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ARTICLE

Experimental Shear Study on Reinforced High Strength Concrete Beams Made Using Blended Cement

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ABSTRACT

With the increased application of High Strength Concrete (HSC) in construction and lack of proper guidelines for structural design in India, behavioral study of high strength concrete is an important aspect of research. Research on the behavior of HSC reinforced beams with concrete strength more than 60 MPa has been carried out in the past and is still continuing to understand the structural behavior of HSC beams. Along with the many benefits of the high strength concrete, the more brittle behavior is of concern which leads to sudden failure. This paper presents the behavior of reinforced HSC beams in shear with considering the effects of various factors like shear reinforcement ratio, longitudinal reinforcement ratio, l/d ratio (length to depth ratio), etc. Ten numbers Reinforced Concrete Beams of various sizes using concrete mix with three different w/c ratios (0.46, 0.26 and 0.21) were cast for shear strength assessment. The beams were tested in simply supported condition over two fixed steel pedestals with load rate of 0.2 mm/minute in displacement control. Mid-point deflection was measured using LVDT. A comparative analysis of theoretical approaches of Euro code, extension of current IS code up to M90 and the experimental data was done to understand the behavior of beams. Shear capacities of beams without any factors of safety were used to assess the actual capacities and then was compared with the experimental capacity obtained. Results of this study can be used in the design of high strength concrete and will be more reliable in Indian continent as the regional materials and exposure conditions were considered.

1. Introduction

The advancement of concrete technology has led to the production of higher grades of concrete. High strength concrete offers far better engineering properties like compressive strength, tensile strength, durability, modulus of elasticity and overall better performance when compared to the conventional concrete [1,2]. However, high-strength concrete is more brittle in nature because cracks in this material do not always follow the aggregate-

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hardened cement paste interfaces due to the improved interfacial bond strength and interfacial transition zone of high-strength concrete but may cut right through the hardened cement paste and even the aggregate particles leading to rapid propagation of the cracks and sudden or sometimes explosive failure of the concrete. Because of this problem, many structural engineers hesitate in using high-strength concrete, despite its obvious advantages. Research on the behavior of HSC beams with concrete strength higher than 55 MPa has been carried out in the past and is still continuing, to understand the behavior of HSC beams [3,4].

The shear failures of reinforced concrete beams can be sudden, brittle, and non-ductile. The mechanisms of shear transfer in reinforced concrete structures are complex. However, the understanding of shear behaviour and failure modes has improved significantly in recent years. All structural elements depend on concrete to resist a component of the shear force applied to them. It is therefore important that the design equations that are used by structural engineers to evaluate the shear strength of beams were also applicable to members made with high strength concrete. The failure of the beam is governed by the crushing of the compression struts between the cracks, or by the crack slip. Generally, for a normal strength concrete beam, the crushing of the concrete governs the beam failure. In a high-strength concrete beam, the struts are able to carry more compressive stress, and failure is most likely initiated by the crack slip. Diagonal cracks are the main mode of shear failure in reinforced concrete beams located near the supports and caused by excess applied shear forces. Beams fail immediately upon formation of critical cracks in the high-shear region near the beam supports. Whenever the value of actual shear stress exceeds the permissible shear stress of the concrete used, the shear reinforcement must be provided. The purpose of shear reinforcement is to prevent failure in shear, and to increase beam ductility and subsequently the likelihood of sudden failure will be reduced [5].

Piyamahant (2002) showed that the existing reinforced concrete structures should have stirrup reinforcement equal to the minimum requirement specified the code. The theoretical analysis shows that the amount of stirrup of 0.2% is appropriate. The paper concluded that small amount of web reinforcement is sufficient to improve the shear carrying capacity. The study focused on the applicability of the superposition method that used in predicting shear carrying capacity of reinforced concrete beam with a small amount of web reinforcement at the shear span ratio of 3. Also the failure mechanisms were considered when small amount of stirrup used [6].

