Engineering Design and Fabrication of Three Hinged Arch Apparatus

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ABSRACT: Arches are important structural elements in engineering that provide economical solutions in buildings and bridges. Three-hinged arch structures are pinned at the supports (springing) and somewhere along the barrel, which is usually at the crown. The structural analysis and design of three-hinged arches involve the determination of the internal stresses (bending moment, shear force, axial force and torsion in the structure) due to externally applied load and providing adequate sections to resist the applied load. The hinged arch is a statically determinate structure with the axial thrust assisting in maintaining the stability. A three-hinged arch apparatus was design and fabricated in order to experiment action of different loads at different points on arch structures. In this apparatus, the major components are arch, point or distributed load and force gauge. Out of two ends of the arch one is fixed and the other one is on the roller bearing. The purpose of force gauge is to measure the internal stresses of arc under the horizontal thrust which is created by applying loads on the arch. Loads are applied on the arch at equal distances. The corresponding stresses at rolling end were recorded to evaluate horizontal thrust experimentally and compared the result with theoretical value

Keywords: Structural elements, structure, three-hinged, stresses, stability, thrust, arch, determinate.

I. INTRODUCTION
Parabolic arches are popular elements in construction engineering. They can be employed as bridges or beams for example. Normally these bridges are statically indeterminate. The special feature of the arch is that only normal forces and bending moments occur, but no shear forces. That is the case when the arch is subjected to a uniform distributed load and both ends are mounted in fixed bearings. This enables arches to be constructed from loosely set stones – a construction technique which has been in existence for many centuries.

Loads acting upon the inner of the arch are primarily compressive forces in the direction of the normal force at every point of the arch.

A three-hinged arch, which is usually made from steel or timber is statically determinate. Unlike statically indeterminate arches, they are not affected by differential settlement or temperature changes. Three-hinged arch structures have three natural hinges as the name implies. The two supports are hinged and another internal hinge is usually located at crown.

A three-hinge arch has four unknown reactions that is two vertical reactions and two horizontal reactions at the support. For their determination, three equilibrium equations can be formulated considering the whole of the structure.

Since it is well known that the bending moment at any internal hinge is zero, the internal hinge in the barrel of the arch provides an additional equilibrium of any part of the system. This means that the sum of the moments of all external forces, which are located on the right (or on the left) part of the structure with respect to the internal hinge is zero. Therefore, a three-hinged arch is a geometrically unchangeable and statically determinate structure. A three-hinged bolt-laminated Ekki timber bridge is at Finowfurt, Germany.

The peculiar feature of arched structures is that horizontal reactions are induced even when the structure is subjected to vertical load only. These horizontal reaction vertical loading A=B=H are called the thrust of the structure. At any cross-section of the arch, bending moments, shear, and axial forces are developed. However, the bending moments and shear forces are smaller than corresponding internal forces in a simply supported beam covering the same span and subjected to the same load.

This fundamental property of the arch is due to the thrust developed. Thrusts in both supports are pointed towards each other and consequently reduce the bending moments that

would arise in beams of the same span and load configuration. The two parts of an arch may be connected by a tie. In this case, in order for the structure to remain statically determinate, one of the supports of the arch should be supported on a roller.

The three-hinged arch apparatus designed and fabricated is a pre-shaped parabolic arch. It can be subjected to point or distributed loads. One of the

arch's supports is fixed; the other is on a roller bearing. Digital weighting sets are used to cancel this movement. The movable support thus becomes a fixed support.

