DOI: http://dx.doi.org/10.12989/sem.2011.37.1.039

Shear strength analysis and prediction of reinforced concrete transfer beams in high-rise buildings

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(Received November 30, 2009, Accepted September 7, 2010)

Abstract. Results of an experimental investigation on the behavior and ultimate shear capacity of 27 reinforced concrete Transfer (deep) beams are summarized. The main variables were percent longitudinal (tension) steel (0.28 to 0.60%), percent horizontal web steel (0.60 to 2.40%), percent vertical steel (0.50 to 2.25%), percent orthogonal web steel, shear span-to-depth ratio (1.10 to 3.20) and cube concrete compressive strength (32 MPa to 48 MPa).The span of the beam has been kept constant at 1000 mm with 100 mm overhang on either side of the supports. The result of this study shows that the load transfer capacity of transfer (deep) beam with distributed longitudinal reinforcement is increased significantly. Also, the vertical shear reinforcement is more effective than the horizontal reinforcement in increasing the shear capacity as well as to transform the brittle mode of failure in to the ductile mode of failure. It has been observed that the orthogonal web reinforcement is highly influencing parameter to generate the shear capacity of transfer beams as well as its failure modes. Moreover, the results from the experiments have been processed suitably and presented an analytical model for design of transfer beams in high-rise buildings for estimating the shear capacity of beams.

Keywords: shear resisting capacity; horizontal and vertical steel bars; shear span-to-depth ratio; national codes; transfer beam.

1. Introduction

High-rise buildings are characterized by their high susceptibility to lateral drift under the effects of lateral loads such as wind and earthquake loads. Therefore, in order to achieve architectural and functional requirements of large column-free space in high-rise buildings, the RC columns are placed at the periphery of the built-up plan area. With a view to developing high flexural and torsional stiffness, these columns are very closely spaced and interconnected through very stiff beams; called as Spandrel beams. These closely spaced columns at the periphery, however, pose hindrance to the free flow of people and goods at the ground floor and basement levels. To fulfill this requirement, the columns at these floor levels have to be placed at larger spacing. As a result, an interface has to be provided between the closely spaced columns of upper floors and the widely spaced columns at the ground/basement floor level. This interface has to be a horizontal RC element and hence is referred to as Beam. Conventionally, a beam is a flexural member of a structural system. The above mentioned interface beam, however, does not behave as a flexural member since it gets sandwiched between closely spaced upper columns and a little widely spaced supporting

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columns below it. Also to transfer the high magnitude of loads collected from all the upper floors of a high-rise building, the depth of the interface beams has to be kept much higher than the conventional beams, ranging from 1 m to 4.5 m. As a result of this, *a/d* ratio of such beams becomes different than the conventional beam which in tern makes the load transfer mechanism through these beams altogether different. Such a beam is also referred to as a Transfer Beam.

Transfer (deep) beams are horizontal members, and have shear span-to-depth ratio < 2, which transfer heavy gravity loads predominantly through shearing action by forming a diagonal crack, Since a diagonally cracked deep beam behaves as a tied arch (Ley *et al.* 2007, Zhang and Tan 2007), the conventional plane section remaining plane approach is not applicable to analyses of deep beams (Kong 1990). Besides, for beams without web reinforcement, it has been shown that shear strength decreases as member size increases. This is associated with a phenomenon called size effect (Tan and Cheng 2006, Tan *et al*. 2008, Yang *et al.* 2007).

Shear strength in reinforced concrete beams has been the subject of many controversies and debates since the beginning of 20th century and it has been extensively studied over the last five decades (Russo *et al.* 2005). A large number of experimental and analytical works have been carried out for the case of slender beams (having a shear span to depth ratio *a/d* > 2.5) with and without shear reinforcement under two-point loading (Ahmad and Shaha 2009, Ashor and Yang 2008, Foster and Gilbert 1998) and proposed a design equation for predicting the shear strength of deep beams (Bakir and Boduroglu 2002, Hwang *et al.* 2000, Leong and Tan 2003, Russo *et al.* 2004). Transversely loaded reinforced concrete beams may fail in shear before attaining their full flexural strengths if they are not adequately designed for shear. Unlike flexural failures, shear failures are very sudden and unexpected, and sometimes violent and catastrophic (Londhe 2007). A thorough knowledge of the different modes of shear failures and the mechanisms involved is necessary to prevent them (Zarris 2005).

