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Finite Element Analysis of Bridge Cranes' Proof Load Test Data

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ABSTRACT
Despite the strict regulatory steps taken by many countries and organizations to ensure and guarantee the safety in usage of lifting equipment, mishaps/incidents have been occurring. Some of these incidents have been attributed to machine/equipment failures, human errors, supervisory failures and climatic factors. It is thought that a good statutory proof load test of bridge cranes backed by an effective analytical method of test data (such as Finite Element Analysis) could go a long way to improve cranes performance and minimize incidents. To this extent, the 2, 4 and 6- Element model of the Finite Element Method was used in analyzing the proof load test Data of three cranes. The outcome of this test and analysis of data, reveals that: in order to avoid tedious computations associated with multiple complex loading of beams of cranes, the Finite Element Method is preferred to the traditional Analytical methods. Also, the two Element model of the Finite Element Method is significantly sufficient for the proof load test of cranes and lifting equipment; and that the Finite Element analytical methods significantly add value to the results of the Bridge Crane inspection.

Key Words: ***Proof Load Tests, Statutory Inspection, Finite Element Analysis***

INTRODUCTION

It is now appreciated and accepted that one of the greatest cost factors in productivity is Handling or short range transportation [1]. It is important to eliminate or at least reduce movement of both materials and people and the need to mechanize what movement remains, subject to certain human and economic conditions. Materials Handling Equipment(MHE) [2] is used for the movement and storage of materials within a facility or at a site. MHE can be classified into the following five major categories: a) Transport Equipment, b) Positioning Equipment, c) Unit load formation Equipment, d) Storage Equipment and e) Identification and Control Equipment.

Transport Equipment [2] are the Equipment used to move materials from one location to another (for example, between work places, between a loading dock and storage area, et cetera). The major sub-categories of transport equipment are conveyors, cranes and industrial trucks. Cranes [2] are further classified into:- Jib, Bridge, Gantry, Stacker and Tower cranes. The design of cranes [2] is based on two principles, namely: a) Hydraulics- this entails the transmission of forces from one point to the other through fluid; b) Block and Tackle system (pulleys). Pulleys [3] are machines used for hauling heavy loads to higher floors. When an arrangement of pulleys is made with some upper ones fixed and some lower ones movable, the set is referred to as block and tackle. The velocity ratio is equal to the number of pulleys, which is a general rule for this system of pulleys. Any form of equipment used in lifting that is between the load and the lifting equipment is called tackle [4]. These include: slings, shackles, eyebolts, hooks, thimbles, snaps, button stops, link and connectors. Riggers use ropes and pulleys to move items [5],[6],[7]. When pulleys, ropes and other gear are set up properly, riggers can lift heavy items without using much force. Consequent on the foregoing, trusting a team of riggers to hang 40tonne of equipment is a big responsibility, and choosing the proper rigging is just as much an art [8]. Once an appropriate lifting equipment is selected based on a lifting plan, a lifting operation flow chart is developed, also risk assessment is done, and toolbox talk is conducted and the outcome is used to modify the lifting plan [9]. The world over, lifting equipment are identified as high risk equipment and as such they have been grouped into special class of equipment with strict regulations for their testing, certification and usage [2]. Such Regulations and Codes of Practice include: the International Labour Organization(ILO) Regulations; the Provision and Use of Work Equipment Regulations(PUWER); Lifting Operations and Lifting Equipment Regulations(LOLER), and in Nigeria, the Factories Act 1990(Sections24 and26) [2]. All these efforts are aimed at reducing incident levels to as low as reasonably possible(ALARP) while at the same time guaranteeing efficiency and productivity in equipment usage. Cranes should be thoroughly examined at least once in every period of14 months [10]. The primary motive for these statutory inspections is to achieve safety and standard. Statutory inspection of lifting Equipment can be divided into two broad aspects, namely: Visual inspection and Proof Load/Safe Working Load Tests. Visual inspection is a thorough inspection carried out on the lifting equipment visible components such as the booms, the hooks, ropes, chains, fluids, outriggers, limit switches, winches, tracks and wheels etc. this inspection is in two parts. Firstly, the observations are made under static state of the equipment and then while the equipment is active in operation regime. The outcome infer whether the equipment is in good operating condition or not. This mode of inspection rely on hundred percent on the five senses, namely, seeing, hearing, touching, smelling and tasting. Good experience, good sense of judgment and common sense must be brought in to bear to minimize error in the assessment. On the other hand, statutory requirements demand that once in every two years and following a major overhaul of lifting equipment, a proof load test should be conducted for such equipment [10]. The proof load test consists of the application of 1.25 times of the Safe Working Load rated for the equipment over a period of time (not less than one hour) [10]. During the application of the load, the equipment parameters such as beam deflection (in the case of bridge cranes, gantry, cantilever) are measured; stress/strain in chains, ropes, slings and shackles are also measured. The data so collated through these tests are then analyzed and the results so obtained forms the basis for taking a decision on the equipment so inspected.

