# BEHAVIOR OF CONCRETE DEEP BEAMS WITH HIGH STRENGTH REINFORCEMENT

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**Abstract — The high performance reinforcement continues to gain wider acceptance in industry practice, due to improved mechanical properties of new materials. For decades, methods of design and analysis of concrete members reinforced with normal strength steel have been developed. Recently, reinforcing steel (550 & 550D) with strength higher than conventional steel has become commercially available. The introduction of high strength reinforcing steel can be useful to reduce the quantity of reinforcement required, thereby lessening reinforcement congestion and improving constructability. This paper presents construction and testing of several high strength reinforced concrete deep beams which includes three beams, designed for three different country codes, for each shear span to depth ratio as described and the test data is presented. The beam consists of simple span subjected to two point loading, each span being 0.7 m in length. The shear span to depth ratios ranged from 0.62 to 0.77. Measurements were made during each test inclusive of applied loads and mid span deflections directly from programmed instrument (K.P.T.L.) through load cell and L.V.D.T's. Cracks were marked and photographed at each initial and final crack. The beams generally failed in shear, exhibiting the behavior of deep beam depending on shear span to depth ratio.**

**Index Terms— Deep Beam, Two Point Loading, Finite Strip Method, Finite Element Method**

## I. INTRODUCTION

For decades, methods of design and analysis for concrete members reinforced with normal strength steel have been developed. Recently, reinforcing steel with strength higher than conventional steel has become commercially available. The introduction of high strength reinforcing steel can be useful to reduce the quantity of reinforcement required, thereby lessening reinforcement congestion and improving constructability. The strut and tie modeling technique is a widely accepted approach for reinforced concrete deep beams.

However, there are significant differences between various design code implementations for this technique with respect to reinforcement tie, which influences on the capacity of adjacent concrete struts. Furthermore, each design code specifies different limits on the maximum permitted stress in the ties. Since high performance reinforcement continues to gain wider acceptance in industry practices, it is necessary to validate existing design approaches, for the mechanical properties of these new materials.

Considerable increase in load carrying capacity occurs with increasing concrete strength and decreasing shear span to depth ratio (K. N. Smith and A. S. Vantsiotis, 1982) [1]. Application of consistent equilibrium and ultimate strength consideration to the designing and detailing of reinforced concrete beam (Peter Marti, 1985) [2]. The effect of top & bottom loading simultaneously on reinforced concrete deep beams. Proposals are made for predicting shear strengths of such beams (S. C. Less & W. B. Siao, 1994) [3]. Simply supported reinforced concrete deep beams subjected to variables, affecting shear strength of deep beams (A. F. Ashour, 2000) [4]. Behavior of deep beams is described in terms of cracking pattern, load vs. deflection, failure mode & strains in steel reinforcement & concrete (Gerardo Aguilar et al, 2002) [5]. The purpose of this study is to

1. Check whether high strength reinforcing steel can be useful to reduce the quantity of reinforcement required, thereby reducing reinforcement congestion and improving constructability.
2. Understand the performance of deep beams constructed with high strength reinforcement.
3. Observe & explain the deflection, cracking & failure modes of deep beams subjected to two point loading.
4. Compare the flexural steel requirement as per various code provisions with that calculated using the finite strip method.

## II. BEHAVIOR OF DEEP BEAMS

The behavior of deep beams is significantly different from that of beams of more normal proportions, requiring special consideration in analysis, design and detailing of reinforcement. In deep beams, the bending stress distribution across any transverse section deviates appreciably from the straight line distribution assumed in the elementary beam theory. Consequently a transverse section which is plane before bending does not remain approximately plane after bending and the neutral axis does not usually lie at the mid depth. The ultimate failure due to shear is generally brittle in nature in contrast to the ductile behavior and progressive flexural failure with large number of cracks observed in normal beams. Because of their proportions, they are likely to have strength controlled by shear. On the other hand, their strength is likely to be significantly greater than predicated by usual equations.

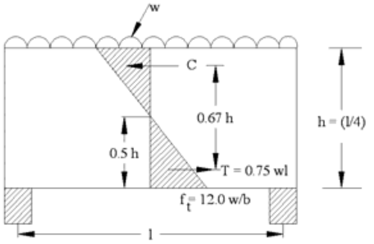
### A. Shear strength of Deep Beams

Shear strength of deep beams may be as much as 2 to 3 times greater than that predicated using conventional equations developed for members of normal proportions. For deep beams, however a significant part of the load is transferred directly from the point of application to the supports by diagonal compression strut. Diagonal cracks that form roughly in a direction parallel to a line from the load to support isolate a compression strut, which acts with the horizontal compression in the concrete and the tension in the main reinforcement to equilibrate the loads. The geometry of this mechanism and the relative importance of each contribution to shear strength clearly depend on the properties of the member as well as the placement of the loads and reactions.

