# SHEAR STRENGTH CHARACTERISTICS OF LIGHTLY REINFORCEDSELF COMPACTING CONCRETE BEAMS

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## ABSTRACT

*The use of self-compacting concrete has become obligatory in major construction projects; where as its mechanical properties are still at a research phase. In this study attempt has been made to experimentally investigate the effect of concrete grade, percentage longitudinal reinforcement and shear span on the shear strength of self compacting concrete beams. A total of 12 beams were tested under four points loading system. Beam section was kept constant at 150 mm x 300 mm, while shear span to depth ratio varied was between 1.5 to 3.5. Two concrete grades of M40 and M60 and two longitudinal reinforcement ratios of 1.0% and 2.0% were the other test parameters selected. The performance of self compacting concrete beams was evaluated based on ultimate shear resistance and failure mode. Experimental results were compared with Indian, Japanese and US code based equations.*

***Keywords:*** *failure mode, longitudinal steel, self-compacting concrete, shear strength, diagonal crack, aggregate interlock, compression zone*

## 1. INTRODUCTION:

Self-compacting concrete (SCC) is a new generation of high performance concrete known for its excellent deformability and high resistance to segregation and bleeding. Lack of information regarding in situ properties and structural performance of SCC is one of the main barriers to its acceptance in the construction industry. There is some concern among researchers and designers that SCC may not be strong enough in shear because of some uncertainties in mechanisms resisting shear notably the aggregate interlock mechanism [1]. Most of the research till date [1] has reported that shear strength is derived from the contributions of the un-cracked conventionally vibrated concrete (CVC) in the compression zone (ranging between 20% and 40%), aggregate interlock mechanism (ranging between 35% and 50%) and dowel resistance of the longitudinal reinforcement (ranging between 15% and 25%). Therefore, a major component of the shear transfer across a fractured interface arises from the friction forces that developed across the diagonal shear cracks due to 'aggregate interlock' which provides resistance against slip. Since aggregate interlock is reported to form a significant component of the mechanisms of shear resistance, it is desirable to investigate the shear strength of beams made with SCC to ascertain the validity of the CVC shear design provisions in the current design codes for SCC beams.

## 2. FACTORS EFFECTING TYPE OF SHEAR FAILURE

The factors governing the type of failure, out of the many described above, likely to occur in a given beam, as well as the load carrying capacity of the beam, are believed to be:

### 2.1 Ratio of shear span to effective depth of beam

The shear span-effective depth ratio, a/d, has a decisive influence on the mode of shear failure of reinforced concrete beams. With a very low a/d ratio, perhaps less than 1, the strut-like failure occurs. When the a/d ratio exceeds 1 but is small, the diagonal tension cracks are directed from the point of application of the load to the support in almost a straight line, which, with increase in load extends direct into the compression zone and shear-compression failure takes place. When a/d is much larger than 1 but less than 2.5, usually one diagonal tension crack forms, either developing first at mid-depth of the beam or, more often, from a flexure-tension crack, and generally, with increase in load, causes shear-tension failure.

### 2.2 Percentage area of main tension and compression reinforcement

The main tension steel contribute materially to the shear resistance of the beam and the role of the main steel is greater in the case of shear-tension failure, i.e., generally for high a/d ratios. Data from tests shows a considerable increase in the shear capacity of a beam when p is increased for a/d ratios between 3 and 5. When a/d is less than 2 the effects of increase in p are small or non-existent.

### 2.3 Size of tension bars and their method of anchoring

Moody et al [2] have shown that when the same steel area is provided by more than one bar there appears to be some increase in both the cracking and the ultimate loads, but after a certain number of bars corresponding to a given width, there appears to be no increase in load, and there is possibly even some decrease.

### 2.4 Compressive strength of concrete

The influence of this factor is greatest when the failure is of the shear-compression type and for this reason the effect of the compressive strength of concrete on the ultimate strength of a beam in shear decreases with increase in the a/d ratio.

### 2.5 Arrangement of loading

There seem to be two broad groups of loading arrangement as far as the shear failure of simply supported beams is concerned. The first group, limited to beams loaded by one or two point loads, one diagonal tension crack generally forms in such a position that the upper end of the crack points towards the point of application of the load and the lower end extends in the direction of the support, either in the form of a nearly straight line or along the level of tension steel. Thus the failure occurs at the section subjected to both the maximum bending moment and the maximum shearing force. The second group, where the loading consists of four or more point loads or is uniformly distributed, more than one diagonal tension crack in either half of the beam may be formed; some of these cracks may develop from initial flexure-tension cracks. The position of the diagonal tension crack that causes the ultimate failure may not be at the section of maximum shear.