The Finite Element as an Analytical Method For Crane Inspection

The Finite Element Method (FEM) is a numerical technique for formulating and solving the governing differential equations for continuum problems [11]. This method has developed into the dominant practical analytical technique for complex structures of all types across many industries throughout the world. One of the reasons for the popularity of the method in different fields of engineering is that once a general computer programme is written, it can be used for the solution of any problem, simply by changing the input data. The Finite Element Method has its birth in the field of solid mechanics in papers by McHenry and Newmark [11]. The steps in Finite Element Analysis include[11]:

a) modeling the design; b) selecting the Element Nodal Variable Function; c) setting up Element Derivatives and constitutive Relationships; d) deriving the stiffness matrix: i) Direct equilibrium method, ii) work or energy method, iii) weighted residuals ; e) assembling the Element Equations and adding Boundary conditions: i) invert the stiffness matrix, ii) direct solution of the set of equations, iii) iterative method requiring an indefinite number of steps to converge; f) find the answer; g) display and interpret result.

The basic steps in the Finite Element procedure can also be expressed as [12]: i) Element Definition, ii) Element interpolation, iii) Calculation of element energy, iv) Assembly, v) Minimization and solution. Also the Finite Element Method generates discrete models for continuous systems under two basic assumptions, namely [13]:

Assumption I: that the displacement at any point in the structure due to the combined application of all the external load is equivalent to the sum of the displacements at the same point due to the application of each load separately; and

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Assumption II; that the displacement of any point due to the application of each load varies linearly with the magnitude of the load. Consequent on the foregoing, the Finite Element Method is regarded very much as a tool for practical analysis rather than as a theoretical entity in its own right [13].

Formulation of the Finite Element Equilibrium Equation for the Selected Crane.

a)Two Element Model

The assembly and solution of a simple model is illustrated using a two element idealization for a uniform beam of length 2L. The problem to be solved and the model used are shown in Figure1in Appendix. The beam is of flexural rigidity EI, is simply supported at each end and carries a concentrated load P at its midpoint. The beam is modeled using two simple beam elements. The unconstrained degrees of freedom are numbered δ_1 ----------- δ_4 as shown. The stiffness matrices for elements 1 and 2 are identical and the nodal displacement vectors are:

$$d(1) = \begin{pmatrix} \delta_3 \\ \delta_1 \\ \delta_2 \end{pmatrix} \quad \text{and} \quad d(2) = \begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_4 \end{pmatrix}$$

the stiffness matrix for the assembled model is obtained in the usual way by inserting the stiffness contributions from each element into an initially zero 4x4 array using the degree of freedom numbers in d(1) and d(2) to determine the row and column locations. On the assembly of the first and second element, the stiffness relationship for the model is

$$\begin{pmatrix} 24a & 0 & -6aL & 6aL \\ 0 & 8aL & 2aL^2 & 2aL^2 \\ -6aL & 2aL^2 & 4aL^2 & 0 \\ 6aL & 2aL^2 & 0 & 4aL^2 \end{pmatrix} \begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{pmatrix} = \begin{pmatrix} -P \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \text{Equation 1}$$

Where $a = EI/L^3$

Assumptions

i) from symmetry point of view, $\delta_2 = 0$

ii) from symmetry point of view, $\delta_3 = -\delta_4$.

Substituting these assumed values into equation 1 and simplifying, this model yields an exact result for δ_1, i.e.

$\delta_1 = PL^3/(6EI)$ Equation 2

b) Four Element Model

Also the beam is modeled using four elements (see fig.2). the unconstrained degrees of freedom for elements 1 and 4 are identical and they are numbered δ_1------ δ_8 as shown in fig.2. The stiffness matrices and nodal displacement vectors are:

$$d(1) = \begin{bmatrix} \delta_3 \\ \delta_5 \\ \delta_6 \end{bmatrix} \quad d(2) = \begin{bmatrix} \delta_5 \\ \delta_6 \\ \delta_1 \\ \delta_2 \end{bmatrix} \quad d(3) = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_7 \\ \delta_8 \end{bmatrix} \quad d(4) = \begin{bmatrix} \delta_7 \\ \delta_8 \\ \delta_4 \end{bmatrix}$$

The stiffness matrix for the assembled model is obtained in the usual way by inserting the stiffness contribution from each element into an initially zero 8x8 array using the degree of freedom numbers in d(1) to d(8) to determine the row and column locations.

