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Experimental and Numerical Study of Deep Beams by Finite Element Method (FEM)

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ABSTRACT
The paper deals with the comparison between experimental and analytical deflection results of reinforced (M20 grade) concrete deep beams. Three deep beams were designed according to the Indian Standard (IS) code provisions with different length to depth (L/D) ratios (1.5, 2, and 2.5). The beams were cast and tested by subjecting it to single central point loading (three point bending test). The loads at first crack and failure, deflections at first crack and failure and the crack widths were observed. Those parameters were also analyzed using software, ANSYS 9.0., which uses non-linear FEM. A graphical plot of load versus deflection was obtained for both experimental and numerical deflection values separately. The comparison between the experimental and analytical behaviour of the beams are also discussed.

Keywords - ANSYS 9.0., Deep Beam, L/D (Span to depth) ratio, Non – Linear FEM

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I. INTRODUCTION

Deep beam is an interesting subject in Structural Engineering due to economical reason. They find application in high rise building and allow the engineers to achieve a column free surface. Many researchers have studied and come out with their own methods for design of deep beams. This is because the deep beams are unable to be understood using the classical beam theory. Beam with larger depth to span ratio is called as deep beam. ACI (American Concrete Institute) and committee members in Euro code are the formers in developing design methods for deep beams. According to ACI design guide, the deep beams must satisfy at least one of the following conditions: 1) clear span is equal to or less than four times the overall member depth or 2) regions with concentrated loads are within twice the member depth from the face of the support. On the other hand, Euro code suggests that for a deep beam, the span must be equal to or larger than 3 times the overall depth of the member. (Eurocode 2, 1984). Usually, for designing a deep beam, method of strut and tie model is used. In this paper, Indian Standard Code is used for designing the deep beams. (ACI Code 318–83 (revised 1986)). As per the standard specified in IS 456 (2000), Clause 29, the span (L) to depth (D) ratio of the deep beam is given as: 1) simply supported beam, L/D < 2 and 2) continuous beam, L/D < 2.5. The effective span for deep beams is given by lesser of the following two values: 1) Centre – to – centre (c/c) distance between the supports or 2) 1.15 times the clear span. The present investigation is to prove that the depth of the beams plays role in increasing the performance in aspects of deflection and stress.

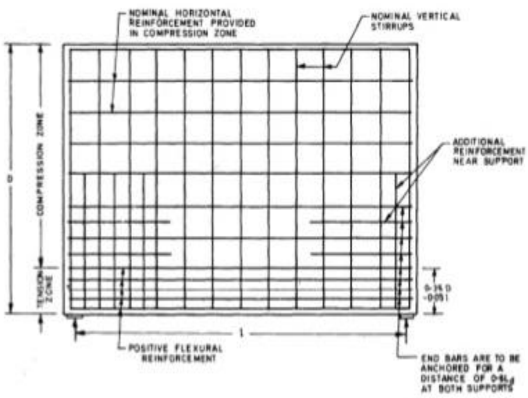


Fig. 1 Schematic detailing of the deep beam

SOLIDWORKS is separate software used to model the beams for analysis through other software. Beams with dimensions, 1000mm x 650mm x 150 mm, 1000mm x 500mm x 150 mm, and 1000mm x 400 mm x150mm were modeled and exported to ANSYS 9.0.

Software - ANSYS was used for analyzing the beams which was modelled in SOLIDWORKS. All the three beams of different depths, 400mm, 500mm and 650mm were analyzed. Deflections of the beams at corresponding loads were observed and load versus deflection curves were plotted.

II. MATERİALS AND METHODS

The various materials and the methodology used for the work are dealt below.