To estimate the shear resistance of beams, standard codes and researchers all over world, have specified different formulae considering different parameters into consideration. The parameters considered are varying for different codes and researchers leading to disagreement between researchers, making it difficult to choose an appropriate model or code for predicting shear resistance of reinforced concrete. Therefore an extensive research work on shear behaviour of normal and self-compacting concrete is being carried out all over the world. Estimation of shear resistance of high strength concretes is still controversial [3,4] and therefore is a thrust area for research. The shear transfer mechanisms helps identify predictive parameters that may affect the shear strength of a RC beam, such as concrete compressive strength, beam depth, shear span-to-depth ratio, amount of longitudinal reinforcement and axial forces [2].

The shear strength of a beam increases as the compressive strength of concrete increases [3]. The concrete tensile strength is known to have a great influence on the shear strength, but the concrete compressive strength is used instead in most shear strength formulas. This is because tensile tests are more difficult to conduct and usually show greater scatter than compression tests.

## 3. PRESENT STUDY

This study was undertaken to experimentally evaluate the shear strength characteristics of beams casted with medium and high grade of self-compacting concrete [5]. For this, self-compacting concrete beams of varying length with different values of effective-span to depth ratios and different reinforcement percentage were casted with constant depth [3,4]. Since the efficient use of web reinforcement depends on the accuracy with which the strength of the unreinforced web can be predicted, all the beams in this experimental investigation of the shear behavior were without any shear reinforcement.

### 3.1 Material Used

The materials required for the casting of the beams were cement, fine aggregate (sand), coarse aggregate of nominal sizes 12.5 mm, fly ash, silica fume, super-plasticizer and steel reinforcing bars of diameter 8 mm, 10 mm, 12 mm and 16 mm and water. Ordinary Portland cement of 43 grade confirming to IS8112 [6] was used. To increase the paste content silica fume and fly ash were used as pozzolanic material. Natural river sand and 12.5 mm maximum size crushed stone were used as fine and coarse aggregates, respectively. High range water reducer (HRWR) confirming to IS9103[7] was used to adjust the flow ability and cohesiveness of SCC mixture. Fe500 steel bars of different diameter and confirming to IS1786 [8] were used as reinforcement.

### 3.2 Concrete Mix Design

Concrete mix was designed for M40 and M60 grade. The preliminary proportioning of the mixtures was done using the ACI method of mix design and subsequently, the mixture proportions were suitably adjusted by using trial mixes to achieve the desired fresh properties of SCC. A high content of fine materials for stability and a high dosage of super plasticizers for ensuring flow ability is necessary to achieve self-compacting properties. Lower volume of coarse aggregate was compensated by higher volume of fine aggregate and paste content. Details of mix proportion are presented in Table 2. Visual observation showed that SCC properly filled the forms with ease of movement around the reinforcing bars in each reinforcement configuration.

**Table 1: Mix Proportions**

| Grade | Cement | Fly Ash | Silica Fume | Fine Aggregate | Coarse Aggregate | Superplasticizer (% by wt of cement) | w/c |
|---|---|---|---|---|---|---|---|
| M40 | 1 | 0.50 | 0.05 | 3.75 | 2.30 | 2.0 | 0.45 |
| M60 | 1 | 0.35 | 0.10 | 3.25 | 2.15 | 3.0 | 0.30 |

## 4. EXPERIMENTAL PROGRAM

In this work, 12 beam specimens were tested for shear strength after 28 days of standard curing under four point loading system. All the beams had constant overall cross section of 150 mm x 300 mm while the overall length was 1.7 m, 2.3 m and 2.9 m for corresponding a/d ratio = 1.5, 2.5 and 3.5 respectively. The shear span of the beams was varied and central portion was kept constant at 600mm for all the beams. Longitudinal steel percentage was kept at 1.0% and 2.0%. To ensure that all the beams fail in shear, the central 600 mm portion of the beams was over reinforced and 4 additional bars of 12 mm diameter (2 each in tension and compression zone) were provided. Beam specimen details are given in table 2.

Two concrete grades of M40 and M60 were used. The slump flow test was carried out to assess the horizontal free flow of SCC in the absence of obstructions. To check other self-compaction properties like filling ability and passing ability U-box and V-Funnel tests were carried out. GTM screen stability test was used to assess the stability and segregation resistance of fresh self-compacting concrete.