2. Discussion on shear

Shear force is present in beams at sections where there is a change in bending moment along the span. It is equal to the rate of change of bending moment. An exact analysis of shear strength in reinforced concrete beam is quite complex. Several experimental studies have been conducted to understand the various modes of failure that could occur due to possible combination of shear and bending moment acting at a given section (Oh and Shin 2001, Pendyala and Mendis 2000, Vecchio *et al.* 1994, Yang *et al*. 2003).

Despite the great research efforts, however, there is still not a simple, albeit analytically derived formula to predict quickly and accurately the shear strength of slender beams. In addition, many of the factors that influence the determination of the required minimum amount of shear reinforcement are not yet known. As a consequence, the current provisions for shear in standard codes such as ACI code, BIS code, BS code are still based on empirical or semi empirical considerations.

3. Experimental program

3.1 Test material and material properties

Ordinary Portland Cement of 43-grade confirming to Indian Standard[3], (specific gravity and

Table 1 Concrete mix proportions

Descriptions	Cement Content (kg/m^3)			
	320	360	400	440
	Cube compressive strength of Concrete (MPa)			
	32	37	43	48
Water-Cement Ratio	0.40	0.36	0.32	0.29
Water (Liter)	7.800	7.800	7.800	7.800
Plasticizer as% of wt. of cement	0.60	0.75	0.85	1.00
Mix-Proportions	1:2.36:4.31	1:2.10:3.75	1.:1.82:3.31	1:1.63:2.93

fineness respectively were 3.14 and 275 m^2/kg), locally available Yamuna river sand of specific gravity was 2.60 and fineness modulus was 2.29, Crushed granite metal of maximum size 20 mm obtained from a local source. and thermo-mechanically treated (TMT) rebar of 8 mm, 10 mm and 12 mm diameter of F_e 415 grade as reinforcement were used throughout the investigation.

3.2 Concrete mix design

The concrete mix was designed in accordance with the Indian Standard[4] recommended method of concrete mix design. The concrete mix was prepared for various cement content. To improve the workability of concrete and to get high strength, a modified melamine base highly effective high range water reducing concrete admixture was used. The detail of the mix design is shown in Table 1. The beams were cast taking special care in placing and vibrating the concrete externally to ensure the uniform compaction. For each of the series of beams, three cubes (150 mm × 150 mm × 150 mm), three cylinders (150 mm, 300 mm high) and three prisms (500 mm × 500 mm × 1000 mm in length) as control specimens were also cast to ensure the quality and strength of each concrete mix.

3.3 Design and details of the beam specimens

Twenty seven simply supported rectangular beams of constant width of 100 mm and varying depth were cast and tested in the laboratory. A bottom clear covers of 20 mm, and side converse of 15 mm for reinforcement, were provided according to the Indian Standards. The specimens were cast in two batches of same concrete compressive strength producing two sets of geometrically identical specimens. A table vibrator was used for compaction of the specimens. After twenty four hour, the specimens were removed from the mould and placed in the water tank for 28 days curing. The full details are given in Table 2.