2.1 Materials

The beam specimens are composed of 4 major construction materials as stated below:

- Cement
- Fine aggregate
- Coarse aggregate
- Rebar
- water

Those materials used are listed in detail below. (Mohammadhassani, et al., 2011)

2.1.1 Cement

The cement grade used for casting the beams was OPC - 53 grade cement conforming to the requirements of IS: 269 1976 (Specification for ordinary and low heat Portland cement (third version)). Usually 53 grade OPC is used for higher strength concretes. According to BIS, the 28 days compressive strength of the 53grade OPC must not be less than 53 N/mm^2. (Bureau of Indian Standards)

2.1.2 Fine Aggregate

The portion of aggregate used in concrete that is smaller than about 2⁄16 inch is known as fine aggregate. They can pass the 3/8" (9.5-mm) sieve and almost entirely passing the No.4 (4.75-mm) sieve and predominantly retained on the No. 200 (75-micrometer) sieve. (BIS). Among the three types of fine aggregates (natural sand, crushed stone sand & crushed gravel sand), natural sand was used in the specimens.

2.1.3 Coarse Aggregate

It is the aggregate which do not pass and is retained in the 4.75mm IS sieve. Crushed gravel or stone (hard stone is stone is crushed) was used in the specimens.

2.1.4 Rebar

Rebar (reinforcing bar) is also known as reinforcing steel, is a tension device in reinforced concrete and reinforced masonry structures which do not allow any concrete to fail by tension. Fe415 HYSD bars were used as reinforcements in all the three specimens.

2.1.5 Water

Usually, water plays major role due to its participation in chemical reaction with cement. Also, the new supplement material for cement, steel dust, when absorbs water and oxygen, reacts with the atmospheric moisture, forms rust and imparts strength to the concrete. Hence, both quality and quantity of water is notable.

2.2 Methods

The methods include the mix design, method of experimental investigation and the method of software analysis.

2.2.1 Mix design

The mix design is adopted according to the specifications of IS 10262 – 2009. The stipulations considered to arrive at the mix design are, 20 N/mm^2 of characteristic compressive strength required in the field at 28 days, 20mm (angular) sized aggregate, 0.90 compacting factor, good quality control and a mild exposure condition. Water absorption test and specific gravity test (using pycnometer) were conducted on the materials.

Based on the properties of materials, the mix design was carried out and the proportion was obtained to be 1: 1.10: 2.37, maintaining a W/C ratio of 0.40.

2.2.2 Experimental execution and set up

The experimental work of the study deals with the following sequence for the process of execution. (Vengatachalapathy, 2010)

- Batching
- Bar bending
- Shuttering
- Mixing
- Casting and Compacting
- De-shuttering
- Curing
- Testing

2.2.2.1 Batching

The method of weight batching was adopted. All the concreting materials were separately weighed using electronic weighing machine as mentioned in TABLE 1.

Table 1 Batching of materials

Beams	**Cement (kg)**	**Sand (kg)**	**Aggregate (kg)**
01-L/D=1.5	46.7	51.68	110.76
02 - L/D=2	35.93	39.75	85.2
03 - L/D=2.5	28.7	31.8	68.16
TOTAL	111.37	123.2	264.12

2.2.2.2 Bar bending

Fe415 bars of 10mm diameter were used in both tension and compression zone for all the three beams. Stirrups were of 8mm diameter bars with spacing higher at centre and minimum at the supports (fig. 2). Proper cover was maintained and the process was under the guidance of professional bar benders.


Fig. 2 Bent Bars

2.2.2.3 Shuttering

The mould was prepared using plywood, considering the dimension of the largest beam (1000mm x 650mm x 150mm). The same mould was used for the other two beams also. Proper markings were done inside the mould according to the depth of other beams (500mm & 400mm). The preparation of mould was performed under the supervision of a professional carpenter.

2.2.2.4 Mixing

The concrete was mixed in a mixing tray, as per the proportion mentioned earlier. Guidance of experienced mason was obtained. Proper water-cement ratio was maintained throughout the casting process.

2.2.2.5 Casting and Compacting

The cover blocks of 40mm length were used on all the faces of the reinforcing bars before the concrete mix was placed. Vibrator compactor was used for compaction to avoid honey combings. A limited and required compaction was done to avoid bleeding.

2.2.2.6 De-shuttering

De-shuttering of beam was done once the concrete was dried and hardened enough. A properly compacted concrete deep beam specimen was obtained without honey combing. Corresponding to the depth, 650mm, 500mm & 450mm, the beams were named B1, B2 and B3.