**Table 2: Beam Specimen Details**

| Sr. No. | Specimen | Shear span to depth ratio (a/d) | Longitudinal steel (%) | C/C beam span (mm) |
|---|---|---|---|---|
| 1 | M40S1A1.5 | 1.5 | 1.0 | 1396 |
| 2 | M40S1A2.5 | 2.5 | 1.0 | 1926 |
| 3 | M40S1A3.5 | 3.5 | 1.0 | 2456 |
| 4 | M40S2A1.5 | 1.5 | 2.0 | 1396 |
| 5 | M40S2A2.5 | 2.5 | 2.0 | 1926 |
| 6 | M40S2A3.5 | 3.5 | 2.0 | 2456 |
| 7 | M60S1A1.5 | 1.5 | 1.0 | 1396 |
| 8 | M60S1A2.5 | 2.5 | 1.0 | 1926 |
| 9 | M60S1A3.5 | 3.5 | 1.0 | 2456 |
| 10 | M60S2A1.5 | 1.5 | 2.0 | 1396 |
| 11 | M60S2A2.5 | 2.5 | 2.0 | 1926 |
| 12 | M60S2A3.5 | 3.5 | 2.0 | 2456 |
| For all beams overall depth(D) = 300 mm, effective depth(d) = 265 mm, width = 150 mm | | | | |

### 4.1. Test Setup and Loading Procedure

The beam specimens were tested as simply supported beams under four-point loading condition as shown in Fig. 1. The central span was kept constant at 600mm, while the shear span (a) was varied as 398mm, 663mm and 928mm respectively. The test setup included the use of a hydraulic jack that applied load gradually on the mid of a stiffened girder from which the load is distributed equally to the test beam specimens until failure. Four linear variable displacement transducers (LVDTs) were attached at $45^0$ on the front surface of each beam to measure the shear strain. Three equally spaced LVDTs were placed under the central 600mm span of beam to measure central deflection. The load was applied at a constant rate and throughout the loading history, load and displacement data were recorded by a computer controlled data acquisition system which also automatically monitored the load and deflection at pre-selected time intervals throughout the loading period. The tests also provided information on the overall behavior of beams including development of cracks, crack patterns, crack width, load transfer mechanisms and failure modes. The loading was continued until failure of the beam.

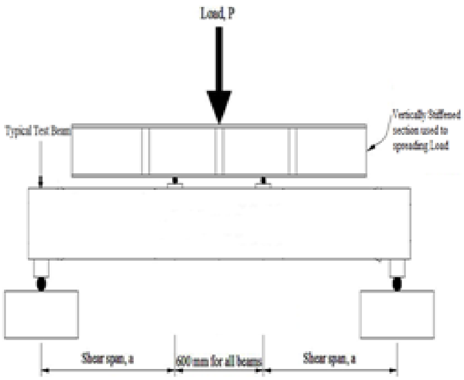


Figure 1 – Experimental Setup

## 5. EQUATIONS TO PREDICT SHEAR STRENGTH

Experimentally calculated shear strength values are compared with ACI 318R equation and IS 456:2000 code equation.

*ACI 318R Equation:*

According to ACI 318R-05 [9,10] building code requirements, the shear strength of concrete members without transverse reinforcement subjected to shear and flexure is given by following equation.

$$Vc = \left(.158\sqrt{f'_c} + 17.24\frac{\rho d}{a}\right)b_w d$$

Where $f_c$'=cylinder strength in MPa

ρ = longitudinal reinforcement ratio.

d = effective depth of beam section in mm

$b_w$ = section width in mm

a = shear span

*Japan Society of Civil Engineers(JSCE-07 )Code Equation:*

As per JSCE-07[11], codal provisions for shear strength of reinforced concrete members without shear reinforcement, the allowable shear strength is as below:

$$Vc = d^{-1/3}(100\rho_w)^{\frac{1}{4}}(0.2f_c'^{1/3})b_w d$$

Where $\rho_w$ = longitudinal reinforcement ratio

$f_c$' =cylinder strength in MPa

d = effective depth of beam section in mm

$b_w$ = section width in mm

*IS 456:2000 Code Equation:*

As per IS 456:2000[12] the magnitude of the design shear strength ($V_c$) depends on the various factors that are related to the grade of concrete ($f_{ck}$) and percentage of tension steel $p_t$ = 100$A_{st}$/bd. The value of allowable shear stress ($\tau_c$)given in the code (table 19) are based on the following empirical formula.

$$Vc = \frac{(0.85\sqrt{0.8f_{ck}})(\sqrt{1+5\beta}-1)}{6\beta}b_w d$$

where $\beta = \left[\frac{0.8f_{ck}}{6.89p_t}\right]$ or 1, whichever is greater