Assumptions

From symmetry point of view,

$\delta_2 = 0$ $\delta_5 = -\delta_7$ $\delta_6 = \delta_8$ $\delta_3 = -\delta_4$

Substituting these assumed values into an initially zero 8x8 array and simplifying, this model yields an exact result for δ_1, i.e.

$\delta_1 = 4PL^3/(3EI)$

Equation 3

c) ***Six Element*** Model

In a similar vein, the beam is modeled using six beam elements. The unconstrained degrees of freedom are numbered δ_1------ δ_{12} as shown in fig. 3. The stiffness and nodal displacement vectors are:

$$d(1) = \begin{pmatrix} \delta_3 \\ \delta_5 \\ \delta_6 \end{pmatrix} \quad d(2) = \begin{pmatrix} \delta_6 \\ \delta_5 \\ \delta_{10} \\ \delta_9 \end{pmatrix} \quad d(3) = \begin{pmatrix} \delta_{10} \\ \delta_9 \\ \delta_1 \\ \delta_2 \end{pmatrix} \quad d(4) = \begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_{12} \\ \delta_1 \end{pmatrix}$$

$$d(5) = \begin{pmatrix} \delta_{12} \\ \delta_{11} \\ \delta_8 \\ \delta_7 \end{pmatrix} \quad d(6) = \begin{pmatrix} \delta_8 \\ \delta_7 \\ \delta_4 \end{pmatrix}$$

Assumptions

From symmetry point of view, $\delta_2 = 0$ $\delta_5 = -\delta_7$ $\delta_9 = -\delta_{11}$

$\delta_3 = -\delta_4$ $\delta_{10} = \delta_{12}$ and $\delta_8 = \delta_6$.

Substituting these assumed values into the initial zero 12x12 array and simplifying, this yields an exact result for δ_1, i.e.

$\delta_1 = 9PL^3/(2EI)$ Equation 4

Computing The Moment Of Inertia(I) Of The Crane [14].

For greater accuracy of computing, the web and flange area of the beam may be treated separately using the parallel axis theorem for the flanges. From fig. 4a, then the moment of inertia(I) is

$I = I_y = 1/12[2t_1B^3 + dt_2^3]$ Equation 5

MATERIALS AND METHODS

MATERIALS

The materials and equipment for this research include the following:

a) New Indian Crane 1 rated SWL of 10Tonne (located in Sheet Mill)

b) New Indian Crane 2 rated SWL of 5 Tonne (located in New Paint Line)

c) New Indian Crane 3 rated SWL of 5 Tonne (located in New Paint Line).

These cranes are resident in First Aluminum Nig PLC, Port Harcourt.

d) Load cell (50Tonne rating) - standard load measurement is done with a range of load cell shackles and links fully calibrated to an accuracy of 1% full scale deviation(15),(16).
e) Two water weight bags SWL 10 Tonne each
f) One water weight bag SWL 5 Tonne

Water weights water filled proof load bags are a unique and simple product specifically designed to provide test load instead of traditional solid weights for all forms of testing. These water weight bags are certified to ISO 9001:9002. The water weight bags are certified in accordance with Health and Safety Executive requirements. The bags have a physically proven factor of safety in excess of 6:1 and are proof tested to over 2:1 prior to being put into service [17],[18],[19].

g) Two Leveling Equipment and Leveling Staff - - to measure the deflection of the cranes' beams.
h) Two 15- Tonne water tankers - - to supply the required quantity of water for the test.
i) Two shackles rated SWL 50 Tonne
j) Two shackles rated SWL 10 Tonne
k) Restriction zebra tapes and beacons to condone off test area.
l) Two survey tapes - - to measure the physical dimensions of the beam of the bridge crane.
m) DN75mm water hoses (sufficient quantity).

METHODS

Method For The Proof Load Test Of Bridge Crane 1.