2.**2.2.7 Curing & testing**

The method of water curing was adopted for 28 days (fig.3). To investigate the beams, a three point bending test was performed using UTM (fig.4).


Fig. 3 Curing of beam


Fig. 4 Three point bending test on beam

2.2.3 Software analysis

The analysis part deals with two softwares namely,

- SOLIDWORKS (for modeling)
- ANSYS (for analysis)

2.2.3.1 Model creation by SOLIDWORKS

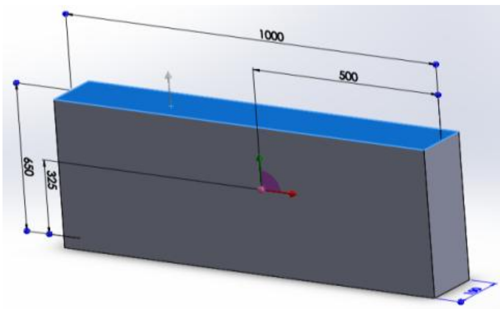


Fig. 5 Model of B1

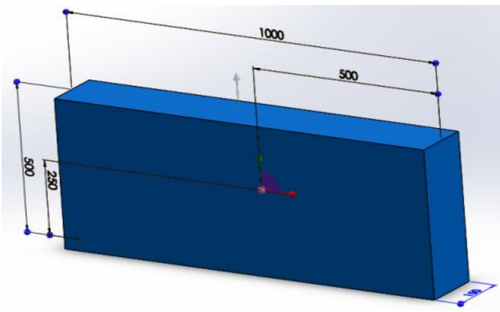


Fig. 6 Model of B2

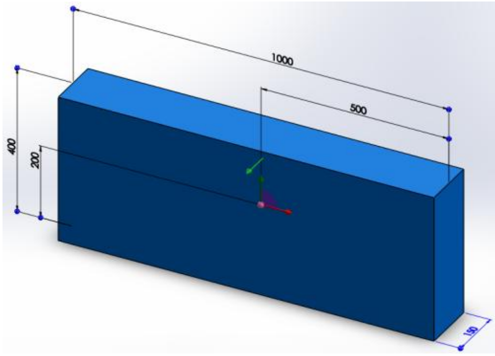


Fig. 7 Model of B3

2.2.3.2 Analysis of the beams through ANSYS

Three different central point loads of 300 kN, 400 kN and 500 kN were employed. The following observations were made during the analysis and the corresponding images are shown.

- Stress patterns
- Deflection
- Load at first crack
- Load at failure

III. RESULTS AND DISCUSSIONS

Results for the material tests, experimental and analytical investigations are included below.

3.1 Material test results

The materials were tested for the properties and their respective results are tabulated below (TABLE 2).

Table 2 Material Test results

Property	**Material**	**Result**
Specific gravity	Cement	3.15
	Coarse aggregate	2.60
	Fine aggregate	2.6
Water absorption (%)	Coarse aggregate	0.50
	Fine aggregate	0.10
Free surface moisture (%)	Coarse aggregate	Nil
	Fine aggregate	2

3.2 Experimental observations

The test was conducted using the UTM and the detailed results from the experiment are tabulated as follows (TABLE 3).

Table 3 Experimental Results

Beam	**B1**	**B2**	**B3**
Depth (D) in	650	500	400
Effective	1.5	2	2.5
Design	IS 456	IS 456	IS 456
Lever arm	460	400	360
Flexural steel required in	278.62	373	489
Flexural steel provided in mm^2	157 2 - 10Φ	157 2 - 10Φ	157 2 - 10Φ
Minimum shear required in mm^2 (a) Vertical (b) horizontal	72 120	72 120	72 120
Vertical steel required in	143.11	177.35	209.34
8mm diameter (a) Vertical (b) horizontal	4 bars 2 bars	4 bars 2 bars	4 bars 2 bars
First crack	150	115	90
Failure load,	425	325	230
Deflection at	0.32	0.47	0.55
Maximum	1.75	1.55	1.52
Permissible	2.4	2.4	2.4
Crack width	0.345	0.387	0.390
Permissible	0.3	0.3	0.3

3.2.1 Crack pattern observed experimentally:

The crack pattern observed during the test is shown in the figure below.