A three hinged arch is a statically determinate structure with the axial thrust assisting in maintaining the stability. The horizontal thrust H in the arch for a number of loads can be obtained as follows:
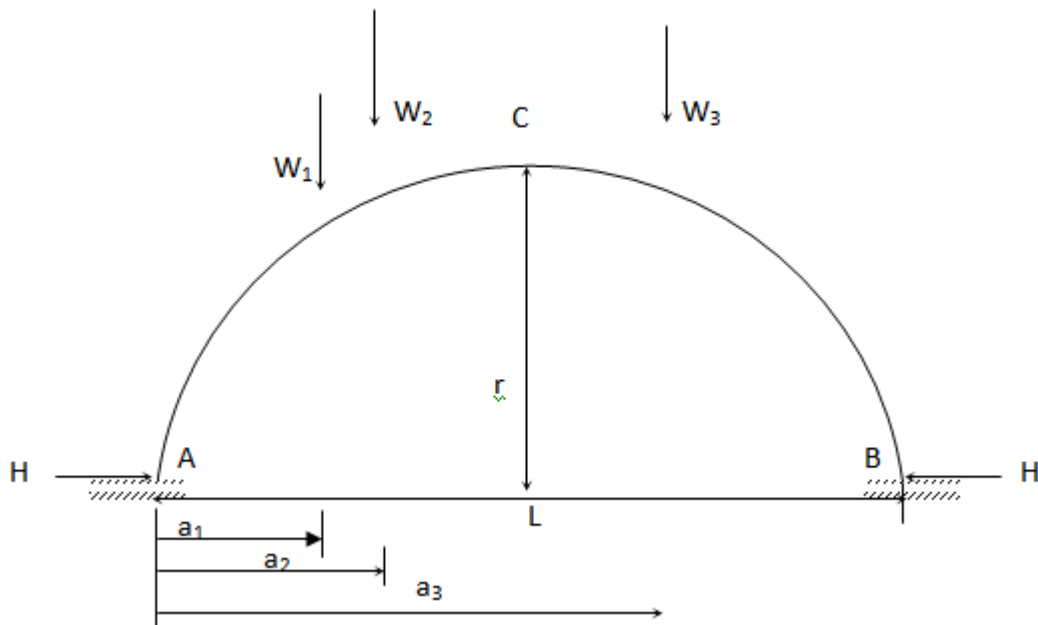
Taking moment about A

$$R_B \times L = W_1 a_1 + W_2 a_{2+} + W_3 a_3$$

$$R_B = \frac{W_1 a_1 + W_2 a_{2+} + W_3 a_3}{L}$$

Taking moment about B

$$R_A = \frac{W_1(L - a_1) + W_2(L - a_{2)} + W_3(L - a_3)}{L}$$

Taking the moment of all the forces on left hand side about C, we get

$$H \times r + W_1\left(\frac{L}{2} - a_1\right) + W_2\left(\frac{L}{2} - a_2\right) = R_A \times \frac{L}{2}$$

$$H = \frac{1}{r}\left[\frac{1}{2}[W_1(L - a_1) + W_2(L - a_2) + W_3(L - a_3)] - W_1\left(\frac{L}{2} - a_1\right) - W_2\left(\frac{L}{2} - a_2\right)\right]$$

$$H = \frac{1}{r}\left(\frac{R_B L}{2} - W_3\left(a_3 - \frac{L}{2}\right)\right) \qquad (1)$$

The value of horizontal reaction can be evaluated by Eq. (1).

The influence line of any reaction at a point is a graph showing the variation of load functions like reactions, moments, shear forces, stress or deflections at a point for various positions of unit moving load. Therefore, to draw the

influence line for H, a unit load of 1kg is placed at varying distance x from either of the supports.
Let a load of 1kg be placed at a distance x from A.

$$R_B = \frac{x}{L}$$ then, taking moment about C for all the

forces on R.H.S. of C we have
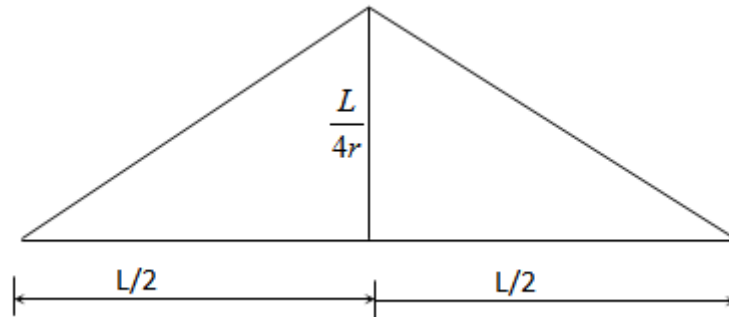
$$\frac{x}{L} \cdot \frac{L}{2} - H \cdot r = 0$$

(2)

$$\therefore H = \frac{x}{2r}$$

Thus, the Eq. (2) is the equation of a straight line and gives the influence line diagram for the horizontal reaction H.

