# Shear strength of RC deep beams

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ABSTRACT: This paper reports on some experimental investigations on the shear behaviour of reinforced concrete (RC) deep beams without and with shear (web) reinforcement. Twelve large scale deep beams made of 60 MPa concrete were tested. Three different beams of depth 250mm, 500mm and 750 mm were tested to understand size effect. The behaviour of deep beams including load-deflection curves, web strains and crack width, shear ductility and reserve strength has been investigated. The beams tested under three-point loading failed in shear and failure modes were influenced by the beam depth and amount of shear reinforcement. The shear strength was found to decrease with increase of beam size and large size beams exhibited brittle failure, which was attributed to size effect. Sufficient shear reinforcement in beams turned brittle failure in to ductile. The load-deflection curves are regular in small size beams with heavy shear reinforcement. The web strains and the width of shear cracks increase at failure with web reinforcement. With increased quantity of shear reinforcement, more confinement is offered to sustain greater web strains and crack widths. Shear ductility (= capability of withstanding severe cracking and deformation) decreases in deep beams and increases in highly shear-reinforced deep beams. Significant reserve strength beyond diagonal cracking was observed in deep beams. As a matter of fact, this reserve strength was to two times larger in small-size beams, compared to large-size beams.

## 1 INTRODUCTION

The shear behaviour of deep beams is very complex and there is still no agreement on the role of size effect in shear due to lack of information. Deep beams are classified as nonflexural members, in which plane sections do not remain plane in bending. Therefore, the principles of stress analysis developed for slender beams are neither applicable nor adequate to determine the strength of deep beams. An important characteristic of deep beams is their high shear strength. The greater shear strength of deep beams is due to internal arch action, which transfers the load directly to a support through concrete struts. The reinforcement acts as a tie and, hence RC beams are analogous to steel trusses. Deep beams are also classified as disturbed regions, which are characterized by nonlinear strain distribution. Elastic solutions of deep beams provide good description of their behaviour before cracking. However, after cracking major redistribution of strains and stresses takes place and the beam strength must be predicted by nonlinear analysis. For a simple deep beam with concentrated load on top, the top load and bottom reactions create large compressive stresses at a right angle to beam axis. These stresses interact with shear stresses to form complicated stress field in the web. Because of short horizontal distance between top and bottom load points i.e. small a/d ratios, the effect of such stresses result in arch action unique in deep beams. Because of these complexities, study of deep beams has become a special interest. Over the years various models have been proposed by many researchers and extensive test campaigns have been carried out.

## 2 REVIEW OF LITERATURE

Several research efforts have been made to understand the shear strength of deep beams and size effect. Due to complex behaviour of deep beams limited information has been reported over the years and further evidence is needed on the role of the many parameters involved, as demonstrated by some recent studies. The study on deep beams has been an interesting topic by varying the parameters. However, some studies have been reported on the investigations on the behaviour of deep beams in shear recently. As for the definition of deep beams, ACI 318 defines deep beams as those loaded on one face and supported on other face and the shear span-to-depth ratio is less than or equal to two. Due to their geometric proportions deep beams fail in shear. A disturbance in internal stresses is caused by shear action with compression in one direction and tension in the perpendicular direction. This leads to an abrupt shear failure of beam as the beam depth increases *(Yang and Chung, 2003)*. The development of crack pattern is much faster than small size deep beams and then leading to sudden failure (Bakir and Boduroglu, 2004).

Several modifications have been incorporated in the shear design of deep beams in the codes of practice. ACI 318-2005 and IS 456-2000 consider the contribution of concrete, percentage longitudinal and transverse reinforcement, shear span-to-depth ratio for estimating the shear strength of deep beams, while BS 8110 does not specify any guidelines for design of deep beams. However, it explicitly says that for design of deep beams specialist literature should be referred. Unlike in ACI 318 and IS 456, BS 8110 considers size effect in shear design of RC beam. However, the maximum depth is limited to 400mm. Therefore, in order to understand the shear design of deep beams and to evaluate size effect serious research efforts are needed.