Fig. 8 Crack pattern – Front view

Fig. 9 Crack pattern – Bottom view

3.2.2 Graph for experimental observation

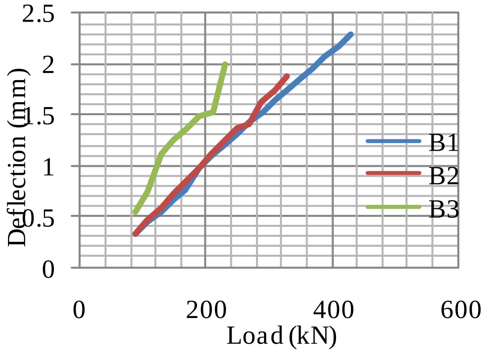


Fig. 10 Experimental load vs. deflection curve for B1, B2 & B3

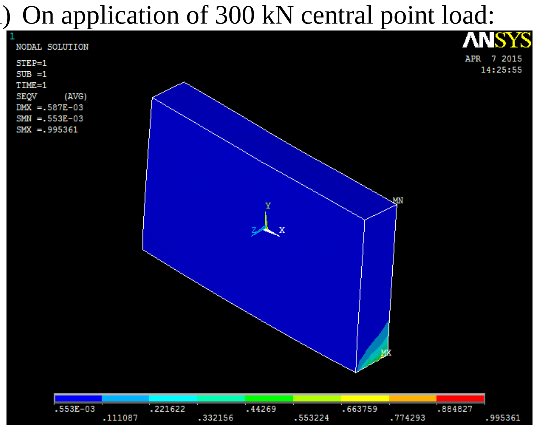
From the above graph, it is evident that the deflection value increases with increase in load, experimentally. Also, the beam with more depth tolerates more load than the other two which is of smaller depths. The deflection remains larger and the crack width remains smaller for B1. Also, the first crack for B1 occurs at a load higher than that for the other two beams. B1 is found to be more tolerant that the other two beams. The deflection, crack width and stress values of B2 are found to lie between the values of the B2 and B3. B3 is found to have the least values in all the aspects such as deflection, crack width and stresses. It could withstand only a lesser value of load and cracks were found to develop at a lower load value. Also, the crack widths were larger in comparison with the other two beams. The stresses in B3 were larger than the other.

3.3 Analytical results

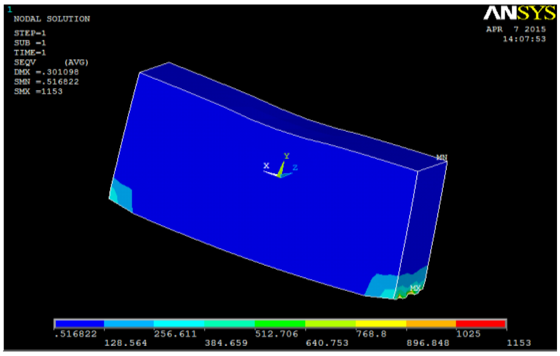
The stress patterns for the beams were observed using the software and are discussed as follows.

3.3.1 Stress Patterns

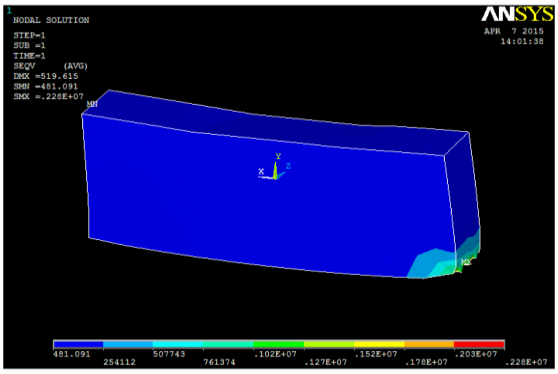
(i) On application of 300 kN central point load:



(a)