II. MATERIAL AND METHODS
Description of the Apparatus
Three-hinged arch apparatus' model has a span of 1000mm and rise 250mm, with hinges at supports and crown. One of the end rests on rollers. Along the horizontal span of the arch various points are marked at equidistant for the application of load. The arch is mounted on a rectangular testing frame. A digital force/weighting gauge is attached at the roller end support to evaluate equivalent horizontal force to the applied load on the apparatus. See plate 1- 3 in the Appendix for pictorial description.

Materials used
The materials used to construct this apparatus were procured from local market. These are highlighted below:
1. Metal frame was fabricated with a thick rectangular iron pipe of 50mm x 25mm section.
2. Arches was made with combination of a square aluminum pipe of 30mm x 30mm section as skeletal frame and covered with plastic sheet of 5mm thick.
3. The ends of the arches are fabricated with 50mm x50mm square iron pipe. An end is

fixed by a u-shape flat bar of 25mm. The other end has a digital force gauge attached and the arch at the end has two rollers attached.

Design and Fabrication methods
Step by step adopted in fabricating the three-hinge arch apparatus with reasons were enumerated below
1. **Construction of structural frame-** Having considered the need for stability, durability, portability and adaptability of a proposed frame for the apparatus, a standing frame of 1200mm x 1200mm was produced with a footing of 500m long as shown in plate 2. A 50mm x 25mm rectangular pipe was cut by specification and joined together by welding. See figure 1 below for details. The arc welding adopted is to promote a rigid joint. The frame was painted to prevent rusting and improve the beauty of the structural frame.

2. **Construction of Arches**- the arch of 1000mm span and height of 250mm was fabricated with a square aluminum pipe of 30mm x 30mm section as skeletal frame. Aluminum pipe was used to avoid undue weight. A plastic material of 5mm thick was used to cover the frame by

screwing with bolt. The arch was divided into two symmetrically and linked by hinges to form a hinge joint. See figure 2 below.

3. **Construction of ends supports**- the ends of the arches have a fixed base and are fabricated with 50mm x50mm square iron pipe. A end is fixed by a u-shape flat bar of 25mm attached to a base. The other end has a digital force gauge attached and the arch at the end has two rollers attached.
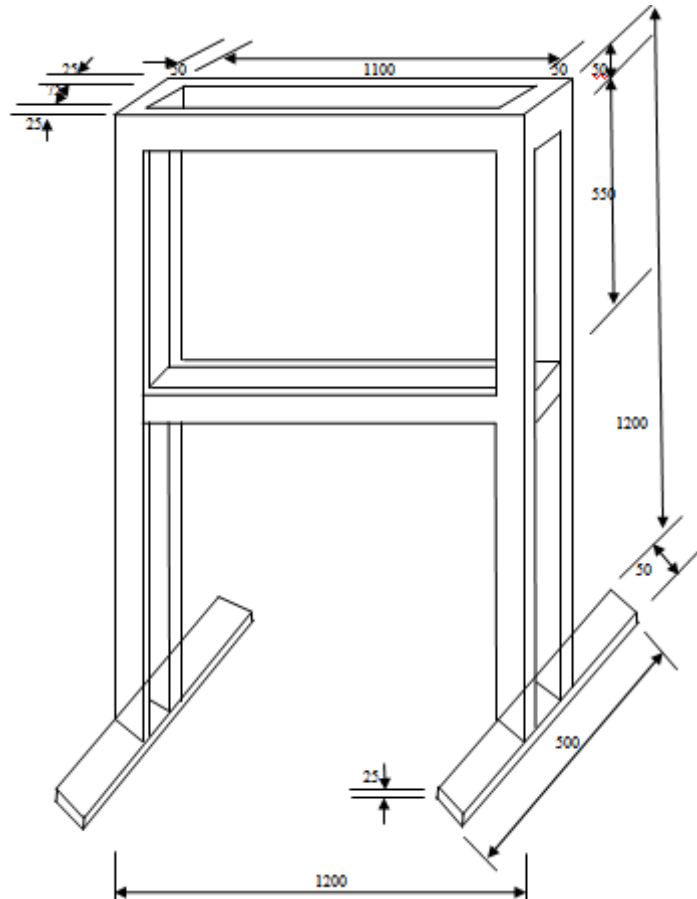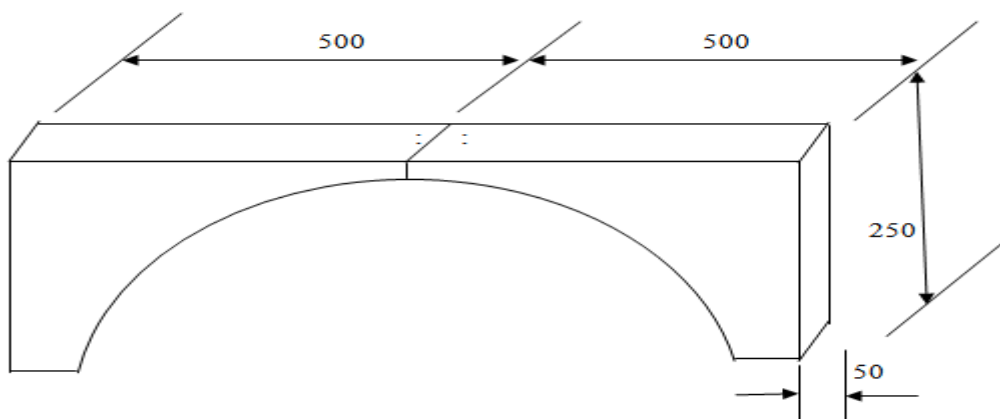

