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Empirical equation and experimental validation of shear parameters for high strength concrete (HSC)

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Abstract: With many benefits of the high strength concrete (HSC) the more brittle behaviour that leads to sudden failure makes it important for proper understanding of its behaviour and safe and efficient estimation of capacities. Research on the behaviour of HSC has been extensively carried out since last decade. HSC has higher tensile strength hence a higher cracking shear can be expected. This paper analyzes the different international standards available for estimating concrete's component of shear strength for reinforced cement concrete (RCC) beam. Different important factors mainly strength in compression, steel reinforcement (dowel action), ratio of shear span and depth, size effect i.e. depth along with the aggregate type (density of concrete) contributing to shear stress (Tc) of concrete has been also analyzed and thereafter, an equation has been proposed to compute or predict T_c value for concrete of both normal and higher grade or strength. The proposed equation has been validated by experimental results wherein 12 RCC beams (with and without reinforcement for shear) were cast and tested to fail in shear. The experimental results validated the proposed equation with considerable factor of safety keeping in view the sudden and brittle nature of failure in concrete in case of shear.

Keywords: High strength concrete, Shear stress, Shear reinforcement, Span to depth ratio, Reinforced concrete beams

1. Introduction

Concrete mixes of higher grade possess better engineering properties in comparison to standard/normal grade concrete in terms of strength (i.e. compressive and tensile), modulus of elasticity along with other long term properties related to durability of concrete [1, 2]. However, concrete of higher strength exhibits brittle behaviour in comparison to conventional concrete in which cracks tend to propagate through interfacial transition zone (interface of hardened cement paste and aggregate). In case of HSC cracks tend to occur right through the aggregate particles or even hardened cementitious matrix due to significantly improved interfacial transition zone which causes cracks to propagate rapidly and this may sometimes lead to failure of explosive nature. Studies on concrete beams made up of concrete having compressive strength in excess of 55 MPa are being carried out all across the globe to generate data and to develop a better understanding of behaviour of HSC beams.

In stress-strain curve mentioned in Indian Standard IS: 456-2000 for concrete, strain value of 0.0035 has been prescribed as the maximum strain which will get developed on the outermost (extreme) compression fibre of any concrete beam section in bending. This strain limit will not hold good in case of HSC above M50. Eurocode-2 also gives fixed strain values to be considered at peak stress and ultimate strain values for concrete up to M50 grade for design purposes. Whereas, for concrete above M50 grade it prescribes different strain values at peak stress and ultimate strain. Stress-strain curve of Euro Code EC-02 gives more realistic value of ultimate strain of concrete above M55 to M90 [3]. The change in stress-strain characteristics of concrete might also have an impact on the behaviour of concrete in shear.

Failure of RCC beams in shear can be of non-ductile nature i.e. sudden and brittle. Mechanism involved in transfer of shear in RCC structures are quite complex in nature. However, due to large number of studies and research work being carried out all across the globe, there have been significant improvement in developing an understanding on modes of failure and behaviour of RCC structures in shear. Structural components in RCC structure depend on its concrete to tackle some component of

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shear force subjected on them. Therefore, it is pertinent that the design engineers use design equations which are suitable and applicable for concrete of higher grades for determination of shear strength of RCC beams. Crushing of compression struts in between the developed cracks or by crack slips governs the failure of the beam. In case of concrete beam made up of normal strength concrete, failure of beams is generally governed by crushing of concrete. However, for beams made up of HSC, struts in between the cracks are able to withstand more stress in compression and most likely the failure in such cases has tendency to get initiated by the crack slip.

Total amount of shear force i.e. V_u which is subjected on beam gets bifurcated between concrete (as V_c) and stirrups (as V_s). At initial stage after loading, majority of the load is carried by concrete itself and very little portion of it is subjected upon the stirrups (i.e. the shear reinforcement). However, after development of the first inclined crack, shear stress gets redistributed between concrete and stirrups. Till the development of the diagonal cracks, total shear is assumed to be resisted or carried by concrete only [4, 5]. In view of the same, it is very important to take into account the shear stress while estimating the shear strength of the members of RCC structures. Apart from that, various mechanism involved in transfer and redistribution of stress in between concrete and stirrups play a vital role in overall capacity of concrete beams in shear [6-9].

Contribution of concrete shall be evaluated and estimated carefully as the behaviour of concrete changes with increase in compressive strength (i.e. grade) of concrete. It is well known that stress-strain characteristics of concrete gets changed and it becomes more and more brittle with increase in its compressive strength. As the compressive strength of concrete mix approaches to 100 MPa, the gap or difference between the strain value at peak stress and the ultimate strain value almost reduces to almost zero. This changes the strength reduction factor which counteracts the more brittleness behaviour of HSC by providing additional factor of safety.