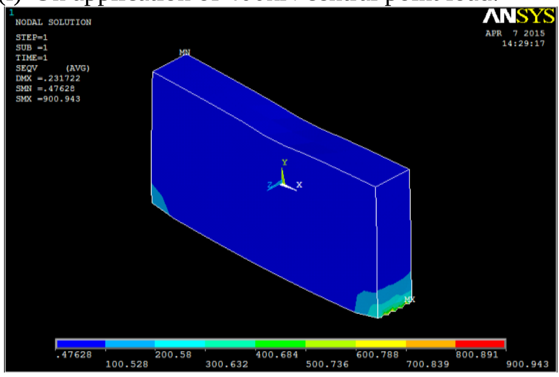
(b)



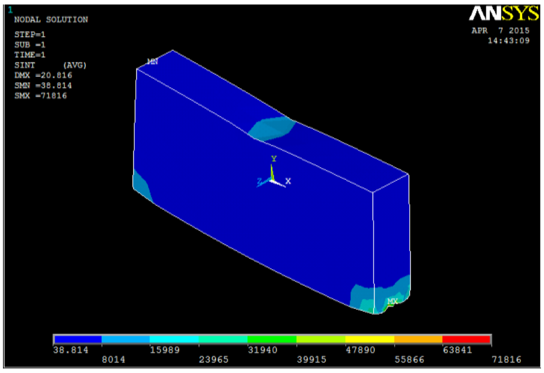
(c)

Fig. 11 Stress and deflection patterns of (a) B1, (b) B2 & (c) B3

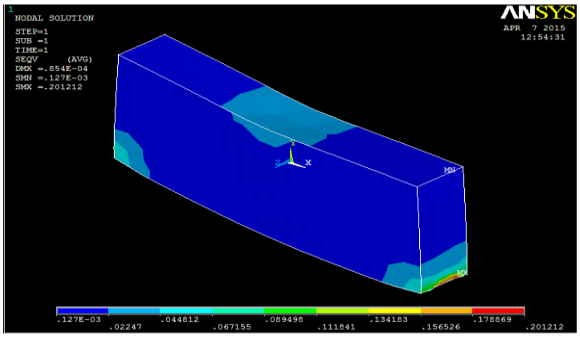
(i) On application of 400kN central point load:



(a)



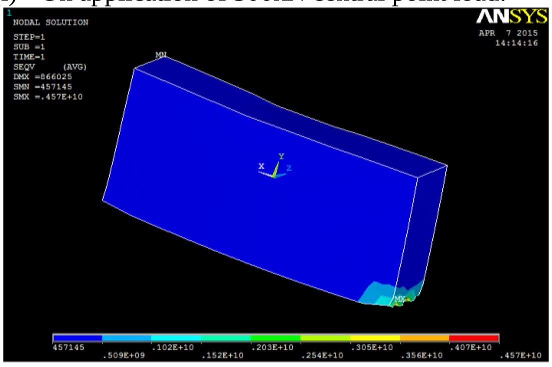
(b)



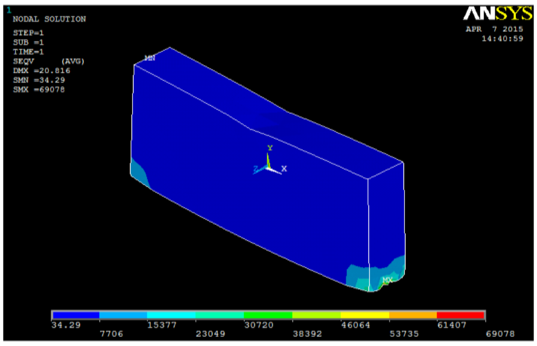
(c)

Fig. 12 Stress and deflection patterns of (a) B1, (b) B2 & (c) B3

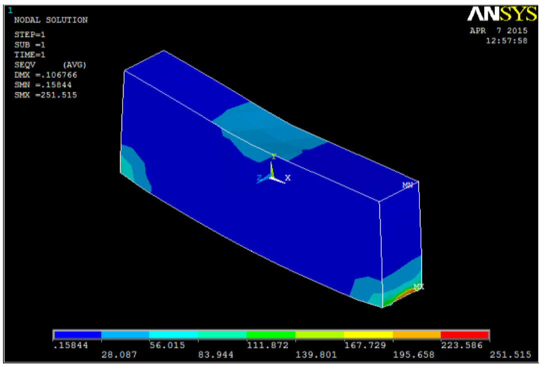
(i) On application of 500kN central point load:



(a)



(b)



(c)

Fig. 13 Stress and deflection patterns of (a) B1, (b) B2 & (c) B3

3.3.2 Software results

The analytical results were obtained through ANSYS 9.0 and are tabulated below (TABLE 4).

