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Experimental Verification and Analysis of A U-Shaped Curved Beam Plate by Using FEA Tool

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Abstract— U-Shaped plate represents an important class of machine members which find their application in components such as crane hook, C – clamp, frames of presses and etc. The stress analysis of the critical section of the curved beam is a crucial step in its design. There are two methodical used for stress analysis of curved beams: a plane elasticity formulation and Winkler's theory. The Winkler's theory has long been the primary means of curved beam stress analysis in engineering practice. This paper describes the stress analysis of a U – shaped specimen, the base of which represents a curved beam using the standard Winkler's theory and follow on experimental stress analysis using strain gauges. The specimen is loaded such that a known bending moment is applied to it. The circumferential stresses along the critical section of the curved beam are determined using Winkler's theory. The experimental procedure of an aluminium U – shaped specimen is instrumented with several strain gauges along the critical section. The gauges are used to measure the circumferential strains along the critical section. The circumferential stresses are then calculated using Hooke's law. In this paper analytical method and experimental method illustrates many essential elements of experimental stress analysis of a U shaped curved beam.

Keywords— Strain Gauges, Winkler's Theory, Circumferential Stress, Wheatstone Bridge, Strain Indicator etc.

I. Introduction

The curved plate can be defined as a beam in which the neutral axis in unloaded condition is curved instead of straight. In straight beams the neutral axis of the section coincides with its centroidal axis and the stress distribution in the beam is linear, however in the case of curved beams the neutral axis is shifted towards the center of curvature of the beam causing a non- linear (hyperbolic) distribution of stress. The neutral axis lies between the centroidal axis and the center of curvature and will always be present within the curved beams. Curved beams find wide applications in many machine members such as crane hooks, C clamps, frames of presses, punches, shears, boring machines, planers etc. The stress analysis of the critical section of the curved beam is a crucial step in its design, earlier to the widespread use of the computer; two methods were existing for curved beam stress analysis: one is plane elasticity formulation and the other one is Winkler‟s theory. The Winkler‟s theory has long been the primary means of curved beam design and stress analysis in engineering practice. This is because it is applicable to cross – sections of any shape and it is shown to give results that agree well with the experimental stress measurements. The electrical resistance strain gauge is the most frequently used device in stress-analysis work throughout the world today. The bonded-foil gauge monitor with a Wheatstone bridge has become a highly perfect measuring system. Precise results for surface strains can be obtained quickly using relatively simple methods and inexpensive gauges and instrumentation systems. The basic principle based on which an electrical resistance strain gauge works is that the resistance of a wire increases with increasing strain and decreases with decreasing strain. The modern metal-foil strain gauges consist of the grid configuration formed from metal foil by a photo-etching process. The etched metal film grids are very fragile and easy to distort, wrinkle or tear. For this reason the metal film is usually bonded to a thin plastic sheet, which serves as a backing or carrier before photo etching. The carrier material also provides electrical insulation between the gauge and the component after the gauge is mounted. The Wheatstone bridge is circuit that is usually employed to determine the change in resistance which a gauge undergoes when it is subjected to a strain. The bridge may be used as a direct- readout device, where the output voltage ΔV is measured and related to strain. The bridge in the strain indicator is powered by a battery supply equipped with a voltage regulator that applies a fixed DC voltage to terminals. Also, the indicator is equipped with fixed resistors so that the bridge may be used in quarter, half or full bridge configuration. The output of the bridge is the input of an instrument amplifier with a specific gain. The analog output from the amplifier is converted into digital format and displayed on a liquid crystal display of the strain indicator. In the present work, the stress analysis of a U – shaped specimen, the base of which can be considered as a curved beam with rectangular in cross-section is performed using the standard Winkler‟s theory and experimental method using three strain gauges.

II. Stress Analysis of Curved Beams Using Winkler‟S Theory

The Winkler‟s theory[2]uses the following assumptions.

1) The cross section has an axis of symmetry in the plane of symmetry.

2) Plane cross sections remain plane after bending. 3) The modulus of elasticity is same in tension as in compression.