Figure 1: Structural Frame

Figure 2: Three- Hinged Arch

WORKED EXPRTIMENTAL EXAMPLE:
Experimental Aim and Objectives:
(1) To determine the horizontal thrust in a three hinged arch for a given system of loads experimentally and verify the same with calculated values.
(2) To obtain influence line diagram for horizontal thrust in a three hinged arch experimentally and to compare it with the calculated values.

Experimental Procedures:
Step1: Use lubricating oil at the roller end of the arch so as to have a free movement of the roller end. Switch on the force/weighing gauge and set to initiate the readings as zero.
Step2: Place a few loads on the arch in any chosen positions. Record the reading on the gauge which is the horizontal thrust and compared the result with calculation value.

Step3: To obtain the influence line for H, place a load of 1kg in turn on each hanger one by one and record the readings from the gauge.

Step4: Plot the ordinate representing $\frac{1}{2}$ of the balancing weights on the load positions as base. This gives the influence line diagram for horizontal thrust.

III. RESULTS AND DISCUSSIONS:
The table 1 below shows the horizontal thrust for a given set of load experimentally and theoretically. Table 2 shows the observed values of influence line ordinates and a graph of influence line ordinate against correspondence distance to A was plotted.

Sample Data Sheet:
Span of the arch, L=10cm
Central rise, h   =25cm

Table 1: Horizontal thrust

S/No.	Load on hanger member from roller end		Distance from left hand support (cm)	Additional load on thrust hanger i.e.H (kg)	Calculated value of H (kg)
	Set No.	Load (kg)			
Set I	W_1 W_2 W_3	0.1 0.1 0.1	a_1 =15.0 a_2 =30.0 a_3 =60.0	1.074	1.062

$$H \times r + W_1\left(\frac{L}{2} - a_1\right) + W_2\left(\frac{L}{2} - a_2\right) = R_A \times \frac{L}{2}$$

$$H = \frac{1}{r}\left[\frac{1}{2}[W_1(L - a_1) + W_2(L - a_2) + W_3(L - a_3)] - W_1\left(\frac{L}{2} - a_1\right) - W_2\left(\frac{L}{2} - a_2\right)\right]$$

H = 0.04[0.5(85+70+40)-35-20]
   H = 1.062kg

Discussion: The calculated value (1.062kg) with experimental value (1.074kg) has an insignificant difference, hence the experimental result with the apparatus fabricated is accurate.