Sneed, and Julio (2008) discussed the results of experimental research performed to test the hypothesis that the effective depth does not influence the shear strength of reinforced concrete flexural members that do not contain web reinforcement. The results of eight simply supported reinforced concrete beam tests without shear and skin reinforcement were investigated. The beams were designed such that the effective depth is the variable while the values of other general parameters proven to influence the shear strength (such as the compressive strength of concrete, longitudinal reinforcement ratio, shear span-to-depth ratio, and maximum aggregate size) were held constant [7].

Various studies were carried out in the 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 [8,9].

Similar findings were reported for shear strength of deep beams which have shear span / depth equal to 1.0 [10,11]. 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 [12]. 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 [13].

This paper presents the behavior of reinforced HSC beams in shear with considering the effects of various factors like shear reinforcement ratio, longitudinal reinforcement ratio, l/d ratio (length to depth ratio).

2. Experimental Program

Concrete Ingredients

Coarse aggregate with a maximum nominal size of 20 mm was used as coarse aggregate and natural riverbed sand confirming to Zone II as per IS: 383-2016 was used as fine aggregate. Their physical properties are given in Table 1. The petrographic studies conducted on coarse aggregate indicated that the aggregate sample is granite. For both coarse aggregate and fine aggregate sample the strained quartz percentage and their Undulatory Extinction Angle (UEA) are within codal limits. The silt content in fine aggregate as per wet sieving method is 0.75 percent.

One brand of Ordinary Portland cement (OPC 53 Grade) with fly ash and silica fume are used in this study. The chemical and physical compositions of cement OPC 53 Grade, Properties of flyash and silica fume are given in Table 2. Polycarboxylic group based superplasticizer for w/c ratio 0.21, 0.26 and Naphthalene based for w/c ratio 0.46 meeting with requirements of IS: 9103 is used. Water meeting requirements of IS: 456-2000 for construction was used. The 3 days, 07 days and 28 days compressive strength of cement OPC 53 Grade were 37.00 N/mm^2, 47.00 N/mm^2 and 59.00 N/mm^2 respectively. The 28 days compressive strength of controlled sample and sample cast with flyash was 36.33 N/mm^2 and 29.34 N/mm^2 respectively, when testing was done in accordance with IS: 1727. The 07 days compressive strength of controlled sample and sample cast with silica fume was 13.26 N/mm^2 and 15.32 N/mm^2 respectively, when testing was done in accordance with IS: 1727.

Table 1. Properties of Aggregates

Property 20 mm		**Granite**		**Fine Aggregate**
		10 mm		
Specific gravity		2.80	2.78	2.61
Water absorption (%)		0.28	0.27	0.77
Sieve Analysis Cumulative Percentage Passing (%)	20 mm	95	100	100
	10 mm	3	64	100
	4.75 mm	0	4	91
	2.36 mm	0	0	83
	1.18 mm	0	0	64
	600 µ	0	0	34
	300 µ	0	0	8
	150 µ	0	0	5
	Pan	0	0	0
Abrasion, Impact & Crushing Value		21, 15, 18	-	-
Flakiness % & Elongation %		30, 24	-	-

Table 2. Physical, Chemical and Strength Characteristics of Cement

Characteristics	**OPC -53 Grade**	**Silica Fume**	**Fly Ash**
Physical Tests:			
Fineness (m^2/kg)	322.00	23000	410
Soundness Autoclave (%)	00.06	-	-
Soundness Le Chatelier (mm)	0.9	-	-
Setting Time Initial (min.) & (max.)	180.00 & 240.00	-	-
Specific gravity	3.12	2.21	2.19
Chemical Tests:			
Loss of Ignition (LOI) (%)	1.54	1.19	-
Silica (SiO_2) (%)	20.78	94.33	-
Iron Oxide (Fe_2O_3) (%)	3.99	0.77	-
Aluminium Oxide (Al_2O_3)	4.90	-	-
Calcium Oxide (CaO) (%)	61.71	-	-
Magnesium Oxide (MgO) (%)	4.18	-	-
Sulphate (SO_3) (%)	2.17	-	-
Alkalies (%) Na_2O & K_2O	0.59 & 0.61	-	
Chloride (Cl) (%)	0.03	-	-
IR (%)	1.30	-	-
Moisture (%)	-	0.47	-