Different international standards follow different approaches for computing the shear strength of the RCC beams, some considers contribution of steel stirrups only while others consider contribution of both concrete and steel reinforcement. Computation of concrete component of shear strength is complex due to involvement of several contributing factors wherein quantification of each factors is itself a complex process. Therefore, a combine effect of all the factors is considered while computing concrete component. The main factors contributing to the concrete component of shear strength are its strength in compression, dowel action by longitudinal (i.e. main) steel reinforcement, ratio of shear span and depth (a/d), effect of size of member (i.e. depth) and type of aggregate (concrete's density).

Various studies were carried out in past to analyze and estimate the shear capacity of RCC beams. Studies revealed that ultimate strength of concrete beam in shear is significantly affected by the size of member and its effect cannot be ignored on diagonal cracking strength of reinforced concrete beams (similar in geometry) having 1:16 size range [10]. Similar findings were reported for shear strength of deep beams which have shear span / depth equal to 1.0 [11, 12]. Complex nature of stress distribution mechanism in dowel splitting region of concrete beams which do not possess any stirrups (i.e. reinforcement for shear) still remains empirical in nature [13]. Concrete beams of higher grade are sensitive and significantly affected by the size effect. Reduction in ultimate strength in shear is related with maximum (centre to centre) spacing of different layers of the reinforcement in horizontal direction instead of overall depth of RCC beam [14].

This paper analyzes the different international standards for estimating concrete's component in shear strength of an RCC beam. Different important factors mainly strength in compression, longitudinal (main) steel, ratio of shear span and depth, depth of RCC member and type of aggregate present in concrete mix contributing to shear stress (T_c) of the concrete has been also analyzed. Thereafter, an equation has been proposed to compute or predict Tc value for concrete of normal and higher grade or strength. The proposed equation has been validated by experimental results wherein 12 number of RCC beams (with and without reinforcement for shear) were cast and tested to fail in shear to understand the effect and contribution of steel reinforcement in carrying shear loading.

1.1 Shear Provisions as per different International Standards

Most of the international standards have been updated to include the design provisions for HSC. All these codes consider different factors which have an impact on the shear component coming from concrete such as effect of size, impact of axial compression, percentage of longitudinal (i.e. main) reinforcement, angle of inclination of shear crack, etc. The methods for predicting shear capacity by various international standards is discussed below so that the experimentally obtained concrete component can be compared.

ACI 318: 2014 [15]

ACI 318:2014 considers contribution of both concrete (i.e. V_c) as well as shear reinforcement (i.e.

V_s). Shear force dealt by concrete, V_c, is estimated as mentioned below:

$$V_c = 0.17\lambda bd\sqrt{f'c} \quad (1)$$

Maximum value of $\sqrt{f'c}$ is restricted to 69 MPa. λ represents the factor for reduction in shear strength for light weight concrete

$$V_{max} = \Phi V_c + 0.66\sqrt{f'c}b_w d \quad (2)$$

ACI 318:2014 takes into account the influence of several factors for example, ratio of shear span and depth (a/d) and dowel action by longitudinal (i.e. main) reinforcement for estimating the contribution of concrete. Few factors for example, effect of member size, factor for interlocking effect of aggregate are not taken into account in provisions of ACI 318:2014.

AS 3600: 2009 [16]

AS 3600: 2009 considers contribution of both concrete (i.e. V_c) and shear reinforcement (i.e. V_s). The concrete component for shear force is calculated as per following expression,

$$V_{uc} = \beta_1\beta_2\beta_3 b_w d_0 f'cv\left[\frac{A_{st}}{b_w d_0}\right]^{1/3} \quad (3)$$

$f'_{cv} = (f'c)^{1/3}$, it shall be less than or equal to 4 MPa (shear strength of concrete)

$$\left.\begin{aligned} \beta_1 &= 1.1\left(1.6 - \frac{d_0}{1000}\right) \geq 1.1 \\ \beta_2 &= 1 \\ \beta_3 &= 1 \end{aligned}\right\} \text{different factor if axial tension or compression}$$

$$V_{umin} = V_{uc} + 0.6 b_u d_0$$
$$V_{umax} = 0.2 f'_c b d_0$$

Φ = 0.6 represents reduction factor for strength.