Table 2: Values of influence line

1kgs load at hanger number	1	2	3	4	5	6	7	8	9
X from A (cm)	10	20	30	40	50	60	70	80	90
wt. on thrust hanger (kg)	0.175	0.350	0.540	0.740	0.920	0.740	0.505	0.320	0.140

Influence line ordinate (wt./2) observed	0.088	0.175	0.270	0.370	0.460	0.370	0.253	0.160	0.070
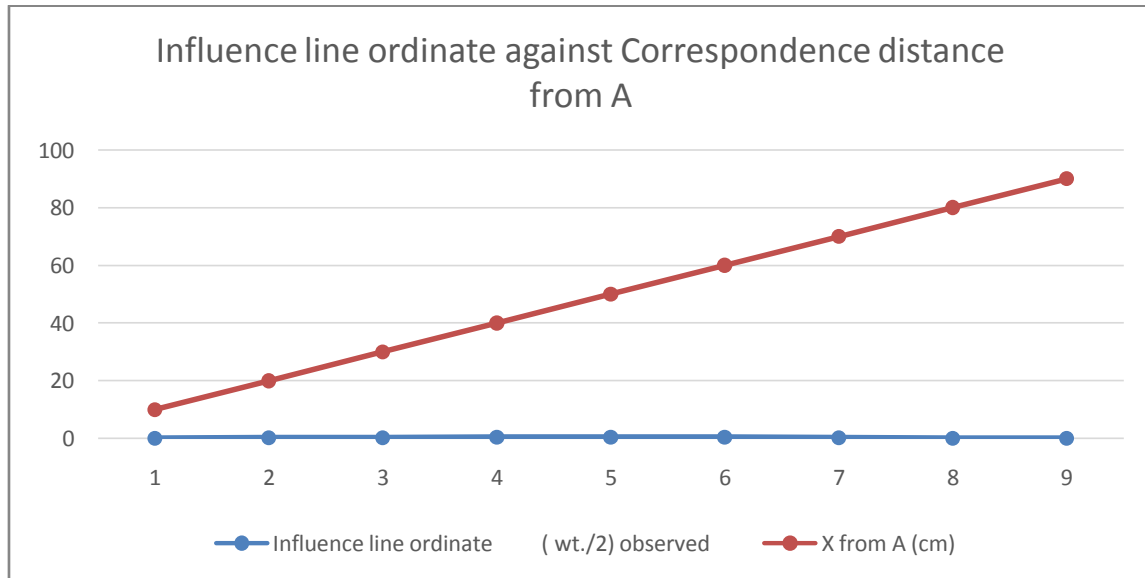
Precautions:
- Put the weights in thrust hanger very gently without a jerk.
- Measure the distance of loaded points from left hand support accurately.
- Perform the experiment away from vibration and other disturbances.

CONCLUSION

Most engineering based courses include practicals and laboratory experiments to complement the theoretical knowledge acquired by the students, promote their understanding. Practicals and experiments in some cases show real situation effects and consequently give in depth knowledge of the course. In engineering education, the focus of laboratories is mostly on integrity theory and practice. However, a lack of coherent learning objectives for laboratory has limited the effectiveness of laboratory instruction and has hampered meaningful research. Both teachers and students see the laboratory as a means to increase the learner's theoretical understanding with practice. In addition, a fundamental component of engineering education is a practical activity conducted in instructional laboratories and the objective can only be achieved through laboratory based investigations where students have to demonstrate understanding of and ability to apply a systems approach to engineering problems. However, where there are no or insufficient equipment, tools, apparatus etc to achieve the mentioned objectives, then the trainer who knows that practical and experiments play a vital role in engineering education would have to improvise a working alternative where the research, experiments, tests etc would be carried so as to complement whatever had been taught in the claasroom. Hence, in such a situation, design and fabrication with engineering principles become inevitable and the reason for the choice of this project which in actual fact, had enhanced the learning of engineering courses by the students.

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APPENDIX

Plate 1: Three-Hinged Arch Apparatus

Plate 2: Digital force gauge

Plate 3: Arch Roller

Plate 4: Three-Hinged Arch Apparatus