Failure in deep beams is generally due to crushing of concrete in either reduced region of compression zone at the tip of inclined cracks or by fracture of concrete along the crack. In deep beams with shear span-to-depth ratio 2.5, there seems to be some reserve strength in the post-cracking region, resulting in relatively less brittle in nature (Khaldoun, 2000, Lin and Lee, 2003). Therefore, to estimate the reserve strength and ductility of deep beams in shear, the influence of various parameters need to be investigated. This paper presents some experimental observations on behaviour and size effect in RC beams with different shear reinforcements.

Ashour and Morley (1996) carried out an upper bound mechanism analysis on continuous reinforced concrete deep beams. The effect of horizontal and vertical web reinforcement on the load carrying capacity is mainly influenced by the shear span-to-effective depth ratio. In deep beams, the horizontal shear reinforcement is effective than the vertical shear reinforcement. Ashour (2000) reported analysis of shear mechanism in simply supported RC deep beams. Concrete and steel reinforcement are modeled as rigid perfectly plastic materials. The failure modes were idealized as assemblage of rigid blocks separated by failure zones of displacement discontinuity. The shear strength of deep beams is derived as a function of location of the instantaneous center of relative rotation of moving blocks.

Tang and Tan (2004) proposed an approach to account for the effect of transverse stresses to the load carrying capacity of concrete in the diagonal strut based on strut-and tie concept. This involves an interaction between two modes of failure; diagonal tensile splitting and diagonal crushing of concrete due to compression. Russo et al. (2005) proposed an explicit expression that considers the shear strength based on strut and tie mechanism due to diagonal concrete strut and longitudinal reinforcement as well as vertical stirrups and horizontal web reinforcement. Bakir et al. (2004) recommended the strut and tie model for the design of short and deep beams. The model consists of three separate mechanisms; direct strut mechanism, truss mechanism which takes in to account the horizontal shear reinforcement and truss mechanism, which takes in to account of the stirrups.

Several fracture mechanics models have been proposed in order to characterize the failure of concrete (Hillerborg and co-workers (1976), Bazant and Oh (1984), Jenq and Shah (1989). Each one of these models introduces some material fracture properties regardless of the structural geometry and size. Concrete structures exhibit size effect, which has been explained as a consequence of the randomness of material strength. In large structures it is more likely to encounter a material point of smaller strength. Bazant proposed that whenever the failure does not occur at the initiation of cracking, size effect should properly be explained by energy release caused by macro-crack growth, and that the randomness of strength plays a meager role. Nevertheless, size effect in concrete structures ought to be explained by a non-linear form of fracture mechanics that takes in to account the localization of damage in to a fracture process zone (FPZ) of a non negligible size. Bazant's size effect law (Bazant and Oh, 1984) is based on the ductile-brittle transition of the failure mode of geometrically similar fracture specimens. For most practical cases, Bazant's size effect law can be described by the following equation

$$\sigma_N = \frac{B\ f_0}{\sqrt{1+\dfrac{d}{d_0}}} = B\ f_0(1+\beta)^{-\frac{1}{2}} \qquad (1)$$

Where $\beta = d/d_0$, B and $d_0$ are empirical constants to be obtained by fitting equation to the experimental values from different sizes of specimens.

Smith and Vantsiotis (1982) tested 52 RC deep beams under two point loading to study the effect of shear span-to-depth (a/d) ratio and vertical and horizontal web reinforcement on ultimate shear strength and crack width. The web reinforcement produces no effect on formation of inclined cracks but affects the ultimate shear strength. The addition of vertical web reinforcement improves the ultimate shear strength, but addition of horizontal web reinforcement has negligible influence on ultimate shear strength. Iguro et al. (1984) carried out some experimental studies on uniformly loaded reinforced concrete beams of depth varying between 100 to

3000 mm without shear reinforcement, in order to study size effect on shear strength of beams. As the effective depth increases the shear strength gradually decreases. Collins and Kuchma (1999) reported that for large, lightly reinforced concrete beams, reduction in shear stress at failure was related more directly to the maximum spacing between the layers of longitudinal bars rather than overall depth of the member. It has been observed that high strength concrete (HSC) beams exhibit strong size effect in shear. Accordingly, some modifications to ACI shear design provisions are recommended. Karim (1999) proposed an alternative shear strength prediction equation, at both ultimate and cracking stage, for an RC member without web reinforcement. From 350 beam test results collected from the existing literature of RC beams in shear covering a wide range of beam properties and test methods, a technique of dimensional analysis, interpolation function, and multiple regression analysis was carried out, for both normal strength concrete (NSC) and HSC members. An interpolation function was used to account for the difference in behaviour between arch action of short beam and beam action of long beams.