AS 3600: 2009 considers the influence of several factors for example effect of member size, ratio of shear span and depth (a/d), dowel action by longitudinal (main) reinforcement along with impact of the axial force for estimating the concrete's contribution. Factor representing the interlocking effect of aggregate has not been taken into account in provisions of AS 3600: 2009.

BS 8110: 1997 [17]

BS 8110:1997 considers contribution of both concrete (i.e. V_c) as well as shear reinforcement (i.e. V_s). The concrete component for shear force is calculated as per following expression,

$$\underline{Vc} = \frac{0.79k1k2k3}{\gamma m}\left(\frac{100As}{bd}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4bd} \quad (4)$$

k_1 is a factor representing enhancement of support compression. Its value shall be considered as 1 (conservatively)

$$k_2 = \left(\frac{fcu}{25}\right)^{1/3} \quad 1 \leq k_2 \leq \left(\frac{40}{25}\right)^{1/3}$$
$$\gamma_m = 1.25$$
$$f_{cu} \leq 40MPa$$
$$0.15 \leq \frac{100As}{bd} \leq 3$$

A_s represents tensile reinforcement area

$$\underline{V_c} \leq min(0.8\sqrt{fcu}, 5MPa)bd$$

BS 8110: 1997 considers the influence of several factors for example, effect of member size, ratio of shear span and depth (a/d) and dowel action by longitudinal (main) reinforcement for estimation of contribution by concrete. Factor representing interlocking effect of aggregate has not been taken into consideration in provisions of BS 8110: 1997.

CSA A23.3 – 14 [18]

CSA A23.3 – 14 considers the contribution of both concrete (i.e. V_c) as well as shear reinforcement (i.e. V_s). The shear force taken into account by concrete i.e. Vc, is estimated as:

$$V_c = \Phi_c\lambda\beta\sqrt{f'c}b_w d_v$$
$$\sqrt{f'c} \leq 8MPa \quad (5)$$

Φ_c indicates resistance factor for concrete and is kept as 0.65 (CSA 8.4.2).

λ represents strength reduction factor taking low density concrete into account
= 1.00 for concrete of normal density
= 0.85 when natural sand is used as fine aggregate (concrete is of semi low density)
= 0.75 fine aggregate used in the mix is not natural sand (concrete of semi low density)

β represents the factor taking shear resistance of cracked concrete into account (CSA 2.2) and its value ≥ 0.05. Normally, the value of β ranges from 0.1 to 0.4.

b_w represents the effective width of web.

d_v represents the effective shear depth. dv is 0.9d or 0.72h, whichever is greater (CSA 2.3), wherein, d is distance of centroid of tensile reinforcement from extreme compression fibre, whereas, h represents depth of cross-section in direction of shear force (CSA 2.3).

If d exceeds 300 mm, value of v_c is reduced by a factor of $\frac{1300}{1000+}$

$$V_{r,max} = 0.25\Phi_c f'c b_w d \quad (6)$$

CSA A23.3 – 14 takes into account the influence of several factors i.e. effect of member size, ratio of shear span to depth (a/d), dowel action by longitudinal (i.e. main) reinforcement, concrete's density for determining contribution of concrete. Factor representing the interlocking effect of aggregate is not taken into account by provisions of CSA A23.3 – 14.

Euro code 2 – 2004 [19]

The role of concrete (i.e. V_c) as well as shear reinforcement (i.e. V_s) is not taken into consideration by Euro code 2. Rather, it provides different provisions depending upon whether shear reinforcement is required or not. In case of structural members, which do not need reinforcement for shear, the shear strength is estimated as per concrete. Whereas, in case of structural members needing reinforcement for shear, the shear strength is estimated for steel component only, neglecting the role of concrete. The shear force to be taken into account by concrete is estimated as mentioned below:

$$V_{Rdc} = [C_{Rd,c} \times k \times (100\rho 1.fck)^{1/3 + k_1\sigma_{cp}}]b_w d \quad (7)$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0, d \text{ in mm}$$

$$\rho_1 = \text{tensile reinforcement ratio} = \frac{AS1}{bwd} \leq 0.02$$

$$C_{Rd,} = \frac{0.18}{\gamma c}$$

$$k_1 = 0.15$$

$$V_{Rd,max} = \frac{\alpha cwbwzv\,1fcd}{cot\theta + \tan\theta}$$

$$V_1 = 0.6\left(1 - \frac{fck}{250}\right)$$

$$z = 0.9d$$

Where, θ is 45° for combinations including seismic loading (EC2 6.2.3(2)).