The area surrounding the Bridge Crane is condoned off and restricted to Test Personnel only. The physical dimensions of the beam of the crane are then measured and recorded. The geometric centre of the crane's beam is clearly marked out. The initial level of the Bridge crane's beam at the centre point is measured by the leveling equipment and the leveling staff. The load cell is now mounted on the hook through the use of the 50tonne shackle. Another shackle is fastened to the lower end of the load cell and the water weight bags are now rigged up on the shackle. The water hoses are now fastened to the water weight bags and discharge port of the water tankers. The discharge pump of the water tanker is started and the discharge valve is opened to supply water into the water weight bags. Intermittently, the water tanker discharge valve is shut and the deflection level of the Bridge Crane is taken by the leveling equipment and leveling staff. Simultaneously, the weight of water supplied to the water weight bags is read off the remote control of the load cell. This procedure is continued until the point of proof load is reached or creep is experienced. At this point the drain ports of the water weight bags are opened so that the water can drain out. The rig is disassembled.

b) ***Method for the Finite Element Analysis of Data for*** Bridge ***Crane 1***

Physical measurements of the dimensions of Bridge Crane 1 as shown in fig. 4a and b are plugged into equation 5 and the moment of inertia I is computed. The load P measured by the load cell in Tonne is converted to Newton and the equivalent of beam for 2- Element model and the value of modulus of Elasticity E are plugged in equation 1, the value of δ_1 , the deflection corresponding to applied load is obtained. This analysis is repeated for the 4- Element and 6- Element model and the values of deflection δ_1 for 4- Element and 6- Element models are obtained.

d) Acceptance or Rejection Criteria of ***Measured Results.***

Let δ_m = the measured deflection through the leveling equipment and leveling staff

Let δ_1 = the computed value of deflection through Finite Element Method.

If $\delta_m < \delta_1$, Accept results, i.e. equipment is in good working condition and therefore can be put into service at the said proof load.

If $\delta_m > \delta_1$, Reject results, i.e. equipment is not in good working condition and therefore cannot be put into service at the said proof load. A new safe working load has to be defined for the equipment.

The whole process is repeated for cranes 2 and 3 and decision taken accordingly.

RESULTS AND DISCUSSIONS

TABLE 1 - DATA FOR BRIDGE CRANE 1

ROUND OF OBSERVATIONS	LOAD (TONNE)	BEAM DEFLECTION(M)
1	0.14	0.00
2	5.26	0.003
3	9.7	0.007
4	11.03	0.008

5	**12.5**	**0.010**
6	**14.43**	**0.011**

$E = 208{,}000 N/mm^2 = 208 \times 10^9 N/m^2$

Length of beam = 23.59m. Centre of beam = 11.8m.

SOURCE: MEASUREMENT FROM PROOF LOAD TEST OF BRIDGE CRANE 1 AT SITE.

TABLE 2 - DATA FOR BRIDGE CRANE 2

(SERIAL NO. OJ/084A)

ROUND OF OBSERVATIONS	LOAD (TONNE)	BEAM DEFLECTION(M)
1	4.47	0.00
2	5.08	0.002
3	6.39	0.007

Length of beam = 16.45m

SOURCE: MEASUREMENT FROM PROOF LOAD TEST OF BRIDGE CRANE 2.

TABLE 3 - DATA FOR BRIDGE CRANE 3

(SERIAL NO. OJ/084B)

ROUND OF OBSERVATIONS	LOAD (TONNE)	BEAM DEFLECTION(M)
1	4.72	0.00
2	4.84	-

Length of beam = 16.41m

Slip occurred at 4.84Tonne

SOURCE: MEASUREMENT FROM PROOF LOAD TEST OF BRIDGE CRANE 3

Two Element Model

Recall equation 1, i.e.

$$\begin{pmatrix} 24a & 0 & -6aL & 6aL \\ 0 & 8aL & 2aL^2 & 2aL^2 \\ -6aL & 2aL^2 & 4aL^2 & 0 \\ 6aL & 2aL^2 & 0 & 4aL^2 \end{pmatrix} \begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{pmatrix} = \begin{pmatrix} -P \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

This equation represent the formulated Finite Element Equilibrium Equation for the selected crane. Where a = EI/L^3.

Where L = half of the beam span.

Assumptions:

i) from symmetry point of view, $\delta_2 = 0$

ii) from symmetry point of view $\delta_3 = -\delta_4$

Analysis for crane 1

E =208 x 10^9N/m^2

Considering data from Fig.4 and equation 5:

t_1 =0.013m t_2 =0.43m B = 0.45m d = 0.94m.

Therefore: I = I_y = 2[1/12(2 x 0.013 x 0.453 + 0.94 x 0.433)]

= 0.012851m4.