According to Winkler‟s Theory, the bending stress at any section in the curved beam is given by,

$$\sigma = \frac{M \times y}{A \times (r_n - y)} \qquad \text{------} \qquad \text{Eq. 2}$$

where,

M = bending moment;

y = distance of any fibre from the neutral axis;

A = Area of Cross – section;

e = eccentricity = distance between centroidal axis and neutral axis;

rn = Radius of Neutral axis

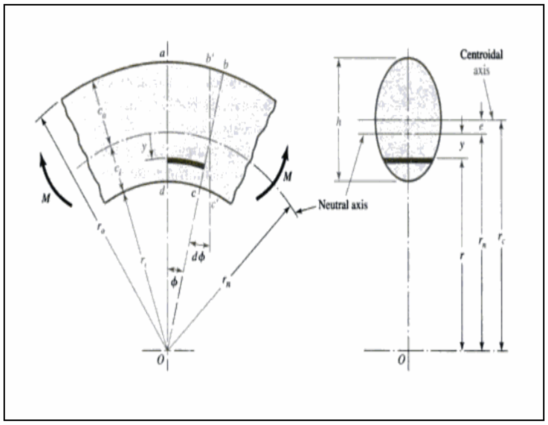


Fig. 1 Curved Beam Subjected to Bending Moment and its related Parameters

In the above figure,

h = depth of cross – section

Co= distance from neutral axis to outer fibre

Ci= distance from neutral axis to inner fibre

rn = radius of neutral axis =

$$S = \frac{A}{\int \frac{da}{r}} \qquad \text{------} \qquad \text{Eq. 1}$$

r_c = radius of centroidal axis

e = distance from centroidal axis to neutral axis

M = bending moment.

The circumferential stress (θ = 90^o from the horizontal)at any point in the critical section of the curved beam is obtained by combining the bending stress at that point obtained from the above formula and the direct stress. The Figure. 2 Shows the theoretical bending stress distribution along the critical section and the maximum bending stress will occur at inner radius

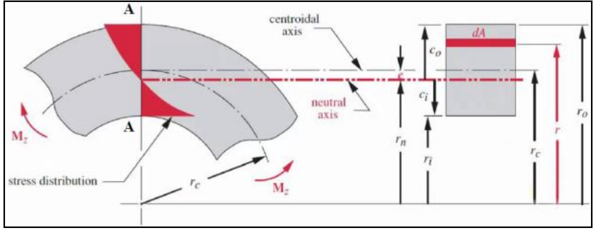


Fig. 2. Theoretical bending stress distribution.

III. Conceptualisation and Design of Experimental Setup

A. The Specimen

Both the analytical method and the follow – on experimental procedure are concerned with the „curved beam‟ portion of the flat U – shaped specimen shown in the figure below.

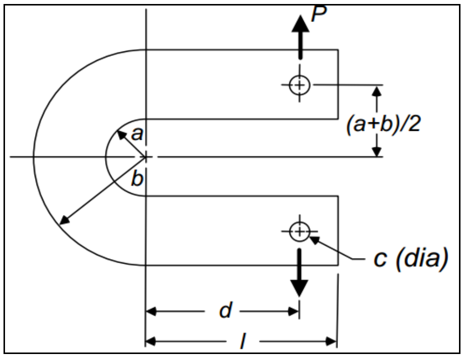


Fig. 3. Overall Specimen Geometry and External Load

The overall specimen geometry is defined by specifying the thickness „h‟, distance „l‟, inner radius „a‟, outer radius „b‟, and the diameters of the two holes „c‟, which are centered on the beam arms and located at distance „d‟ from the curved base of the specimen. A rectangular cross – section is used on account of its simplicity. The values of the above said parameters used in the present work are as follows. h =10mm; l = 155mm; a = 33mm; b = 90mm; c= 13mm; d = 130mm. The material selected for the specimen is 6351 T4 Aluminium alloy in order to reduce the overall weight of the experimental setup. The value of Modulus of Elasticity used is equal to 69 GPa[5].

B. Manufacturing of the Specimen

The manufacturing procedure of the specimen is as follows.

- Initially a 300×260×16 aluminum sheet is taken.
- Slot milling is done to obtain the basic „U‟ shape of the specimen and hence the excess material is also removed from the sheet.
- A hole of 63mm is bored at the center of curvature of the base of the specimen.
- The remaining excess material is removed with milling.
- Two holes of dia. 13 mm are drilled for the purpose of application of loads with one hole and constraining the specimen with the other.
- Finally the dimensions to their close tolerances are obtained by finishing processes like grinding etc.