3. Mix Design Details

In this study, the three different mixes ranging from w/c ratio 0.46 to 0.21 using granite aggregate were selected for determining short term mechanical properties of HSC. For each type of aggregate, three separate batches were prepared. The slump of the fresh concrete was kept in the range of 80-110 mm. A pre-study was carried out to determine the optimum superplasticizer dosage for achieving the desired workability based on the slump cone test as per Indian Standard. The mix design details are given in Table 3. The laboratory conditions of temperature and relative humidity were maintained during the different ages at 27±2 ^oC and relative humidity 65%. The specimens were taken out from the curing tank and allowed for surface drying before it is tested in saturated surface dried condition.

Table 3. Concrete Mix Design Details for study done

w/c	**Total Cementitious Content [Cement C + Flyash (FA) + Silica Fume (SF)] (Kg/m3)**	**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)**
0.46	**362** (290+72+0)	170	1.00	35	45.72
0.26	**525** (400+75+50)	140	0.70	39	88.60
0.21	**750** (548+112+90)	150	1.75	35	97.76

4. Experimental Study on Reinforced Cement Concrete (RCC) Beams in Shear

Research on the behavior of HSC beams with concrete strength higher than 50 MPa has been carried out in the past and is still continuing, to understand the behavior of HSC beams in shear. The experimental data obtained from testing of beams in shear have been considered with a view to compare the ultimate strength of beams in shear to the capacity predicted by Eurocode EC: 02-2004. For a comparison to be made between the actual shear capacities and theoretical shear capacities, the theoretical shear capacities are calculated based on the same parameters as the actual beams tested. Eight numbers Reinforced Concrete Beams of different sizes with different depths and a/d ratios using concrete mix with three different w/c ratios (0.46, 0.26 and 0.21) were cast. The design details of beams are given in Table 4.

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	250	215	530	1030	2 Nos. 20 mm & 2 Nos. 16 mm
2	M80	200	250	215	530	942	3 Nos. 20 mm
3	M90	200	200	165	330	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

Ast= Area of longitudinal tensile reinforcement

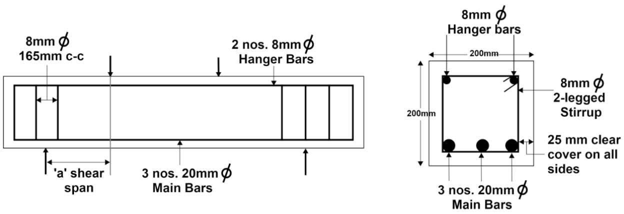

Figure 1. Sketch for design details of Reinforced Concrete Beam

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 (Figure 1). 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 (Figure 2).

The three additional sets 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 obtained from the testing of these cube samples were used for checking the predicted capacities as per design codes.

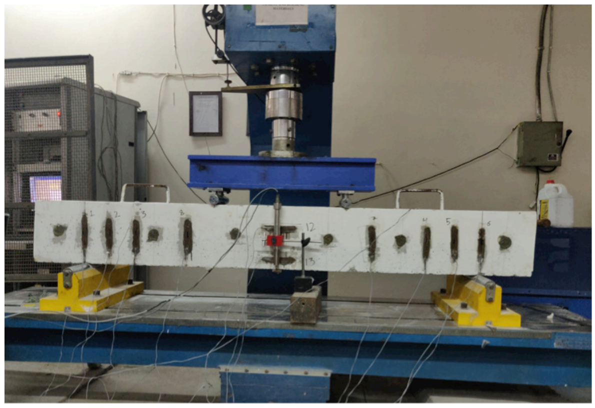

Figure 2. Test set up for Shear Strength of Reinforced Concrete Beams

4.1 Determination of Shear Capacity for High Strength Concrete

High-strength concrete has higher tensile strength hence a higher cracking shear can be expected. In various International codes of practice, the shear strength of a reinforced concrete beam is taken as the sum of the shear force that is carried by the concrete (Vc) and the web reinforcement (Vs). The term (Vc) in a diagonally cracked beam with web reinforcement represents the sum of three components: (a) dowel action resistance of the longitudinal reinforcement, (b) aggregate interlock resistance along the diagonal crack, and (c) the shear resistance carried by the uncracked concrete compressive zone. The term (Vs) represents the vertical component of the shear force carried by the shear reinforcement.

