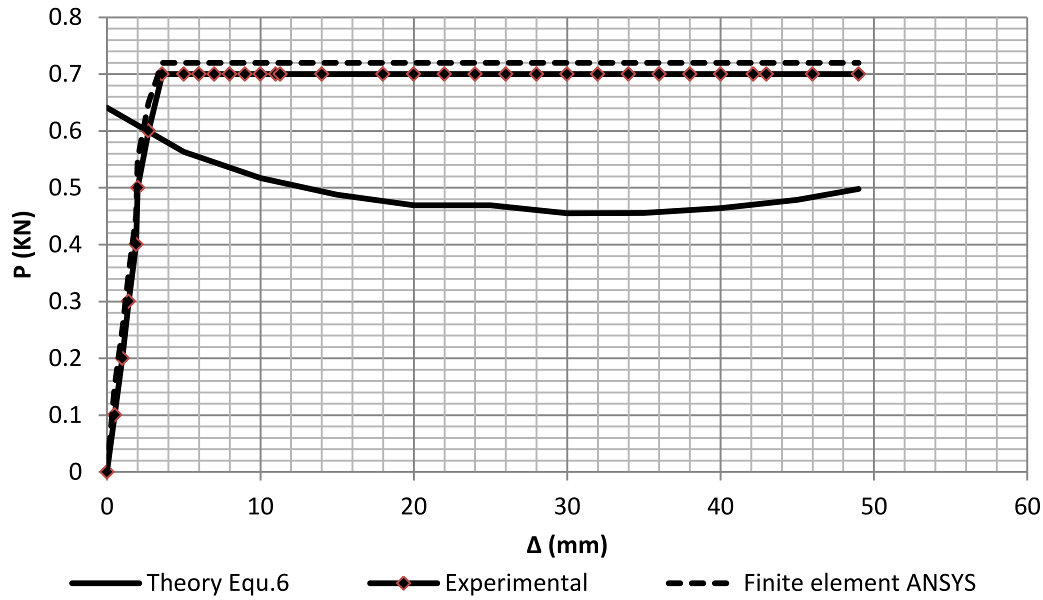

Figure (17) Records the relationship between slope &load, Comparison between theory model, finite element and Experimental results

Heat treatment is very useful to improve energy absorbing with decreasing size of plates. Figure (18) shows comparison between Tempering heat treatment processes at specimen length equal (50 mm) with specimen without heat treatment at length (100mm) that shows energy absorption behaviour which can be improved and increased not only by decreasing length or size of plates but by using suitable heat treatment.

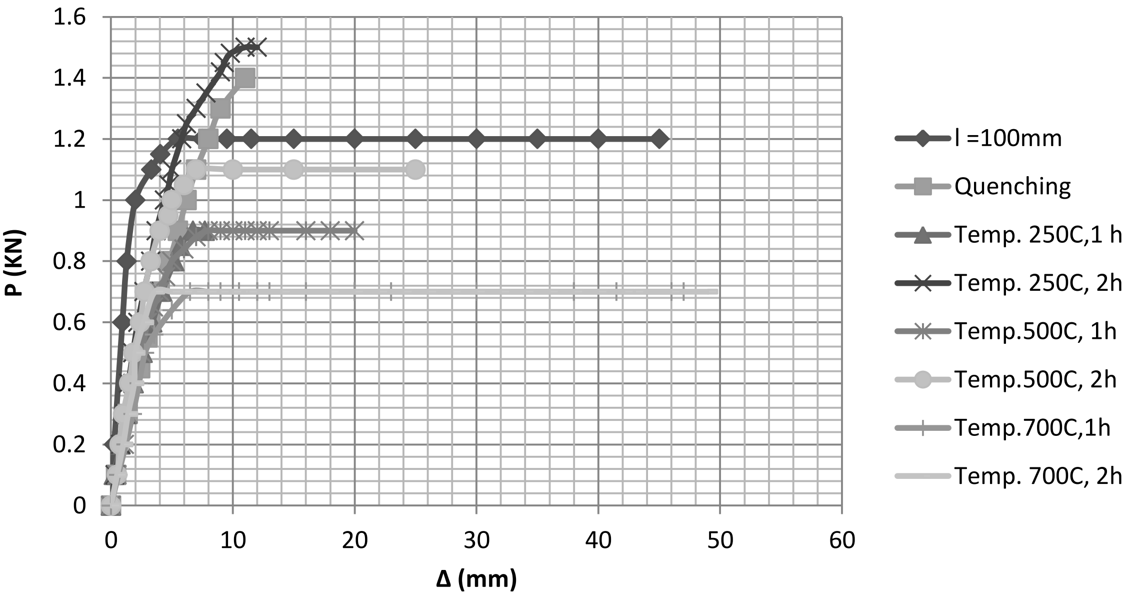

Figure (18) Records the relationship between slope &load for specimen length equal to 100mm, Quenching, and Tempering length equal to 50mm.

5. Conclusions:

The deformation mechanism and heat treatment effects on the absorption of energy during crushing were described and based on theoretical, experimental and finite element simulation results, the results indicate the following.

1. Heat treatments have effects to improve mechanical properties for L-steel plates under axial compressive load.
2. The axial crushing behavior of L-steel plates can be controlled by elastic-plastic region by using suitable heat treatment.
3. Absorbing energy by crushing plates under static axial load can be increased with the increase plastic region, this might happen by using heat treatment for the plates (Tempering at 700 oC in 2 hours), while increasing in elastic region caused a decrease in absorbing energy during crushing L-plates under axial compressive load.
4. The plastic region has increased on the elastic region for L-steel plates under static compressive axial load by using heat treatment (Tempering). The result showed a decrease in elastic region with an increase in plastic region during crushing L- steel plates that caused an increase in absorbing energy.

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