From table 1, L = 23.59m/2 = 11.8m

P = 14.43Tonne = 14.43 x 10^3 x 9.81 Newtons.

Therefore, a = EI/L^3 = (208 x 10^9 x 0.012851)/$(11.8)^3$ = 1.63 x 10^6.

Substituting for a and L in above equation, i.e. equation 1, we get:

$$\begin{pmatrix} \mathbf{24(1.63 \times 10^6)} & \mathbf{0} & \mathbf{-6(1.63 \times 10^6)11.8} & \mathbf{6(1.63 \times 10^6)11.8} \\ \mathbf{0} & \mathbf{8(1.63 \times x10^6)11.8} & \mathbf{2(1.63 \times 10^6)11.8^2} & \mathbf{2(1.63 \times 10^6)11.8^2} \end{pmatrix} \begin{pmatrix} \delta_1 \\ \mathbf{0} \end{pmatrix} = \begin{pmatrix} \mathbf{-141.6 \times 10^3} \\ \mathbf{0} \end{pmatrix}$$

-6(1.63 x 10^6)11.8 2(1.63 x 10^6)11.8^2 4(1.63 x 10^6)11.8^2 0 - δ_4 0

6(1.63 x 10^6)11.8 2(1.63 x 10^6)11.8^2 0 4(1.63 x 10^6)11.8^2 δ_4 0

On simplifying, we get δ_1 =0.014m.

Acceptance/ Rejection Criteria Of Measured Result

If $\delta_m < \delta_1$: Accept result, i.e. the equipment is in good working condition and therefore can be put into service at the said proof load.

If $\delta_m > \delta_1$: Reject results, i.e equipment is not in good working condition and therefore cannot be put into service at the said proof load. A new Safe Working Load has to be defined for the equipment.

For this result, δ_1 = 0.014m and δ_m= 0.011m,

Hence $\delta_m < \delta_1$, i.e , 0.011m < 0.014m.

Thus the result is accepted for the crane number 1.

Similar analysis were carried out for Bridge Cranes 2 and 3 at Two Element Model. Analysis was equally carried out at 4-Element and 6-Element Models for all three cranes and the results are as tabulated below.

TALE 4 – MAXIMUM DEFLECTIONS OF BRIDGE CRANES AT 2, 4 AND 6- ELEMENT MODELS.

S/No.	ANALYTICAL METHOD	CRANE 1 BEAM MAX DEFLECTION (δ_1) METRES	CRANE 2 BEAM MAX. DEFLECTION (δ_1) METRES	CRANE 3 BEAM MAX. DEFLECTION (δ_1) METRES
1	FEM(δ_F)2-L	0.014	0.00434	0.00327
2	FEM(δ_F)4-L	0.0145	0.00434	0.00327
3	FEM(δ_F)6-L	0.0145	0.00434	0.00327
4	MEASURED DEFLECTION AT SITE(δ_m)	0.011	0.007	-

SOURCE: SUMMARY OF COMPUTED DEFLECTIONS FROM TABLES 1, 2 AND 3.

DISCUSSION OF RESULTS

δ_m is less than $\delta_1$at all 2, 4 and 6-Element Models for crane 1.Hence Proof Load Test is successful . This implies that Bridge Crane 1 is in good condition and can be put into service at this Proof Load of 14.43Tonne.

For Crane 2, the measured value of deflection $\delta_m$is greater than δ_1 for all the 2, 4 and 6 – Element Models. Hence Bridge Crane 2 is not in good condition, and cannot be put into service at the Proof Load of 6.39Tonne. A new Safe Working Load has to be established for it pending when effective turn around repairs has to be done on it.

Crane 3 failed at 4.84Tonne. This value is even less than it's earlier Safe Working Load of 5Tonne. A new Safe Working Load has to be established for it pending the overhaul of the crane.

The outcome of the 2, 4 and 6 – Element Models for the three cranes reveals that the improvement in deflection results in moving from two – Element to Four and Six – Elements is not significant. Hence for the purpose of the Analysis of Proof Load Data, the Two – Element Model is sufficiently accurate enough for usage.

Conclusion

1. Analytical tools are essential for the effective and efficient evaluation of Proof Load Test Data of Bridge Cranes.
2. In order to avoid tedious computations associated with multiple and complex loading of beams of Bridge cranes, Finite Element Method is preferred to the traditional Analytical Methods.
3. The Two Element Model of the Finite Element Method is significantly sufficient for the Proof Load Test of Bridge cranes and lifting equipment.
4. The finite Element Analytical Method significantly adds value to the result of the Bridge Crane inspections.