Raghu et al. (2000) conducted a comprehensive experimental and technical investigation to asses the concrete component of shear resistance in beams made of HSC. The experimental program consists of testing of 24 beams, with and without shear reinforcement, to determine the contribution of concrete to shear strength. The data from the experimental observations and literature were compared with shear provisions in codes of practice. When extrapolated the current provisions for shear resistance of HSC, the safety margins for structural designs are reduced. Angelakos et al. (2001) reported on tests of 21 large RC beams in shear. It has been revealed that concrete strength is the most important parameter influencing shear stress at failure and the longitudinal reinforcement has only negligible effect. The shear stress at failure decreases substantially as member size increases and as the longitudinal reinforcement ratio decreases. Aguilar et al. (2002) studied RC deep beams. The experimental results have been compared with the shear design procedures laid down in ACI 318-99. Yang et al. (2003) tested twenty one beam specimens to investigate the shear characteristics with various variables such as concrete strength, shear span-to-depth ratio, and beam depth. It has been found that decrease in shear span-to-depth ratio and increase in beam depth at a shear span-to-depth ratio resulting in more brittle failure with wide diagonal cracks and high energy release rate related to size effect. Also, HSC deep beams exhibited more remarkable size effects with brittle behavior.

Zararis (2003) reported that the shear failure of RC deep beams is due to crushing of concrete in compression zone with restricted depth above the tip of the critical diagonal crack. This theory has been applied to evaluate the shear strength of RC slender beams subject to shear and flexure. According to this, the reason for shear failure is the loss of shear force of the main tension reinforcement, which occurs due to horizontal splitting of concrete cover along the main reinforcement. Lubell et al. (2004) used the specific situation of Bahen Center beams (University of Toronto) to investigate the possibility of shear failure of large size thick deep beams. The conclusions by earlier researchers that the shear strength of wide beams is directly proportional to the width of the beam are found to be correct. Accordingly, modifications have been suggested to ACI code for shear design of large wide beams. Khaldoun et al. (2004) reported the experimental results on shear behaviour of 11 beams made of 65 MPa concrete, reinforced with transverse and longitudinal reinforcement. Performance of specimens based on cracking pattern, crack widths at estimated service load, and on post cracking reserve strength have been evaluated. A significant reduction in crack width was observed with increase in amount of longitudinal reinforcement. The quantity of longitudinal reinforcement provided in the beams can demonstrate what should be limit of minimum transverse reinforcement. The shear strength equations in current ACI, CSA, and AASHTO LRFD specifications are conservative. Russo et al. (2005) proposed an explicit formula that considers the shear strength provided by the strut–and-tie mechanism due to diagonal concrete and the longitudinal main reinforcement as well as the vertical stirrups and horizontal web reinforcement.

The objective of the study is to understand size effect in RC deep beams in shear with and without web reinforcement and also to evaluate the shear ductility of RC deep beams failing in shear. The scope of this study is limited to RC deep beams with shear span-to-depth ratio 1.5, concrete compressive strength of 60 MPa, with longitudinal reinforcement of 2.0% and comparison of existing code values with the experimental values.

## 3 RESEARCH SIGNIFICANCE

The design of deep beams is rather complex, since the very behaviour of these structural members is complex and is still not totally clarified. Due to geometric proportions, the behaviour of RC deep beams is governed mainly by shear strength. The shear strength of deep beams seems to be significantly greater than that of the slender beams due to redistribution of internal stresses. Several parameters affect the strength of RC beams in shear, which include shear span-to-depth ratio, concrete strength, anchorage of reinforcement into the supports, size effect, amount and arrangement of tensile and web reinforcement. The disturbance of internal stresses due to heavy concentrated loads causes reduction of load carrying capacity of deep beams and fosters an abrupt shear failure as the depth increases. Thus, it is necessary to investigate the shear behavior of deep beams with different sizes. The design codes are developed from experimental test results using low strength concrete and on RC beams without shear reinforcement and with depth less than 350mm.