Eurocode considers the influence of factors including effect of size of member, ratio of shear span and depth (a/d), dowel action by longitudinal (i.e. main) reinforcement for estimating the contribution from concrete.

NZS 3101 – 2006 [20]

NZS 3101–2006 considers contribution of both concrete (i.e. V_c) as well as shear reinforcement (i.e. V_s) in computing shear strength which is calculated as:

$$Vc = k_d k_a k_n V_b \quad (8)$$

$$V_b = \left[0.07 + 10\frac{As}{bwd}\right]\lambda\sqrt{f'c}bd$$

$$f'c \leq 50\text{MPa}$$

$$0.08\lambda\sqrt{f'c} \leq v_b \leq 0.2\lambda\sqrt{f'c}$$

K_a to be taken in concrete with a maximum aggregate size of 20 mm or above and aggregate size 10 mm or above as 1.0 and 0.85 respectively. Interpolation to be done for in between values

$k_d = (400/d)^{0.25}$, $k_d = 1.0$: members with effective depth ≤than 400 mm

k_n is factor dealing with axial loading effect

$$V_{max} = min\{0.2f'c, 8\text{MPa}\}bd$$

New Zealand code considers the influence of factors such as member size effect, shear span to depth (a/d) ratio, maximum aggregate size, effect of axial force, dowel action of longitudinal reinforcement in determining the concrete contribution.

IS 456-2000 [21]

IS 456-2000 considers contribution of both concrete (i.e. V_c) as well as shear reinforcement (i.e. V_s) in computing shear strength. Concrete component based on semi empirical expression (SP 24, 1983),

$$Vc = \frac{0.85\sqrt{0.8fck}(\sqrt{1+5\beta} - 1)}{6\beta}bd \quad (9)$$

Where, $\beta = \frac{0.8fck}{6.89pt}$, $pt = \frac{100Ast}{bd}$

$0.8\ f_{ck}$ = cylinder strength in terms of cube strength

0.85 = reduction factor similar to $1/\gamma_{mc}$

Concrete Strength	M15	M20	M25	M30	M35	M40
$T_{c,max}$	2.10	2.80	3.10	3.50	3.70	4.00

IS 456 does not considers the influence of several factors for example, effect of member size, ratio of shear span and depth (a/d), maximum size of aggregate and considers only dowel action by longitudinal (main) reinforcement in determining concrete contribution.

2. Development of Empirical Equation for shear stress of concrete

2.1 Factors contributing to the shear strength of concrete

Different factors which influence concrete component of shear strength of a RCC beam are discussed and their influence is considered while proposing the equation for calculating shear stress of concrete. It is very difficult to quantify the actual individual contribution of these factors and hence sum of contribution of all the factors altogether is considered. Following factors are critical:

2.1.1 Compressive strength of the concrete:

The concrete shear stress is directly related to concrete tensile strength, which in turn can be related to concrete compressive strength. Therefore, concrete shear stress will depend on concrete compressive strength. The shear stress of concrete increases with increase in concrete compressive strength but above 60 MPa strength rate of increase in shear stress becomes negligible (Fig.1).

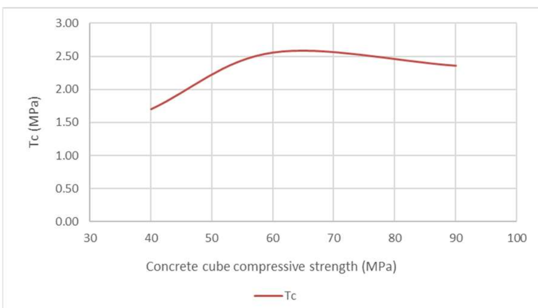


Fig. 1 – Variation of T_c with cube compressive strength of concrete

2.1.2 Percentage of longitudinal reinforcement:

Concrete component of shear capacity of RC beam depends on quantity of longitudinal reinforcement used. Presence of longitudinal reinforcement results in dowel action in transfer of shear stress. Dowel action is defined as capacity of reinforcing bars to transfer forces perpendicular to their axis and dowel action plays an important role in counteracting the shear stresses developed once concrete is cracked and crack passes through the longitudinal reinforcement.

2.1.3 Shear span to depth ratio

Members with lower span length offer more shear resistance wherein shear stress of concrete increases drastically for lower span to effective depth ratio. Concrete beams of M90 grade with different span length and same effective depth were tested for shear failure. Shear stress of the concrete is calculated by removing steel component from experimentally obtained shear capacity of RC beam. Variation of the shear stress with span length is plotted (Fig.2). It is seen that for span to effective depth (a/d) ratio of 2, there is sudden increase in shear stress value. Beam with span length greater than 1.2 m has shown more or less equal value of Tc for M90 grade of concrete. The unexpectedly high value for span length of 1 m can be attributed to the change in the truss analogy or load distribution due to shorter span. Therefore, members with a/d ratio lower than 2 shall be designed accordingly and will sustain higher shear load.