### B. Distribution of flexural stresses

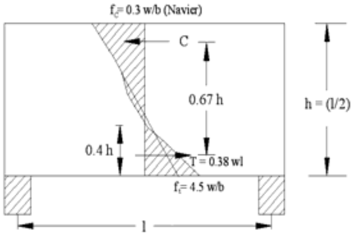
The reinforcement of deep beams differs from that of normal beams. The main flexural steel is placed near the tension edge, as usual, although because of the greater depth of the tension zone it may be advisable to distribute such steel over, the bottom third of the member. As per I. S. 456-2000, flexural steel is placed within a zone of depth equal to (0.25D-0.05L) adjacent to the bottom face of the beam where ‘D’ is the overall depth and ‘L’ is the effective span.

As an example, Figure 2(a) shows the distribution of horizontal flexural stresses at the mid span of simply supported beams having different span/depth (l/h) ratios, when carrying a uniformly distributed load of intensity ‘w’ per unit length. The mid span moment being ($wl^2/8$), the usual extreme fiber stress at mid span of a square panel (l/h = 1.0) would be $f_t = f_c = 6M/bh^2 = 0.75\ w/b$ which indicates that the tensile stresses at bottom fiber are more than twice this intensity.

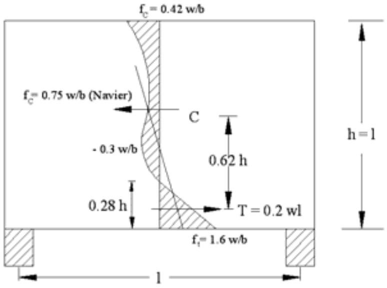


(a) Distribution of horizontal flexural stresses having (l/h) = 4

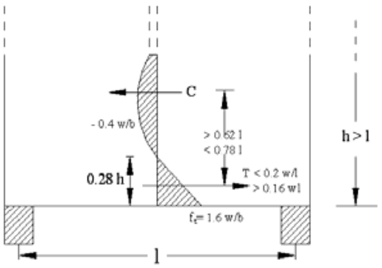
In the case of deep beams, shear flexure and shear modes dominated by tensile cleavage failure are common. It is found that the smaller the span/depth ratio (i.e. less than 2.5), the more pronounced deviation of the stress pattern from that of Bernoulli and Navier as shown in Figure 1 (b, c & d). Significantly warping of the cross-sections occurs because of high shear stresses, consequently flexural stresses are not linearly distributed, even in the elastic range, and the usual methods for calculating section properties and stresses cannot be applied. Similar deviations occur for the distribution of shear stresses. For the determination of principal tensile stresses, the vertical stresses, particularly at the support points of the wall-beam panel, are of great importance. This type of structure is rather sensitive with respective to the loading at the boundaries.



(b) Distribution of horizontal flexural stresses having (l/h) = 2



(c) Distribution of horizontal flexural stresses having (l/h) = 1



(d) Distribution of horizontal flexural stresses having (l/h) > 1

**Fig.1** Distribution of horizontal flexural stresses at mid span

The length of the bearings of the beam in would affect the principal stresses, which can be very critical in the immediate vicinity of this support. One of the most significant aspects of stress analysis would be the manner of application of the load, which is uniformly distributed in the case depicted in Figure 1.

## III. ANALYSIS OF DEEP BEAMS

Numerous classical mathematical procedure of approximation has been developed for the analysis. The methods of approximation used to solve governing differential equation can be grouped into three approaches

1. Direct Approach,
2. Weighted Residual Method
3. Finite Strip Method

The analysis of deep beam is carried out by using Finite strip method which is discussed below.

### A. Finite Strip Method

For a structure with constant cross section and end boundary conditions that do not change transversely, stress analysis can be performed using finite strips. The finite strip method over finite element method includes reduced computer resources and significant reduction in the time taken to model the problem. It is regarded as a special form of displacement formulation of the finite element procedure, in that it employs the minimum total potential energy therein to develop the relationship between unknown nodal displacement parameters and the applied loading. A computer program has been prepared in FORTRAN77 based on direct stiffness approach in order to design deep beams. It is clear that a computer program is necessary for solution of governing differential equation. The results are validated with manual calculations. Such program helps when several numbers of deep beams have to be designed in order to avoid laborious works of manual calculations.