## 4 EXPERIMENTAL PROGRAMME

### 4.1 *Materials*

Concrete used for this program was designed to achieve compressive strength of 60MPa for all the beams. Mix proportions of the concrete used for achieving the required strength were 1: 1.5:2.9 using Portland Pozzolana Cement (PPC). Table 1 shows the constituent materials used for the concrete. The water cement ratio used was 0.32. Along with each set of RC deep beams, six companion plain concrete cubes of size 150x150x150mm were cast and tested to find the characteristic compressive strength of concrete. The coarse aggregate was 20mm maximum size aggregate with specific gravity 2.70 and fineness modulus of 6.93. Sand was naturally obtained with specific gravity of 2.73 and fineness modulus of 2.84. Potable water was used for mixing of concrete and curing purpose. The steel reinforcement consists of high strength deformed bars for longitudinal flexural reinforcement in all the beams. The steel ratio of the flexural reinforcement was 2.0 % in all beams. The properties of reinforcement are shown in Table 2.

Table 1. Constituent materials used for concrete.

| Mix | Cement $kg/m^3$ | Sand $kg/m^3$ | Aggregate $kg/m^3$ | w/c Ratio |
|---|---|---|---|---|
| M60 | 474 | 710 | 1373 | 0.32 |

Table 2. Mechanical properties of reinforcement.

| S No. | φ (mm) | $f_y$ (MPa) | $\varepsilon_Y$ (×10-3) | E ($10^3$, MPa) | $\sigma_{ut}$ MPa |
|---|---|---|---|---|---|
| 1. | 4 | 400 | 2.0 | 200 | 480 |
| 2. | 5 | 479 | 2.4 | 200 | 521 |
| 3. | 6 | 425 | 2.1 | 200 | 600 |
| 4. | 16 | 607 | 2.8 | 217 | 657 |
| 5. | 20 | 543 | 3.2 | 199 | 663 |

### 4.2 *Casting of test beams*

Well seasoned wooden beam moulds were fabricated for casting beams of 250, 500 and 750mm depth and 150mm width. Superplasticizer was used to produce flowable concrete in order to pour the concrete in to the beam moulds to avoid sand pockets. Needle vibrators were used to compact the concrete in beam specimens. After 24hours, the beams were removed from the moulds and cured for 28 days. The curing was done using gunny bags covered around the beams and water was sprinkled in every 3 hrs intervals to avoid evaporation of moisture from the beam surfaces. After curing all the beams were white washed and square grids were drawn on the beam surface in order to visualize the crack pattern and to make crack-width measurements easier.

### 4.3 *Reinforcement and beam dimensions*

Two variables are considered in this study; beam depth and web or shear reinforcement. All the beams were rectangular in cross section with a width of 150mm. The shear span-to-depth (a/d) ratio was 1.5. The beams are grouped in to four series. These series are designated as HSCB-0, HSCB-0.4, HSCB-0.6 and HSCB-0.8. “HSCB” indicates “High Strength Concrete Beam” and the number following HSCB indicates the shear reinforcement index (SRI) which is the measure of amount of shear reinforcement provided in the beam. Each series consists of three beams of depth 250, 500 and 750 mm designated by S, M and L respectively to indicate small, medium and large size beams. The flexural reinforcement has been adopted after evaluating the flexural strength of beams and comparing with the shear strength so that the failure could be initiated by shear failure only. Sufficient reinforcement was provided near the support including for shear and anchorage length. All the flexural reinforcement bars were bent up vertically at the supports to achieve adequate end anchorage. The clear cover of the flexural reinforcement was kept as 25 mm in all the beams. 6mm diameter mild steel bars were used as top corner steel for hanging the shear reinforcement. The stirrups were made from mild steel bars of 6, 5 and 4mm diameter depending on the beam size according to the code provisions for minimum shear reinforcement and minimum spacing of shear reinforcement in beams.