$f_{ck}$= cube compressive strength of concrete in MPa,

$b_w$= effective width in mm,

d= effective depth in mm, $p_t$ = steel percentage

**Table 3: Experimental and Predicted Shear Strength**

| Specimen | Cylinder Strength (MPa) | Ultimate Shear Load(kN) | Ultimate shear stress, $v_{uexp}$ (Mpa) | $v_{uexp}/v_{ACI\,318R}$ | $v_{uexp}/v_{JSCE}$ | $v_{uexp}/v_{IS456:2000}$ |
|---|---|---|---|---|---|---|
| M40S1A1.5 | 42.3 | 110.4 | 2.78 | 2.58 | 2.86 | 4.02 |
| M40S1A2.5 | 41.6 | 80.5 | 2.03 | 1.93 | 2.10 | 2.93 |
| M40S1A3.5 | 41.4 | 63.2 | 1.59 | 1.53 | 1.65 | 2.30 |
| M40S2A1.5 | 39.8 | 178.6 | 4.49 | 4.11 | 3.75 | 4.95 |
| M40S2A2.5 | 40.5 | 124.3 | 3.13 | 2.94 | 2.60 | 3.45 |
| M40S2A3.5 | 41.6 | 67.3 | 1.69 | 1.60 | 1.39 | 1.87 |
| M60S1A1.5 | 62.5 | 142.5 | 3.58 | 2.76 | 3.25 | 5.01 |
| M60S1A2.5 | 60.2 | 101.1 | 2.54 | 2.03 | 2.33 | 3.56 |
| M60S1A3.5 | 61.7 | 89.6 | 2.25 | 1.79 | 2.05 | 3.15 |
| M60S2A1.5 | 62.5 | 216.9 | 5.46 | 4.06 | 3.92 | 5.74 |
| M60S2A2.5 | 63.8 | 131.7 | 3.31 | 2.51 | 2.36 | 3.48 |
| M60S2A3.5 | 60.6 | 73.1 | 1.84 | 1.45 | 1.34 | 1.93 |

## 6. EXPERIMENTAL TEST RESULTS

During loading, the first vertical flexural cracks started appearing within the central 600 mm portion of all beams (zero shear region). In almost all the beams, small flexural cracks appeared within the zero shear span and in the shear span before the initiation of first shear crack. The initial shear crack was developed near the mid-depth of the beam in the shear span. With the increase in load, the shear crack propagated diagonally towards the top and bottom fibre of the beam along with the development of additional shear and flexure cracks along the beam.

With sectional area being constant, the shear resistance of beams was found to depend on shear span-to-total depth ratio (a/d), concrete grade and longitudinal steel ratio. The test results are presented column 2 and 3 of table 3. Experimental shear stress values are compared with calculated shear stress values using ACI318R equation, JSCE equation and IS456:2000 equation in column 5, 6 and 7 of table 3. In general shear strength increases with increase in concrete grade and longitudinal steel ratio and decreases with increase in shear span to depth ratio.

## 7. CONCLUSIONS AND DISCUSSIONS

The SCC beams of M40 and M60 grade were tested for ultimate shear strength with three shear span to depth ratios of 1.5, 2.5 and 3.5 and two longitudinal reinforcement percentages of 1% and 2%. The conclusions drawn from the limited experimental work carried out are as below:-

- Ultimate shear strength of the SCC beams was found to be significantly dependent on concrete grade. For same steel percentage and same a/d ratio, 10% to 30% increase in shear strength for M60 grade was observed as compared to M40 grade.
- For the same grade and same a/d ratio, increase in longitudinal reinforcement increases ultimate shear strength of SCC beams. Change is more significant for lower a/d ratio (1.5) as compared to higher

a/d ratio (3.5). For M40 grade and a/d ratio of 1.5, a 62% increase in ultimate shear strength was noted with increase in longitudinal reinforcement from 1% to 2%. For the same grade and a/d ratio of 3.5, only 6.5% increase in ultimate shear strength was observed with increase in longitudinal reinforcement from 1% to 2%. Similar trends were noted for M60 grade concrete. The reason is more effective dowel action in beams with higher longitudinal reinforcement.

- The ultimate shear strength of the SCC beams were found to be significantly dependent on the shear span-to-depth ratio (a/d) of beams. Shear strength of SCC beams decreases with increase in a/d ratio. For M40 grade concrete and 1% longitudinal reinforcement the reduction in ultimate shear strength was 42%, while for the same grade with 2% longitudinal steel the reduction was 62%. Similar trends can be seen for M60 grade concrete
- Experimental shear stress values were compared with the predicted shear stress values given in table 19 of IS-456 2000. IS 456-2000 does not take into account the influence of a/d ratio on shear strength and gives a constant value for M40 grade concrete and above. The shear strength of SCC beams calculated according to table 19 of IS: 456-2000 underestimate the shear strength by as much as by 85%. As compared to experimental values, ACI-318 code also underestimate the shear strength of SCC beams. This variation is more pronounced for lower a/d ratios. Hence, the code-based shear strength predictive equations for normal concrete can be conservatively used for estimating the shear strength of SCC beams.
- Experimental shear stress values were compared with the predicted shear stress values based on ACI 318R equation and JSCE shear stress equations. ACI 318R equation is more conservative in predicting shear stress as compared to JSCE equation as can be seen from column 5 and 6 of table 3. Ratio of experimental to code predicted values based on ACI 318R lies between 1.45 to 4.11, while it lies between 1.34 to 4.75 for JSCE equation.

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