Table 4 Analytical Results

Beam number	Beam 1	Beam 2	Beam 3
Depth (mm)	650	500	400
Span to depth	1.5	2.0	2.5
Flexural steel required in mm^2	85.06	95.862	102.689
Flexural steel provided in mm^2	157 2 - 10Φ	157 2 - 10Φ	157 2 - 10Φ
Load at first crack (total)	170	135	105
Load at failure (total)	400	300	250
Deflection at first crack, mm	0.35	0.42	0.50
Total deflection at failure, mm	1.364	1.286	1.140

3.3.3 Graph for analytical observations

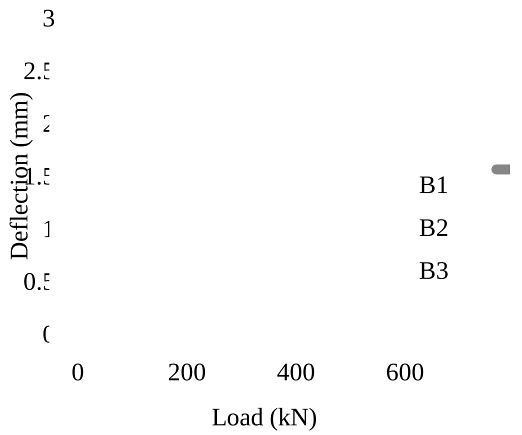


Fig. 14 Analytical load vs. Deflection curve for B1, B2 & B3

Analytically, B1 tends to take more load than in reality. The deflection and crack width are also smaller than that obtained experimentally. The stresses were also found to be more at the point of application of load and at the supports. One of the supports was stressed more than the other support in software analysis. In B2, stresses were found to be more at the supports than at the point of application of load. Also, the deflection and crack width values were smaller than the experimental values. B2 was found to tolerate more load analytically than experimentally. Analytically, 400kN load could develop a stress at the point of application of load but the supports were found to be more prone to stress when loaded for a value of 300kN and 400kN. Deflection values were higher and the stresses were vigorous both at the supports and the point of application of load on B3. Failure load was also higher than the expected experimental load. This beam stands behind the other two beams because of lower depth.

3.4 Comparison between experimental and analytical behavior

Both experimentally and analytically, the performance of the beams increases with increase in depth. The beam with lesser depth was found to perform less. Analytically, at a given load, the stresses and deflections were not vigorous. But the beam with same dimensions did not show such performance during the test. Practically, the deflections were higher than that observed analytically. In analytical figures, it is clearly shown that the stresses were high at support but this was false in the case of experimental analysis. While the test, the stresses were found to be more under the point of application of load. Hence, the analytical and experimental behavior was not coinciding with each other. Since the software uses non-linear finite element method for analysis, the deflection and stress results obtained analytically are accurate. One major advantage of non-linear FEM is that it accurately analyses a member with various material properties.

IV. CONCLUSIONS

Deep beams with various L/D ratios were analyzed. The analysis software uses non – linear finite element method was used. A single central point load was applied and the following conclusions can be drawn as follows.

1. From the load versus deflection graphs, the deviation of the stress - strain pattern was more in case of beams with smaller span/depth ratio i.e. the shallow beams do not follow a linear variation.
2. Deflection variation graphs indicate that the accuracy is reasonably fine in beams with L/D ratio less than or equal to 2.0.
3. The deflection graph shows the shift of neutral axis towards the beam soffit with increase in the L/D ratio.
4. Diagonal cracking was more pronounced while failure, in case of deep beams.

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