The reinforcement arrangement in typical RC beams is shown in Figure 1. For the first series of beams designated as HSCB-0, no web reinforcement was provided. However, in order to maintain the longitudinal bars in their position stirrups are provided one each at the ends and at the center of the beam. This series of beams was tested in order to understand the shear behaviour of deep beams without shear reinforcement for comparison with those with shear reinforcement. The subsequent series of beams were designated as HSCB-0.4, HSCB-0.6 and HSCB-0.8 with different stirrup spacing to achieve the required SRI. The spacing of shear reinforcement was varied in the beam specimens in order to achieve the required shear reinforcement index. All the beams were reinforced with the same steel ratio for the flexural reinforcement. The stirrups were provided with an end hook of $135^0$. Details of all the shear reinforcements are given in Table 3. The yield strength of longitudinal reinforcement is 521 MPa.

Table 3. Details of test specimens

| Beam Designation | D | b | l | $P_t$ % | $f_{yv}$ | SRI |
|---|---|---|---|---|---|---|
| HSCB-S0.0 | 250 | 150 | 930 | 2 | | 0.0 |
| HSCB-M0.0 | 500 | 150 | 1680 | 2 | | 0.0 |
| HSCB-L0.0 | 750 | 150 | 2430 | 2 | | 0.0 |
| HSCB-S0.4 | 250 | 150 | 930 | 2 | 400 | 0.40 |
| HSCB-M0.4 | 500 | 150 | 1680 | 2 | 479 | 0.40 |
| HSCB-L0.4 | 750 | 150 | 2430 | 2 | 479 | 0.40 |
| HSCB-S0.6 | 250 | 150 | 930 | 2 | 479 | 0.60 |
| HSCB-M0.6 | 500 | 150 | 1680 | 2 | 425 | 0.60 |
| HSCB-L0.6 | 750 | 150 | 2430 | 2 | 425 | 0.60 |
| HSCB-S0.8 | 250 | 150 | 930 | 2 | 479 | 0.80 |
| HSCB-M0.8 | 500 | 150 | 1680 | 2 | 425 | 0.80 |
| HSCB-L0.8 | 750 | 150 | 2430 | 2 | 425 | 0.80 |

A shear reinforcement index (*SRI*) is defined to represent the shear reinforcement, which is given by

$$SRI = R.\ f_{yv} \qquad (2)$$

Where $R = \dfrac{A_{sv}}{b.s_v}$

Figure 1. Typical reinforcement in RC Beam.

## 4.4 *Experimental setup and testing of beams*

Twelve simply supported RC deep beams were tested up to failure under three-point loading. Each beam was loaded with a central concentrated load and supported on two simply supported ends as shown in Figure 2.

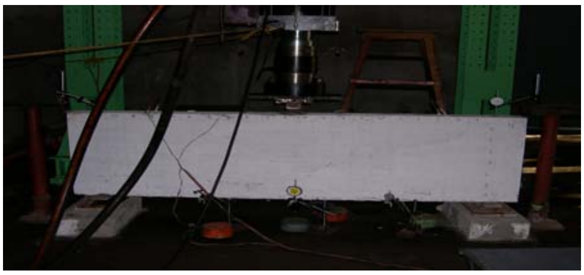

Figure 2. Beam specimen and experimental set up.

Ends of all beams were extended by 150 mm from the line of action of support reaction. Bearing plates of dimensions 100x150x20 mm were provided at the supports and below the point loading. All the beams were tested using 1000kN capacity displacement controlled actuators. LVDT was attached at the mid span to measure the deflection of beams under the point loading. At each displacement increment, the load applied on the beam, mid span deflection, maximum crack width and diagonal strain in concrete were measured.

# 5 DISCUSSION OF RESULTS

## 5.1 *Modes of Failure*

All the beams tested under three-point loading failed in perfect diagonal shear. Typical crack pattern and modes of failure are shown in Figure 3. In all the beams, cracks started as flexural cracks, but no cracks were observed up to 20% of the ultimate load. The first vertical flexural crack was formed in the region of maximum bending moment within a load range of 20–30% of ultimate load. In the range of load between 40-70% of the ultimate load a major diagonal tension crack formed at the middle of shear span. With further increase in the applied load, new inclined cracks appeared within the shear span, their orientation being the same as that of the previously-formed major inclined cracks. Eventually, beam failure occurred due to crushing of concrete in either reduced region of compression zone at the tip of inclined crack or by the fracture of the concrete along the inclined crack.