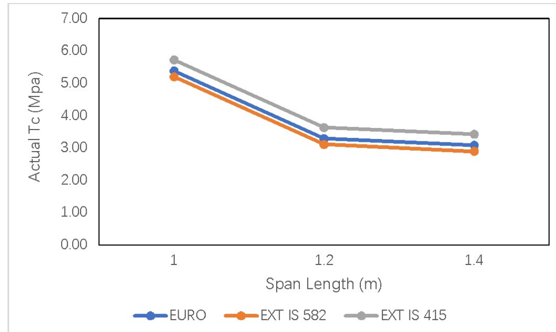


Fig. 2 – Variation of Tc for M90 grade for different span length

Here in chart the three different series represent three different value of Tc obtained by subtracting three different values of steel component of shear capacity. The three different steel component were calculated by Eurocode method, IS: 456 method with actual yield stress of steel used (582 MPa) and IS: 456-2000 method with prescribed limited yield stress of steel to be used for computation (415 MPa).

2.1.4 Depth of member (Size effect):

From various past studies it is evident that shear strength reduces with the increase in effective depth of the RC beam. Some researchers believe that the reduction in shear stress is a consequence of the reduced tensile strength while the other group believes that it is the result of the reduction in ability to transmit shear stresses at crack interface. Most of international standards considers the critical depth as 400 mm for consideration of size effect.

2.1.5 Type of aggregate

The concrete component of shear strength is influenced by aggregate interlocking effect which depends on the aggregate type. The use of light weight aggregate results in more brittle shear failure as compared to normal weight aggregate therefore more safety of factor needs to be considered. Most of the international standards gives strength reduction factor (λ_a) for aggregate type different than normal weight aggregate/concrete.

2.2 Proposed empirical equation for Shear Stress of Concrete

Proposed equation shall consider some important factors which influences concrete shear behaviour such as size effect, aggregate type, dowel action of longitudinal reinforcement, etc. Generally an equation or model is proposed based on the experimental values by using curve fitting method but this method requires large number of data points for more accurate results. Testing of these large RCC beams is tedious process itself and hence a different approach was opted for working out the empirical equation for shear stress. Firstly, a tentative empirical equation using literatures and other international codes was prepared and then was plotted with the experimental results and other international codes. Further the necessary modifications were done to the equations such that it represents the actual behaviour of shear stress of the both normal strength and HSC.

Based on the analysis of all the international standards and literatures, an expression for shear stress of concrete has been prepared considering the most important factors. Factors that are repeated by almost all the international codes and literatures were considered for the equation such as factor for aggregate type, geometry factor, longitudinal reinforcement percentage, etc. Also, the factor K represents the stress reduction factor derived from stress-strain characteristics of the concrete enables to incorporate the variation of stress parameters in the shear stress of the concrete. The expression given as below can be used to compute the concrete shear stress:

$$T_c = K\lambda_a\lambda_g\lambda_s(p_t f_{ck})^{1/3} \quad (10)$$

K	is stress reduction factor including partial material factor of safety
λ_a (the factor for aggregate type)	= 1 for normal weight concrete = 0.85 Semi light weight concrete = 0.75 for light weight concrete
λ_g (Cross-section geometry factor)	= 0.83 for rectangular/square section = 0.70 for circular section
λ_s (Cross-section size factor)	= 1.0 for (d < 400 mm) $=(400/d)^{0.25}$ for (d > 400 mm)
p_t	should be limited to 2% for calculation of shear component.
f_{ck}	should be limited to 80 MPa.

Figure 3 shows the variation of shear stress (T_c) with concrete as given by different international standards. Proposed equation is also plotted for the comparison with different international standards. The proposed equation shows more or less equal or similar values for concrete above 60 MPa. Some international standards restricts the compressive strength for calculation of shear stress for higher strengths of the concrete to have higher factor of safety. The proposed equation itself predicts the more or less constant or similar values of Tc for concrete with strength above 60 MPa.