The Eurocode considers only shear force carried by the web reinforcement while the current IS code accounts for both steel as well as concrete in shear capacity. Since the IS code is applicable only upto M55 grade of concrete, to estimate the shear strength in this study IS approach was extended for high strength concrete. Comparison was done between shear capacity predicted by Euro code and extension IS approach to verify the applicability of the IS approach for higher strength concrete. In this study, comparison is also made by calculating shear capacity of RC beams using actual tested value of reinforcement yield strength (582 MPa) by adopting IS code method and shear capacity calculation by IS code method by restricting the value of reinforcement yield strength to 415 MPa. The equations used to determine the shear capacity are as follows:

Shear Capacity by Euro code

$$V_{Ed} = V_{Ed} = \frac{z\, fyd\, Asv \cot\theta}{s} \tag{1}$$

where, z = 0.9d

θ is taken as 45^0

f_{ywd} = yield stress of the web reinforcement

A_{sw} = cross sectional area of web reinforcement

S = spacing of the stirrups

Shear Capacity by IS approach extended upto higher grade

Concrete component based on semi empirical expression (SP 24, 1983).

$$Tc = \frac{0.85\sqrt{0.8\, fck}\,(\sqrt{1+5\beta}-1)}{6\beta} \tag{2}$$

where, $\beta = \frac{0.8\, fck}{6.89\, pt}$

$pt = \frac{100\, Ast}{bd}$

0.8 fck = cylinder strength in terms of cube strength

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

Steel component,

$$Vus = \frac{0.87\, fy\, Asv\, d}{sv} \tag{3}$$

where, f_y = yield stress of the web reinforcement

A_{sv} = cross sectional area of web reinforcement

s_v = spacing of the stirrups

The comparison of experimental shear capacity to shear capacity predicted by Euro code and IS approach is shown below in Table 5.

From the above table it could be noted that the values predicted from Euro code are much safer as it neglects the stress carried by concrete and considers only steel part. While Euro code uses actual yield strength of the web reinforcement, the current IS code restricts the value to 415 Mpa to be used in design even if the actual yield strength is higher than that. The values show that even if the extension of IS approach is to be used for higher grades of concrete the value of fy should be restricted to 415 Mpa as it will increase the factor of safety which is much needed as the shear failure is sudden or spontaneous in nature and there are no pre-failure symptoms. In case of lower a/d ratio, the ratio of experimental to predicted shear capacity is higher which makes it evident that the factor a/d plays an important role in determination of shear capacity of the member and should be incorporated in the design methods.

4.2 Effect of a/d Ratio on the Shear Design of High Strength Reinforced Beams

To see the effect of a/d ratio on the shear capacity of the high strength RCC beams, beams with different a/d ratios were tested keeping all other parameters constant.

From the above table it could be noted that the predicted shear capacities for all the three design with different a/d ratio is same while the experimentally obtained capacities are different for all the three designs. The results show that for lower a/d ratios the ratio of experimental and predicted shear capacities is very high as compared to when a/d ratio is higher. The experimental shear capacities for a/d ratios 2.42 and 2.83 are comparable while in case of a/d ratio of 2.01, a high experimental shear capacity was obtained. Therefore, the effect of a/d ratio should also be considered while designing the structures. The current method won't hold good when a/d ratio is lower than 2.0 while for a/d ratio higher than 2, the shear capacity decreases with increase in a/d ratio keeping other parameters constant. Over or under estimation of shear capacities can lead to various consequences in terms of loss of money and life.