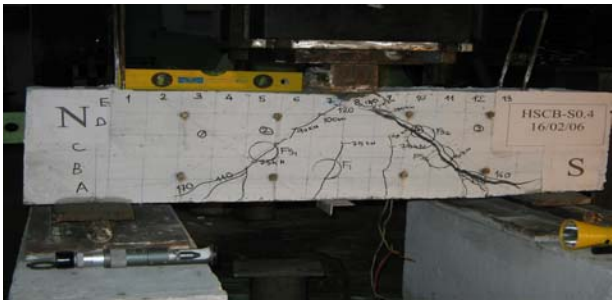


Figure 3. Crack pattern for beams with SRI 0.4.

The modes of beam failure were influenced by the depth of beam and the amount of shear reinforcement. It has been observed that for all smaller size beams i.e. HSCB-S0.0, HSCB-S0.4, HSCB-S0.6 and HSCB-S0.8 and also in medium size beams HSCB-M0.0 and HSCB-M0.4 having relatively smaller amount of shear reinforcement failed by fracture of concrete along the tension diagonal. However, in few medium size beams such as HSCB-M0.6 and HSCB-M0.8, and also in all large size beams HSCB-L0.0, HSCB-L0.4, HSCB-L0.6 and HSCB-L0.8, the failure was shear-compression type of failure. The failure due to crushing of concrete resulted in brittle failure. In all the beam failures, the inclined cracking pattern reveals a tied-arch action, with tension reinforcement acting as a tie rod and portion of beam between the inclined cracks as struts. The cracking pattern was found to be more uniform as the amount of shear reinforcement increases and also as the beam depth increases, keeping shear span-to-depth (a/d) ratio constant. The deterioration of concrete and cracking were symmetric just before failure. However, at the stage of failure cracking propagated rapidly at only one end of the beam due to diagonal cracking. As the depth of the beam increases, the failure mode changes from diagonal tension to diagonal tension-compression type. The deeper the beam, the steeper the inclination of the diagonal crack. In all the large size beams, crushing of concrete in compression at the tip of the diagonal crack has been observed. As the shear reinforcement increases, more inclined cracks formed with small spacing in between the cracks. At failure only a major crack was widened.

### 5.2 *Diagonal cracking and ultimate shear strength*

The diagonal-cracking strength is defined as the strength at which the first fully developed major diagonal tension crack appears in the shear span. The diagonal tension cracking strength was observed to be considerably less than the ultimate strength. Many mechanisms may be responsible for such behaviour. However, the major phenomenon is attributed to the arch action. Deep RC beams exhibited significantly enhanced shear resistance after first diagonal cracking as a result of strong strut action of concrete in compression. The difference between the ultimate shear strength and diagonal cracking strength can be considered as reserve strength. The reserve strength was analyzed from the experimental observations in beams of varying sizes. Defining $V_u$ and $V_{cr}$ as the ultimate and diagonal cracking strength of RC beams, a ratio of $V_u/V_{cr}$ has been evaluated to represent the reserve strength in terms of measured cracking strength. The ratio $V_u/V_{cr}$ in all deep beams lies in the range between 2.0 to 1.08. The highest value has been observed in small size beams. As the beam depth increases beams exhibited brittle failure.

### 5.3 *Load-deflection curves and diagonal strains*

Figure 4 shows the load–deflection curves of beams with SRI 0.0. Similarly, the load-deflection curves in beams with SRI 0.0 to 0.8 respectively with different beam sizes have been drawn. It has been observed that beams of 750 mm depth have higher deflections at ultimate load and their failure is relatively brittle than that of beams of depth 500mm and 250 mm. In different sizes of beams, the maximum deflections have been observed with SRI 0.8 followed by the beams with SRI 0.6, 0.4 and 0.0. The post-peak response seems to be more gradual showing increase of ductility of the beams with increase in percentage shear reinforcement or SRI. The failure of small size beams seems to be gradual indicating sufficient ductility before failure. This showed that being a shear failure, deep beams exhibit reasonable ductility represented by relatively larger deflections at failure and post peak response, with increase in shear reinforcement.