Fig. 4. Fabricated Curved Beam Specimen

C . Frame

Fabrication of supporting frame of a curved beam U Clamp can be fabricated in basic workshop Practice Laboratory

Fig. 5. Fabrication of Frame

D .Strain Gauge Mounting

Since our aim is to finding the variation of circumferential stresses ($\theta = 90^{o}$ from the horizontal)throughout the critical section, we have used three strain gauges bonded in vertical direction at three specified radial positions along the critical section of the fabricated curved beam specimen. The three radial positions are-

- A=35mm from the centre of curvature (2mm from inner radius)
- B=52mm from the centre of curvature (20mm from inner radius)
- C=85mm from the centre of curvature (53mm from inner radius)

- The specifications of the strain gauge used
- are as follows
- BF350-3AA(11)N4-F-X1-V2 (standard specification of the gauge according to the norms)
- Sensitive grid size= 3.2×3.1 (in mm)
- Base size =7.3×4.1 (in mm)
- Material- copper nickel alloy
- Resistance= 350.5 ± 0.1Ω
- Gauge factor= 1.75 ± 1%

The procedures involved in strain gauge mounting on the specimen are as follows

- The surface of the specimen is first degreased in order to remove oils, greases, organic contaminants etc. by wiping the surface with GC – 6 Isopropyl alcohol.
- The surface is abraded with a fine silicon carbide paper to remove surface scales.
- The strain gauge positions are properly distinct on the specimen.
- Bond the strain gauges at the marked positions using an adhesive such as M – bond 610.
- Solder the strain gauge terminals to external tabs placed next to the strain gauges using thin copper wires.
- Check the resistance of the strain gauges using a multimeter.

- Spotless the terminals with flux remover to eliminate solder residuals.
- Then a layer of Silicon-Rubber compound is applied for strain gauge terminal protection.
- Then the specimen is kept in oven for 2 hours at 50^{0}C.
- Finally it is coated with a layer of Teflon tape

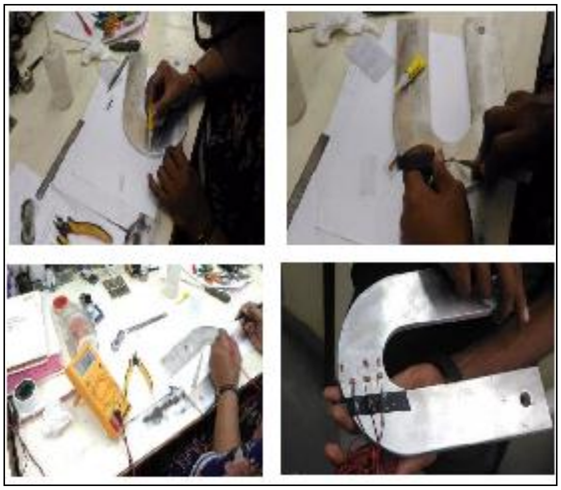


Fig.6. Strain Gauge Mounting Procedure

F. The Experimental Setup

The application of the bending load on the fabricated specimen requires a loading setup. The setup was fabricated for it which consists of mild steel frames of rectangular cross – section which are welded to each other. The U – shaped specimen is fixed to the frame with the help of one of the holes provided on it. Another hole provided on the specimen carries a weighing pan to which dead weights can be added, which applies a known bending moment to the curved beam base of the specimen. The figure 8. Shows the Complete Experimental Setup made by us.

Fig.7 Complete Experimental Setup

IV. Analytical Procedure of Stress Analysis

Considering that and explained earlier, the stress analysis of the curved beam base of the U – shaped specimen is done analytically by using Winkler‟s theory. The parameters determined from the analytical method involve circumferential stress (θ = 90^{o} from the horizontal) at specified radial positions along the critical section of the curved beam and variation of the aforementioned circumferential stress along its width. Three load cases corresponding to 5Kg, 10Kg and 15Kg are considered. The subsequent shows a representative calculation [2] for the load case of 5Kg corresponding to the radial position A.

<u>*Input Data*</u>

r_i= 33mm
r_o = 90mm
h = 10mm

$$r_c = r_i + \frac{r_o - r_i}{2} = 61.5\text{mm}$$

rn = = 56.8124mm
e = 4.6876mm
Distance from centroidal axis to Force = 191.5mm
A = 570mm
y = rn – r = 21.812mm
Load = 5kg = 49.05N
Calculation of Stress

Direct stress, $\sigma_d = \dfrac{F}{A}$

= 49.05/570 = 0.08605 N/mm^2

Bending stress, = 2.1908 N/mm^2

Circumferential Stress (θ = 90^{o} from the horizontal) $\sigma r = \sigma_d + \sigma_b$, = 2.2769 N/$\text{mm}^2$