4.3 Typical Failure Mode of RCC Beams

The beams failed due to widening and extending of cracks into shear zone, between the loading points (Figure 3 and Figure 4). As the intent of failure was to fail the beam in shear therefore flexural capacity was kept on the higher side to avoid any secondary stresses. Hence all beams failed in shear mode only and minor flexural cracks in the concrete were observed in flexural zone without yielding in steel reinforcement. The loading was continued till the major crack is observed in shear zone due to yielding of the stirrups.

Initially load was carried by both concrete and steel. With the initiation of minor carcks load gradually shifts from concrete to steel. Once the complete separation of the concrete takes place due to widening of cracks, the entire load is carried by shear steel reinforcement. When further load is increased stirrups yield and finally breaks to fail. Failure of the stirrups can be attributed to the large single crack in shear zone and sudden drop in the load-deflection or load-time graph.

Table 5. Comparison of Experimental Shear capacity to shear capacity predicted by Euro Code and IS approach

Beam Details	Code	Shear Capacity		Shear Capacity (kN)		Ve/Vp
		Concrete (Vc)	Steel (Vs)	Predicted (Vp)	Experimental (Ve)	
B1 M-40	IS Code with fy 415	49.07	44.84	93.91	145	1.54
	IS Code with fy 582	49.07	62.87	111.94		1.30
	Euro code	67.76	56.58	56.58		2.56
	Euro code (with concrete)	67.76	56.58	124.34		1.17
B2 M-40	IS Code with fy 415	49.07	44.84	93.91	139	1.48
	IS Code with fy 582	49.07	62.87	111.94		1.24
	Euro code	67.76	56.58	56.58		2.46
	Euro code (with concrete)	67.76	56.58	124.34		1.12
B1 M-80	IS Code with fy 415	49.83	56.03	105.86	150	1.42
	IS Code with fy 582	49.83	78.58	128.41		1.17
	Euro code	77.56	70.72	70.72		2.12
	Euro code (with concrete)	77.56	70.72	148.28		1.01
B2 M-80	IS Code with fy 415	49.83	56.03	105.86	189	1.79
	IS Code with fy 582	49.83	78.58	128.41		1.47
	Euro code	77.56	70.72	70.72		2.67
	Euro code (with concrete)	77.56	70.72	148.28		1.27
B1 M-90	IS Code with fy 415	43.74	43.00	86.74	234	2.70
	IS Code with fy 582	43.74	60.31	104.05		2.25
	Euro code	66.70	54.28	54.28		4.31
	Euro code (with concrete)	66.70	54.28	120.98		1.93
B2 M-90	IS Code with fy 415	43.74	43.00	86.74	230	2.65
	IS Code with fy 582	43.74	60.31	104.05		2.21
	Euro code	66.70	54.28	54.28		4.24
	Euro code (with concrete)	66.70	54.28	120.98		1.90

Table 6. Design Details of Beams

Sl. No.	Concrete Grade	B (mm)	d (mm)	Shear Span (a) (mm)	a/d ratio	Ast (mm^2)	Spacing of stirrups (Φ=8)(mm)
1	M90	200	165	333	2.01	942	160
2	M90	200	165	400	2.42	942	160
3	M90	200	165	467	2.83	942	160

Table 7. Comparison of Experimental Shear capacity to shear capacity predicted by Euro Code and IS approach with different shear span to depth (l/d) ratio

Beam Details	Span to Depth (a/d) ratio	Code	Shear Capacity		Shear Capacity (kN)		Ve/Vp
			Concrete (Vc)	Steel (Vs)	Predicted (Vp)	Experimental (Ve)	
B1 M-90	2.01	IS Code	43.74	43.00	86.74	234	2.70
		IS Code fy 582	43.74	60.31	104.05		2.25
		Euro code	66.70	54.28	54.28		4.31
		Euro code (with concrete)	66.70	54.28	120.98		1.93
B2 M-90		IS Code	43.74	43.00	86.74	230	2.65
		IS Code fy 582	43.74	60.31	104.05		2.21
		Euro code	66.70	54.28	54.28		4.24
		Euro code (with concrete)	66.70	54.28	120.98		1.90
B1 M-90	2.42	IS Code	43.74	43.00	86.74	163	1.88
		IS Code fy 582	43.74	60.31	104.05		1.57
		Euro code	66.70	54.28	54.28		3.00
		Euro code (with concrete)	66.70	54.28	120.98		1.35
B2 M-90	2.83	IS Code	43.74	43.00	86.74	156	1.80
		IS Code fy 582	43.74	60.31	104.05		1.50
		Euro code	66.70	54.28	54.28		2.87
		Euro code (with concrete)	66.70	54.28	120.98		1.29