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APPENDIX

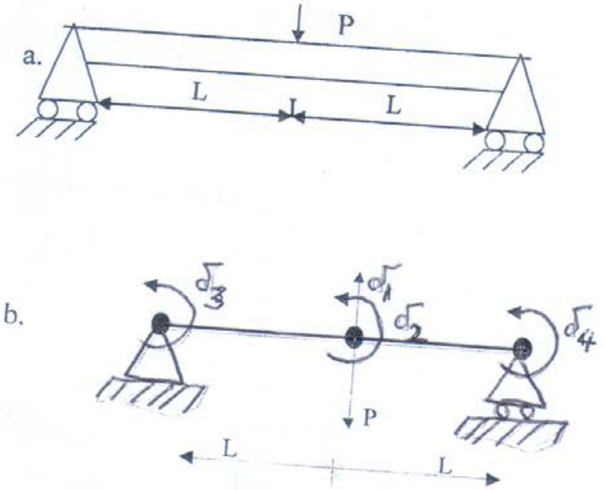


Fig. 1. (a) Geometry and Loading, (b) Finite Element Model

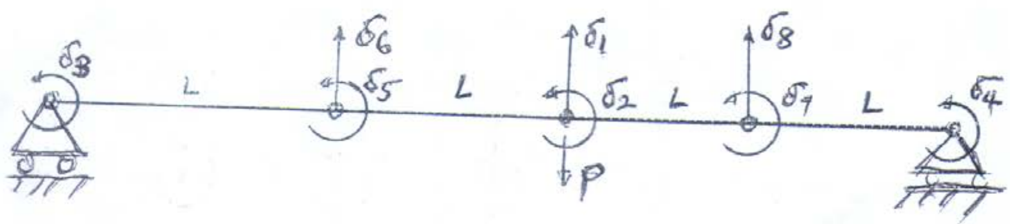


FIG. 2. Finite Element Model (4—Elements)

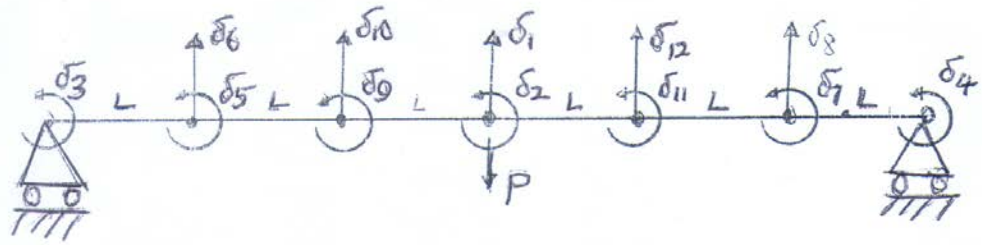


FIG. 3 Finite Element Model (6—Elements)

Length of beam = 23.59m

Centre of beam = 11.8m

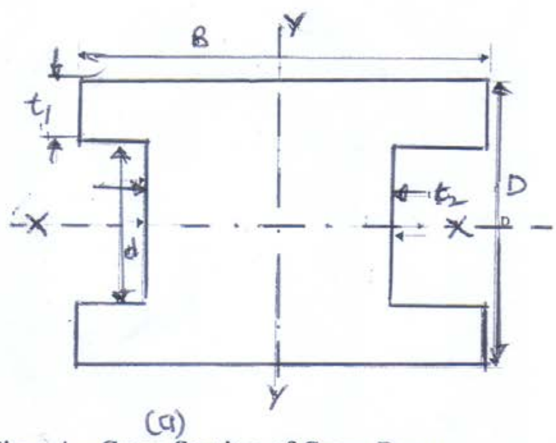
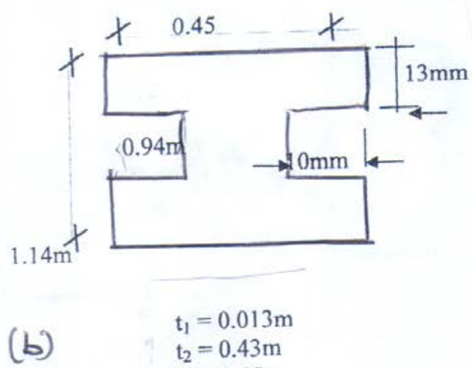


Fig 4 – Cross Section of Crane Beam



$t_1 = 0.013m$
$t_2 = 0.43m$
$B = 0.45m$
$D = 0.94m$

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