### B. Failure Modes

Failure modes of deep beam can be divided in following two main categories.

Mode I-Flexural failure mode

Mode II-Shear failure mode

The strength of deep beams is usually controlled by shear rather than flexure, provided a normal amount of longitudinal reinforcement is used. The shear action in the beam web leads to compression in a diagonal direction and tension in a direction perpendicular thereto. Shear failure mode can be sub divided into following three categories.

**Mode II-1:** Diagonal tension failure, which in the line of thrust become so eccentric and give rise to flexural failure in compressive zone. It is important however to mention that this kind of failure is a result of tensile crack extension in compressive zone due to flexural load.

**Mode II-2:** Shear compression failure where R. C. beam fails due to the development of diagonal crack into the compressive zone and reduces the area of resisting region excessively and beam crushes once generated compressive stress exceeds compressive strength of concrete.

**Mode II-3:** Shear proper or compressive failure of struts, which is often observed in beams with very small shear span to depth ratio (L/D < 1.5). In this case due to the small L/D ratio, the line of thrust will be so steep and arch action not only reserve flexural capacity in most cases but also efficiently sustains required shear force. Arch is clearly observed in those beams and finally beams fail due to either sudden tensile crack formation parallel to the strut axes or compressive crush in normal direction to the strut axes.

### C. Failure Theories of Deep Beams

There are different failure theories for design of deep beams:

1) Tied arch action
2) Truss model
3) Shear friction design method
4) Strut and Tie model

## IV. DESIGN OF DEEP BEAMS

Deep beams are designed and cast for Two Point Loading and for two shear spans viz. 200 mm and 250 mm. In total eighteen deep beams were designed and cast. Point loads of 50 kN are applied on deep beams for design purpose. Dimensions of deep beams chosen for design purpose are, Length = 700 mm, Depth = 325 mm and Thickness = 150 mm. A 30 mm clear cover is provided all around the reinforcement cage. M20 grade concrete and Fe 550 steel was used for casting of deep beams with simple support condition. The Reinforcement Schedule is shown in Table 1.

Design of deep beams is done by following codal provisions:

1. Design by using I. S. 456-2000 method
2. Design by using B. S. 8110-2005 method
3. Design by using A. C. I. 318-2005 method

**Table 1** Reinforcement Schedule

| Code used for Design of Deep Beam | | **I. S. 456:2000** | | **B. S. 8110-05** | | **A. C. I. (318)-05** | |
|---|---|---|---|---|---|---|---|
| Identification Mark | | **a-1** | **a-2** | **b-1** | **b-2** | **c-1** | **c-2** |
| Total No. of samples of Deep beams | | **03** | **03** | **03** | **03** | **03** | **03** |
| Shear Span (mm) | | **200** | **250** | **200** | **250** | **200** | **250** |
| Shear span to depth ratio | | 0.62 | 0.77 | 0.62 | 0.77 | 0.62 | 0.77 |
| **Sr. No.** | **Type of reinforcement** | **Spacing and No. of bars** | | | | | |
| 1 | Horizontal Main steel | 3-8 mm Φ | 1- 10 mm Φ & 2-8 mm Φ | 3-8 mm Φ | 1- 10 mm Φ & 2-8 mm Φ | 3-8 mm Φ | 1- 10 mm Φ & 2-8 mm Φ |
| 2 | Side Face Reinforcement<br>a) Vertical Steel | 5-Two legged 6 mm dia. stirrups @ 165 mm c/c | 5-Two legged 6 mm dia. stirrups @ 165 mm c/c | 4-Two legged 6 mm dia. stirrups @ 220 mm c/c | 4-Two legged 6 mm dia. stirrups @ 220 mm c/c | 6-Two legged 6 mm dia. stirrups @ 130 mm c/c | 6-Two legged 6 mm dia. stirrups @ 130 mm c/c |
| | b) Horizontal Steel (in central zone) | 3-Two legged 6 mm dia. stirrups @ 70 mm c/c | 3-Two legged 6 mm dia. stirrups @ 70 mm c/c | 3-Two legged 6 mm dia. stirrups @ 70 mm c/c | 3-Two legged 6 mm dia. stirrups @ 70 mm c/c | 2-Two legged 6 mm dia. stirrups @ 90 mm c/c | 2-Two legged 6 mm dia. stirrups @ 90 mm c/c |