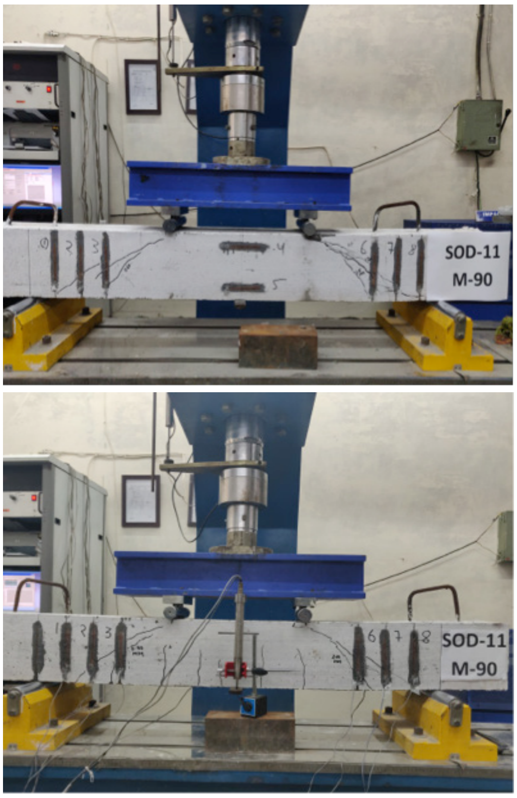

Figure 3. Failure Mode of RCC Beams

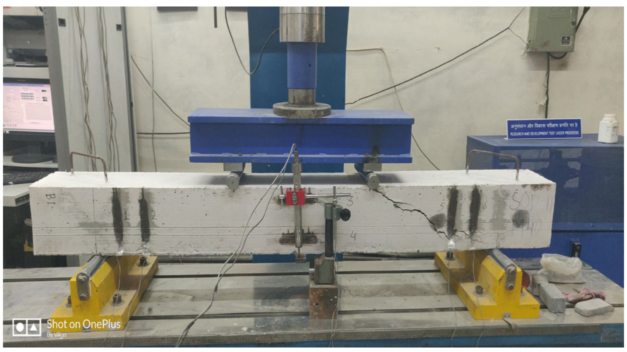

Figure 4. Failure Mode of RCC Beams in Shear

5. Conclusions

For an effective design the theoretical calculation of ultimate strength must be conservative or less than the ultimate failure load whereas for a sustainable design it should be conservative as well as the economically suitable. The design rules should provide similar level of conservativeness as well as sustainability for normal and high strength concrete. The values predicted from Euro code are much safer as it neglects the stress carried by concrete and considers only steel part. While Euro code uses actual yield strength of the web reinforcement, the current IS code restricts the value to 415 MPa to be used in design even if the actual yield strength is higher than 415 MPa. The values show that even if the extension of IS approach is to be used for higher grades of concrete the value of f_y should be restricted to 415 MPa as it will increase the factor of safety which is much needed as the shear failure is sudden or spontaneous in nature and there are no pre-failure symptoms. In case of lower a/d ratio, the ratio of experimental to predicted shear capacity is higher which makes it evident that the factor a/d plays an important role in determination of shear capacity of the member and should be incorporated in the design methods. The experimental shear capacities for a/d ratios 2.42 and 2.83 are comparable while in case of a/d ratio of 2.01, a high experimental shear capacity was obtained. Therefore, the effect of a/d ratio should also be considered while designing the structures. The current method won't hold good when a/d ratio is lower than 2.0 while for a/d ratio higher than 2, the shear capacity decreases with increase in a/d ratio keeping other parameters constant.

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