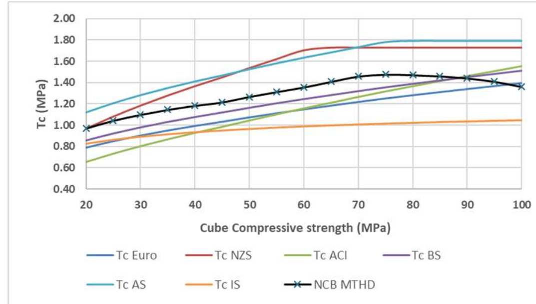


Fig. 3 – Comparison of proposed equation with different international standards

Factor K in the proposed equation decreases with increase in concrete strength and this decrease is due to the decrease in the range between concrete strain at peak stress and ultimate strain. It is known fact that with increase in strength, concrete becomes brittle due to increase in strain at peak stress and decrease in the ultimate strain to a constant value particularly for HSC around M90 grade and above. Increase in strength is countered by the decrease in the factor K resulting in the constant or similar values of shear stress (T_c) above 60 MPa.

3. Experimental validation of proposed equation for shear strength

3.1 Concrete ingredients

Coarse aggregate of maximum nominal size 20 mm and fine aggregate meeting requirement of grading zone II as per IS 383-2016 were used in this study (Table 1). The petrographic study conducted on coarse and fine aggregate indicated that quality of both aggregates are non-reactive as it does not contains any harmful minerals and strained quartz percentages & Undulatory Extinction Angle are within permissible limits. Fine aggregate used in study showed silt content of about 0.73 by wet sieving method.

The characterization of Ordinary Portland cement (OPC-53 grade), fly ash and silica fume used as binder in the study is given in Table 2. Polycarboxylic based superplasticizer is used for w/c ratio 0.20 and 0.36 and Naphthalene based is used for w/c ratio 0.47 complying IS: 9103. Water used in concrete preparation complied with IS: 456-2000 specification. The compressive strength of OPC 53 Grade cement at 3, 07 and 28 days were 36.50 N/mm^2, 45.00 N/mm^2 and 57.00 N/mm^2 respectively. The compressive strength of sample without flyash and with flyash as per IS: 1727 method at 28 days was 38.50 N/mm^2 and 31.60 N/mm^2 respectively. The compressive strength of sample without silica fume and with silica fume as per IS: 1727 method at 07 days was 12.70 N/mm^2 and 14.40 N/mm^2 respectively.

Table 1 – Properties of aggregates

Property		Granite Aggregate (mm)		Fine Aggregate
		20	10	
Specific gravity		2.81	2.80	2.62
Water absorption (%)		0.29	0.28	0.79
Sieve Analysis Cumulative Percentage Passing (%)	20mm	98	100	100
	10 mm	1	68	100
	4.75 mm	0	2	95
	2.36 mm	0	0	87
	1.18 mm	0	0	68
	600 µ	0	0	36
	300 µ	0	0	12
	150 µ	2	3	4
	Pan	0	0	0
Abrasion, Impact & Crushing Value		19.5, 12.8, 18.8	-	-
Flakiness % & Elongation %		28, 26	-	-

Table 2 – Characterization of cement

Characteristics		OPC 53 Grade	Silica Fume	Fly Ash
Physical tests				
Fineness (m^2/kg)		322.00	22000	403
Soundness Autoclave (%)		00.06	-	-
Soundness Le Chatelier (mm)		0.90	-	-
Setting Time Initial (min.) & (max.)		165.00 & 230.00	-	-
Specific gravity		3.14	2.26	2.22
Chemical tests				
Loss of Ignition (LOI) (%)		1.52	1.17	-
Silica (SiO_2) (%)		20.38	95.02	-
Iron Oxide (Fe_2O_3) (%)		3.96	0.80	-
Aluminium Oxide (Al_2O_3)		4.96	-	-
Calcium Oxide (CaO) (%)		60.75	-	-
Magnesium Oxide (MgO) (%)		4.77	-	-
Sulphate (SO_3) (%)		2.07	-	-
Alkalies (%)	Na_2O & K_2O	0.56 & 0.58	-	
Chloride (Cl) (%)		0.039	-	-
IR (%)		1.21	-	-
Moisture (%)		-	0.45	-

3.2 Mix design details

The shear study was done on three concrete mixes with w/c ratios 0.47, 0.36 and 0.20. The workability of concrete in terms of slump value was between 80-110 mm. Mix optimisation was carried out by doing necessary trials where moisture correction for aggregates by adjusting water quantity and optimum dosage of superplasticizer to achieve desired workability was finalized. The mix design details are given in Table 3. The mixes were prepared in concrete mixer. Casting was done as per Indian Standard procedure and the specimens were demoulded after 24 hours. The ambient conditions of temperature and relative humidity were maintained at 27±2°C and relative humidity 65% as per Indian Standard requirements. The concrete cubes were tested in saturated surface dried condition.