The important steps used in the design of R.C. deep beams are as follow:

1. Determine whether the given beam is deep according to the definition or not.
2. Check its thickness with respect to buckling as well as its capacity to carry the major part of the shear force by the concrete itself.
3. Design for flexure.
4. Design for minimum web steel and its distribution in the beam.
5. Design for shear. If the web steel already provided is inadequate, design additional steel for shear requirements.
6. Check safety of supports and loading points for local failure.
7. If the beams are not top loaded, design the special features required for deep beam action under the special loading conditions.
8. Detail the reinforcements according to accepted practice.

## V. EXPERIMENTAL WORK

After analysis and design was over, casting of deep beams was done. In all eighteen deep beams were cast (for 200 mm shear span and for 250 mm shear span) , nine samples each by three design methods viz. I. S. 456-2000, B. S. 8110-05 and A. C. I. -318-05. Three samples for each shear span were cast. Before actual casting, various ingredients of concrete such as cement, sand and aggregate were tested in Laboratory. Reinforcement mesh as shown in Figure 5, for every deep beam was kept ready according to individual designs. Formwork for casting deep beams of required dimensions as mentioned above is kept ready. For M 20 grade concreting, weigh batching is adopted. After casting curing has been done for next 28 days. The concrete cubes and steel bars are tested to assure material quality and stipulated strength. There is a controversy that the web reinforcement makes significant contribution to the maximum load carrying capacity. There are no unique guide lines for provision of web reinforcement.

**Table 2** Average Test Results

| **Case No.** | | **Case 1** | | | **Case 2** | | |
|---|---|---|---|---|---|---|---|
| **Design Method** | | **I.S.456** | **B.S.8110** | **ACI 318** | **I.S.456** | **B.S.8110** | **ACI 318** |
| Shear span (mm) | | 200 | 200 | 200 | 250 | 250 | 250 |
| Shear span to depth ratio | | 0.62 | 0.62 | 0.62 | 0.77 | 0.77 | 0.77 |
| Reinforcement Provided (No. of bars) | Flexural Steel Required in mm$^2$ | 126.14 | 146.25 | 126.14 | 157.41 | 157.42 | 157.95 |
| | Flexural Steel | | | | | | |
| | i) 10 mm Φ | | | | 1 | 1 | 1 |
| | ii) 08 mm Φ | 3 | 3 | 3 | 2 | 2 | 2 |
| | iii) Area (mm$^2$) | 150.73 | 150.73 | 150.73 | 179.02 | 179.02 | 179.02 |
| | Shear Required ( mm$^2$) Vertical | 110.625 | 113.04 | 110.625 | 73.125 | 113.04 | 110.625 |
| | Horizontal | 66.375 | 84.78 | 66.375 | 121.875 | 84.78 | 66.375 |
| | 6 mm dia. | | | | | | |
| | Vertical | 6 | 4 | 6 | 5 | 4 | 6 |
| | Horizontal | 2 | 3 | 2 | 3 | 3 | 2 |
| Average Load at first crack | Total | 390 kN | 370 kN | 430 kN | 370 kN | 360 kN | 420 kN |
| | Each Point load | 195 kN | 195 kN | 215 kN | 185 kN | 180 kN | 210 kN |
| **Average Failure Load** | **Total** | **1000 kN** | **970 kN** | **1000 kN** | **950 kN** | **960 kN** | **970 kN** |
| | Each Point load | 500 kN | 485 kN | 500 kN | 475 kN | 480 kN | 500 kN |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Average Deflection at failure** | **Total** | **3.43 mm** | **3.32 mm** | **3.56 mm** | **3.49 mm** | **3.75 mm** | **3.65 mm** |
| | Permissible deflection | 2.4 mm | 2.4 mm | 2.4 mm | 2.4 mm | 2.4 mm | 2.4 mm |
| | Deflection at 500 kN load | 2.19 mm | 2.59 mm | 2.19 mm | 2.13 mm | 2.22 mm | 2.16 mm |
| Observed mode of failure | | **ModeII3** | **Mode II3** | **Mode II3** | **Mode II3** | **Mode II3** | **Mode II3** |

## VI. RESULTS AND DISCUSSIONS

Before actual testing is started, testing set up such as span adjustment, Two Point Loading arrangement etc. was done. Effective Span of 600 mm was fixed on the testing platform. Positions of shear spans, loading points were marked on beams. Bearing plates were kept first on the support and then beams were kept on these bearing plates. Again bearings were kept at loading points and two transverse bars were kept on these plates for point loadings. Above these bars I-section was kept so as to transfer the load to two points as required as shown in Figure 2. Initial cracking load, failure pattern and failure load of every beam was recorded. Two Point Loading with each point load of 50 kN was applied at the beginning. Manually operated hydraulic pump was used to transfer load.