The calculation shown above is performed for each radial location corresponding to each load case. This gives circumferential stresses at individual radial locations as well as their variation in the critical section

V. Modelling and Analysis

Modeling is prepared and finifhef using the Solid Edge, Solid Works software tool and exported to FEA tool for Stress and strain analysis, which is Carried out using the Autodesk simulation software and simulated which is as follows:

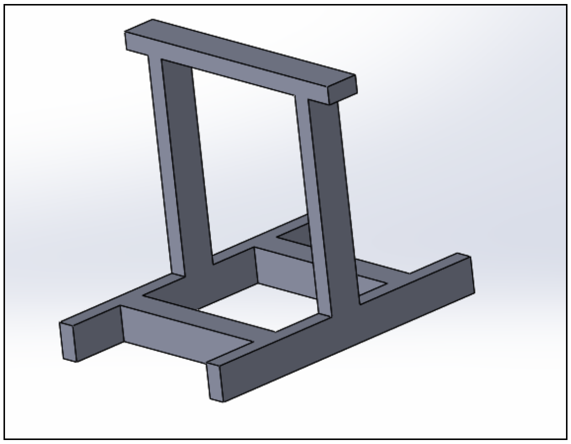


Fig.8. CAD Model of frame Setup

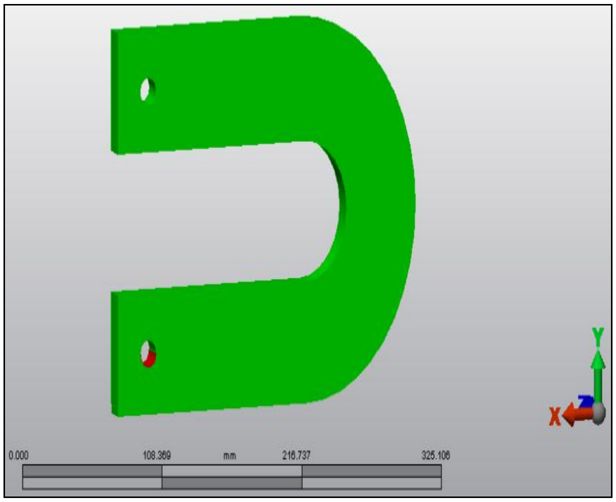


Fig.9 CAD Model of U Clamp

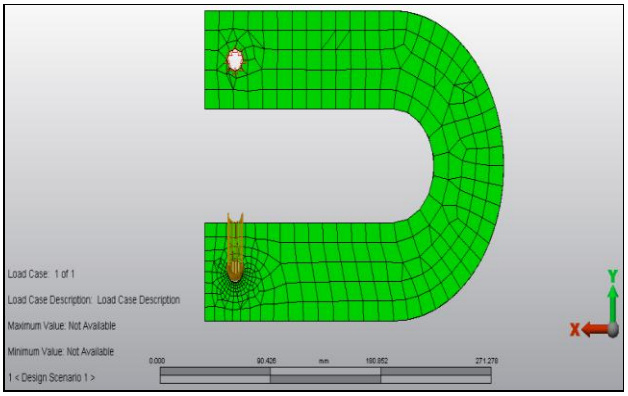
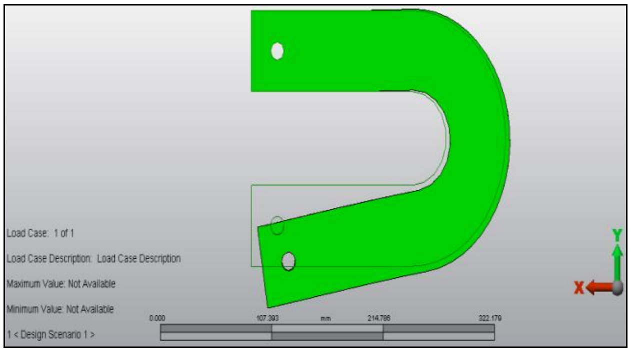

Load Case: 1 of 1
Load Case Description: Load Case Description
Maximum Value: Not Available
Minimum Value: Not Available
1 < Design Scenario 1 >

Fig.10 Mesh and boundary conditions of U Clamp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Load Case Description: Load Case Description
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Minimum Value: Not Available
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Fig. 11 Deformed and Undeformed of U Clamp