Table 3 – Concrete mix design details

w/c	Total Cementitious Content [Cement C + Fly ash (FA) + Silica Fume (SF)] (kg/m^3)	Water Content (kg/m^3)	Admixture % by weight of Cement	Fine Aggregate as % of Total Aggregate by weight	28-Days strength of concrete (N/mm^2)
0.47	362 (290+72+0)	170	1.00	35	45.72
0.36	417 (334+83+0)	150	0.45	39	68.57
0.20	750 (548+112+90)	150	1.75	35	97.76

3.3 Experimental study on RCC beams in shear

For validation of the proposed equation 12 RCC beams were cast and designed in a way to fail in shear so that the shear capacities can be obtained experimentally. The concrete mix used in RCC beams were as per mix design details given in Table 3. For shear strength assessment, Flexural Testing Machine of 500 KN capacity having displacement rate control facility was used. The beam was placed in simply supported condition over two fixed steel pedestals to get the desired clear span. The loading setup was made for four points bending by placing a distributor beam over two roller supports at one-third span distance from supports. Keeping in view the specimen size to be tested and failure load, the loading was decided to be applied at the rate of 0.2 mm/minute in displacement control (Fig. 4). The three additional set of concrete cubes were cast and tested at same day on which the testing was performed. The curing regime for both the RCC beams and concrete cubes were kept same to avoid the variation in compressive strength. The compressive strength of these cube samples were used for checking the predicted capacities as per design codes.

RCC beams with and without shear reinforcement were cast. To understand effect of shear span and to verify inclusion of effect of shear span in proposed equation, RCC beams with two different clear spans (effective length) were studied i.e., 1.2 m and 1.4 m of span length. The design details (Fig. 4) of beams are given in Table 4. Fig. 6 shows the failure modes of the shear beam.

Table 4 – Design details of beams

Sl. No.	Concrete Grade	B (mm)	D (mm)	d (mm)	a (mm)	Ast (mm^2)	Bar Details (HYSD)
1	M40	200	200	165	400 & 430	942	3 Nos. 20 mm
2	M60	200	200	165	400 & 430	942	3 Nos. 20 mm
3	M90	200	200	165	400 & 430	942	3 Nos. 20 mm

Where, B= width of the beam section; D= Total depth of the beam section; d= Effective depth of the beam section; a= shear span of the beam = 1/3 of clear span; A_{st}= Area of longitudinal tensile reinforcement