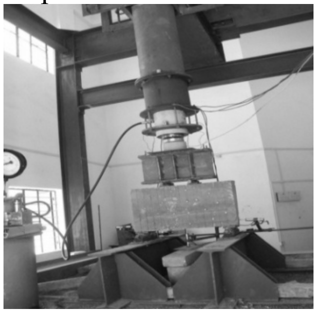


**Fig.2** Loading and sitting arrangement of deep beam

The average initial cracking load, average load at failure, average deflection at centre and mode of failure was studied for each deep beam. A crack width was measured up to failure of the beam as shown in Figure 3. It was observed that as load increases, increment in crack width is observed.

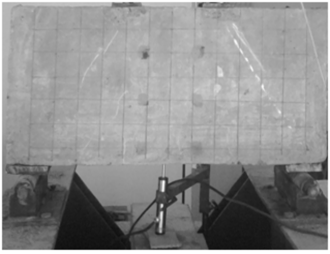


**Fig. 3** Initial cracking of deep beam (for sample 1 a)

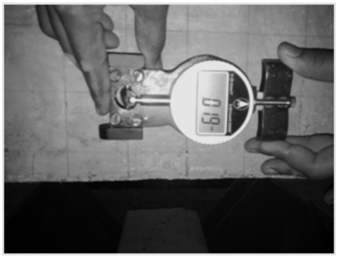


**Fig.4** Crack width measurement

Due to increase in shear span, there was decrease in initial cracking load and failure load. The crack width measurement is shown in Figure 4. The average test result is given in Table 2. Measurements of deflections were made during each test inclusive of applied loads and mid span deflections directly from programmed instrument (K.P.T.L.) through load cell and L.V.D.T's. The Figure 5 shows load vs. deflection variation. It was observed that all the test beams had low deflection at failure as there was no flexural failure.

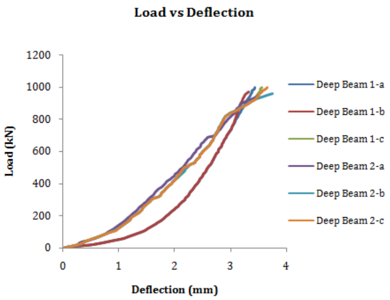


**Fig.5** Average Load vs. Deflection variation

## VII. CONCLUSION

From the data revealed by the analysis, design and experimental work following conclusions are summarized Failure of deep beams was mainly due to diagonal cracking and it was along the lines joining the loading points and supports. The cracks pattern and failure mechanisms for deep beams reinforced with high strength reinforcement were similar to those deep beams with normal strength reinforcing steel. Minimum flexural steel requirement of B. S. 8110-05 as well as A. C. I.-318-05 is more than I.S. 456-2000. (The lever arm of A. C. I.-318 -05 is more by 6% that of B. S. 8110-05 & I. S. 456-2000) The flexural steel required of all three cases is nearly same. The flexural steel required by Finite strip method is approximately 10% less than all three cases. The vertical web reinforcement required by A.C.I.-318-05 code is approximately 40 % more than I. S. 456-2000 and horizontal web reinforcement required by A. C. I. -318-05 code is approximately 40 % less than I. S. 456-2000. The strength of beams with 250 mm shear span is less than that of 200 mm shear span which means the strength of deep beam is inversely proportional to the shear span for the constant depth of the beam. The average failure load of A. C. I. -318-05 code is approximately 10 % more than B. S. 8110 -05 as well as I. S. 456-2000. No separate checking for shear is specified in I. S. 456-2000. It is assumed that the arching action of the main tension steel & the web steel together with concrete will carry the shear. All deep beams had low deflection at failure as there was no flexural failure. As reported by F. K. Kong the shear strength of deep beams is 2 to 3 times greater than that given by usual equations. But in this case due to use of high strength reinforcement the shear strength of deep beam is found 6 times greater than design loads.

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