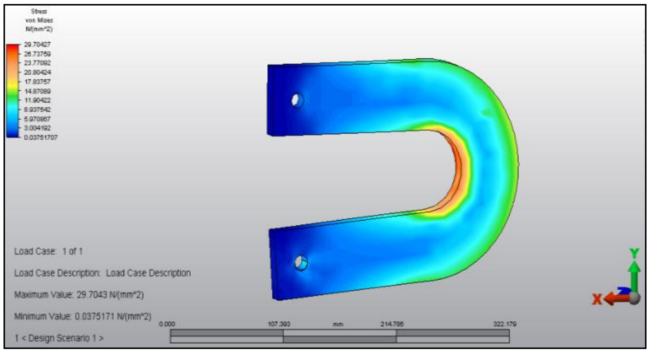
Load Case: 1 of 1
Load Case Description: Load Case Description
Maximum Value: 29.7043 N/(mm^2)
Minimum Value: 0.0375171 N/(mm^2)
1 < Design Scenario 1 >

Fig. 12 Von-Mises's stresses of U Clamp.

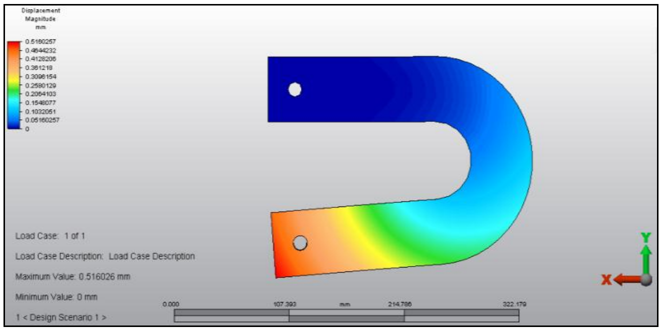
Load Case: 1 of 1
Load Case Description: Load Case Description
Maximum Value: 0.516026 mm
Minimum Value: 0 mm
1 < Design Scenario 1 >

Fig. 13 Deformed U Clamp

Table. 1

Distance from Radius of curvature	**Distance from NA in MM**	**Load in Kg**		
		5	**10**	**14**
90	-33	-0.91262	-1.82526	-2.55536
80	-23	-0.71577	-1.43154	-2.00416
70	-13	-0.46251	-0.92503	-1.29505
60	-3	-0.12458	-0.12458	-0.12458
57	0	0	0	0
50	7	0.34904	0.698085	0.977319
40	17	1.060587	2.121189	2.969665
33	24	1.816728	3.633482	5.086875

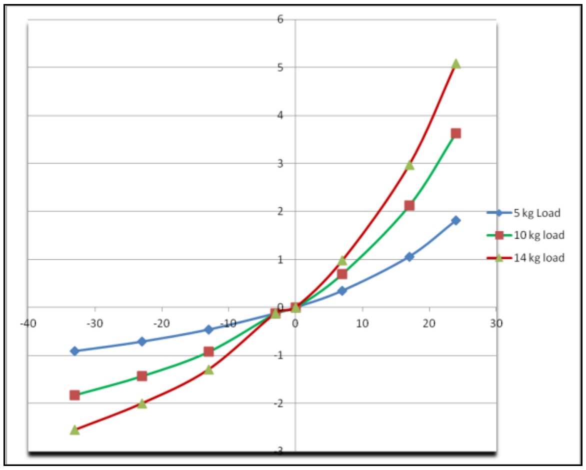

Fig. 14. Bending Stress Distribution curve along the critical section for 5Kg, 10Kg and 15 Kg.

VI. Results and Conclussions

The results obtained from the analytical procedure of U shaped curved beam specimen stress analysis using Winkler"s theory and FEA tool of stress analysis tabulated in the following table2.The Figure 2 and Figure 15 shows the curved beam bending stress theoretical and the experimental results are in same profile and which shows the Neutral Axis moves towards the radius of curvature.

Table. 2

Sl. No.	Load (Kg)	Load (N)	Theoretical Stress (MPa)	Experimental Stress (MPa)
1	5	50	1.589	1.66458
2	10	100	3.428	3.32916
3	15	150	4.898	4.99374

VII. Conclussions

The present work describes the stress analysis and stress distribution on a curve beam by using winkler's theory, analytical method and experimental method together and compared with FEA analysis. The fabrication of U shaped curved beam specimen is simple for loading and economical. The strain gauges also show to be precise and economical way of performing experimental stress analysis as the results calculated and obtained are close with standard analytical results.

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Authors Profile

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