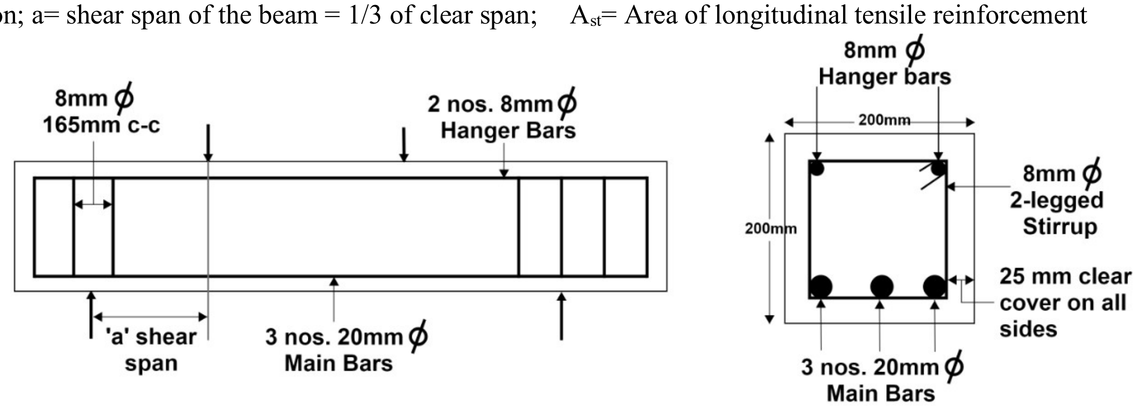


Fig. 4 – Sketch for design details of Reinforced Concrete Beam

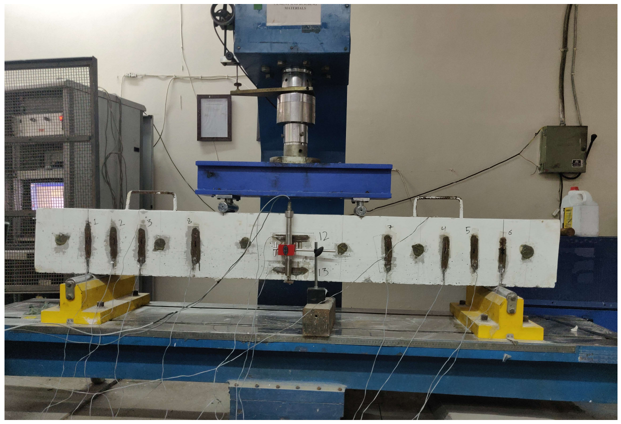
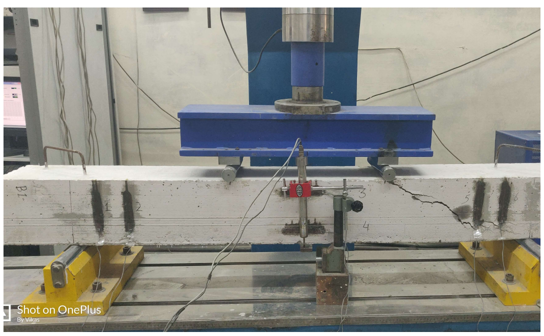


Fig. 5 – Test set up for shear study on reinforced concrete beam



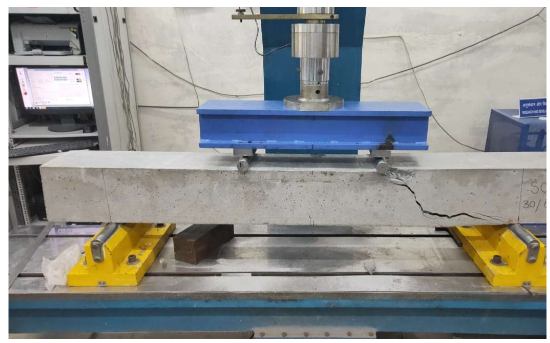


Fig. 6 – Failure pattern of reinforced concrete beams

The Fig. 7 shows comparison of proposed equation with experimental values of Tc. Tc in curve represents the shear stress obtained from RCC beams without shear reinforcement while Tc' represents the shear stress obtained from RCC beams with shear reinforcement. Tc' was calculated by subtracting steel component (calculated without partial factors of safety) from shear strength obtained experimentally.

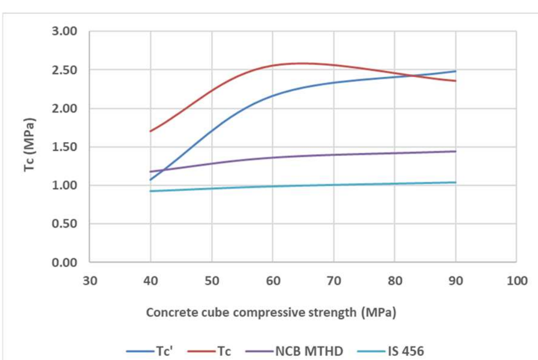


Fig. 7 – Comparison of proposed equation and experimental values of T_c

From Fig. 7, it can be observed that the experimental values are higher than the proposed equation and also higher experimental values are desirable to have a higher margin of safety in shear design to avoid catastrophic and sudden failure of concrete in shear. The developed equation under this study predicts higher values than the values predicted by IS: 456: 2000. The most important point to be observed from the chart is that shear stress (T_c) becomes more or less constant above compressive strength of 60 MPa which is also reflected in the proposed equation. RCC beams with and without shear reinforcement were cast. To understand effect of shear span and to verify inclusion of effect of shear span in proposed equation.

4. Conclusion

This paper has proposed an equation for computing shear stress that helps in calculation of concrete component of shear strength of RCC beam. The proposed equation shows more or less equal or similar values for concrete above 60 MPa. Some international standards restricts the compressive strength for calculation of shear stress for higher strengths of the concrete to have higher factor of safety. The proposed equation itself predicts the more or less constant or similar values of Tc for concrete with strength greater than 60 MPa. The proposed equation has been validated by the experimental results.

The experimental values are higher than the proposed equation and also higher experimental values are desirable to have sufficient margin of safety in shear design to avoid catastrophic and brittle failure of concrete in shear. The developed equation under this study predicts higher values than the values predicted by IS: 456: 2000. The most important point to be observed from the chart is that shear stress (Tc) becomes more or less constant above compressive strength of 60 MPa which is also reflected in the proposed equation.

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