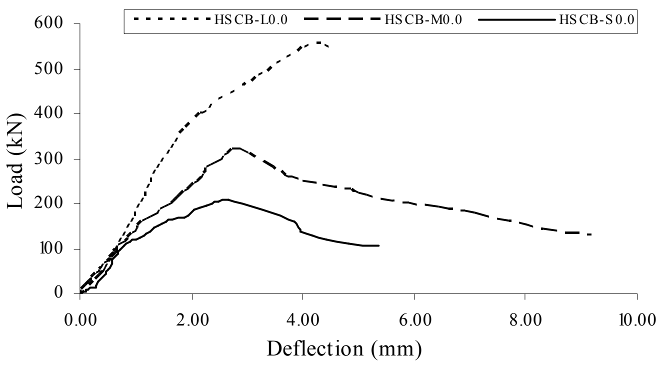


Figure 4. Load-deflection curves with SRI 0.0.

At a given loading, the strain in large size beams seems to be more. However, the large size beams fail at lower stains. Also, it has been observed that as the amount of web reinforcement increases the strain in concrete also increases. This was mainly because, with increase in amount of web reinforcement, the load is shared by the shear reinforcement, allowing concrete to sustain more cracking strain. At any given load, the diagonal tensile strains in large-size beams are larger than in small-size beams, but the strains at the onset of failure are smaller in the former case. Furthermore, the larger the shear reinforcement, the larger the diagonal strains, mainly because of the increasing share of the shear that is resisted by the reinforcement. As a result, concrete can absorb more distributed cracking.

### 5.4 *Shear ductility*

Though deep-beam failure is considered brittle in design provisions, under certain circumstances deep beams exhibit a reasonable ductility. To understand ductility of beams failing in shear, shear ductility is defined as the ratio of $A_c/A_u$, where $A_u$ is the area under the load deflection curve up to ultimate load and $A_c$ is the area under the load deflection curve for a beam up to its complete collapse. With certain limitations shear ductility can measure the ductility of RC beams failing in shear. It has been observed that shear ductility increases linearly as the SRI increases. However, this increase is prominent after

SRI of 0.4. Further, as SRI increases beyond 0.6, the shear ductility has been found to increase significantly. Also, it has been observed that large size beams exhibited brittle failure than those of small and medium size beams, in which the failure seems to be ductile.

### 5.5 *Comparison of code provisions*

The ratio of experimental shear strength and those evaluated using ACI 318, IS 456 and BS 8110, $Vu/V_{ACI}$ and $Vu/V_{BS}$ are compared in all the tested beams. It has been noticed that the shear strength provisions are more conservative for deep beams according to IS 456 and ACI 318 than those of BS8110 for small and medium size beams, while BS8110 code provisions are more conservative for large size beams of depth greater than 750mm. However, code provisions by IS 456 give the most conservative ultimate shear strength of deep RC beams. Further, it is worth mentioning that only BS 8110 considers the size effect in shear strength of RC beams. The design of RC deep beams considering size effect given by BS 8110 seems to be appropriate for shear design of RC deep beams.

## 6 CONCLUSIONS

1. The modes of failure in reinforced concrete deep beam are influenced by the beam size and the percentage of shear reinforcement. However, as the depth of beam and amount of web reinforcement increase the failure seems to be due to shear-compression failure.
2. Deep beams exhibit significant reserve strength in shear measured as the ratio of $V_u/V_{cr}$. After a fully developed diagonal crack, small beams exhibit high reserve strength than large beams.
3. Increase in shear reinforcement increases the ultimate shear strength of RC beams. However, in larger size beams, at a given shear reinforcement large size beams exhibit less strength and fail in a brittle manner.
4. As the depth of beam increases, the crack width also increases. However, with increase in amount of shear reinforcement, the crack width decreases.
5. The shear ductility of RC deep beams increases as the shear reinforcement increases. The increase is significant in beams with shear reinforcement index greater than 0.6.
6. ACI 318 shear strength provisions on deep beams are conservative and it does not consider size effect, while BS8110 code provisions are appropriate for deep-beam design.

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