Based on the various influencing parameters of shear capacity of beams and to generate the shear capacity, the beams were divided into six series. Series I specimens are beams with varying percentage of longitudinal tension steel (ρ_l =0.28% to 0.60%) provided at the bottom of the beam and without transverse steel, Series II specimens are beams with varying percentage of horizontal web steel (ρ_h = 0.60% to 2.40%) provided from the bottom of the beam up to 50% of total depth of beam and without transverse steel (Figs. 1(a) to (d)), Series III specimens are beams with varying percentage vertical (transverse) steel (ρ_v = 0.50% to 2.25%) with constant percentage of longitudinal

Table 2 Details of the Specimens of Series-I, II, III, IV, V & VI

Test Beam Designation	Beam Size ($b \times D$)	Effective depth (mm)	a/d ratio	Concrete strength			Long. Reinf.		Vertical Reinf.		
				f_{cu} MPa	f_c' MPa	f_t MPa	ρl (%)	f_y (MPa	Dia. & spacing mm	ρ_v (%)	f_y MPa
Series I Specimens											
I-1/1.10//43/0.28	100×400	375	1.10	43.69	32.19	3.79	0.28				
I-2/1.10//43/0.42	100×400	375	1.10	43.62	32.17	3.82	0.42				
I-3/1.10/43/0.60	100×400	375	1.10	43.81	32.21	3.79	0.60				
Series II Specimens								445.38	---	---	--
II-1/1.10//43/0.60	100×400	375	1.10	43.81	32.21	3.79	0.60				
II-2/1.10/43/1.20	100×400	375	1.10	43.62	32.18	3.80	1.20				
II-3/110/43/1.80	100×400	375	1.10	43.58	32.22	3.81	1.80				
II-4/1.10/43/2.40	100×400	375	1.10	43.68	32.15	3.78	2.40				
Series III Specimens											
III-1/1.10/43/0.60/0.00	100×400	375	1.10	43.79	32.19	3.77			---	00	
III-2/1.10/43/0.60/0.50	100×400	375	1.10	43.68	32.14	3.80			8ϕ @250	0.50	
III-3/1.10/43/0.60/0.75	100×400	375	1.10	43.74	32.19	3.80	0.60	444.98	8ϕ @150	0.75	445.38
III-4/1.10/43/0.60/1.25	100×400	375	1.10	43.81	32.20	3.83			8ϕ @100	1.25	
III-5/1.10/43/0.60/2.25	100×400	375	1.10	43.70	32.16	3.82			8ϕ @50	2.25	
Series IV Specimens											
IV-1/1.10/43/2.40/0.00	100×400	375	1.10	43.79	32.19	3.77			---	00	
IV-2/1.10/43/2.40/0.50	100×400	375	1.10	43.68	32.14	3.80			8ϕ @250	0.50	
IV-3/1.10/43/2.40/0.75	100×400	375	1.10	43.74	32.19	3.80	2.40	445.98	8ϕ @150	0.75	445.28
IV-4/1.10/43/2.40/1.25	100×400	375	1.10	43.81	32.20	3.83			8ϕ @100	1.25	
IV-5/1.10/43/2.40/2.25	100×400	375	1.10	43.70	32.16	3.82			8ϕ @50	2.25	
Series V Specimens											
V-1/43/0.80/1.10	100×400	375	1.10	43.00	33.0	3.30					
V-2/43/0.80 /1.23	100×350	325	1.23	42.50	3.3.5	3.35					
V-3/43/0.80 /1.45	100×300	275	1.45	43.25	34.0	3.40	0.80	445.38	---	---	--
V-4/43/0.80 /1.78	100×250	225	1.78	43.50	34.2	3.42					
V-5/43/0.80 /2.28	100×200	175	2.28	42.50	34.10	3.41					
V-643//0.80 /3.20	100×150	125	3.20	42.75	33.21	3.30					
Series VI Specimens											
VI-1/1.10/0.60/32	100×400	375	1.10	32.30	24.44	2.91					
VI-2/1.10/0.60/37	100×350	325	110	36.48	27.43	3.48	0.60	444.12	----	----	---
VI-3/1.10/0.60/43	100×300	275	1.10	43.27	32.15	3.82					
VI-2/1.10/0.60/48	100×250	225	1.10	47.55	36.67	4.46					

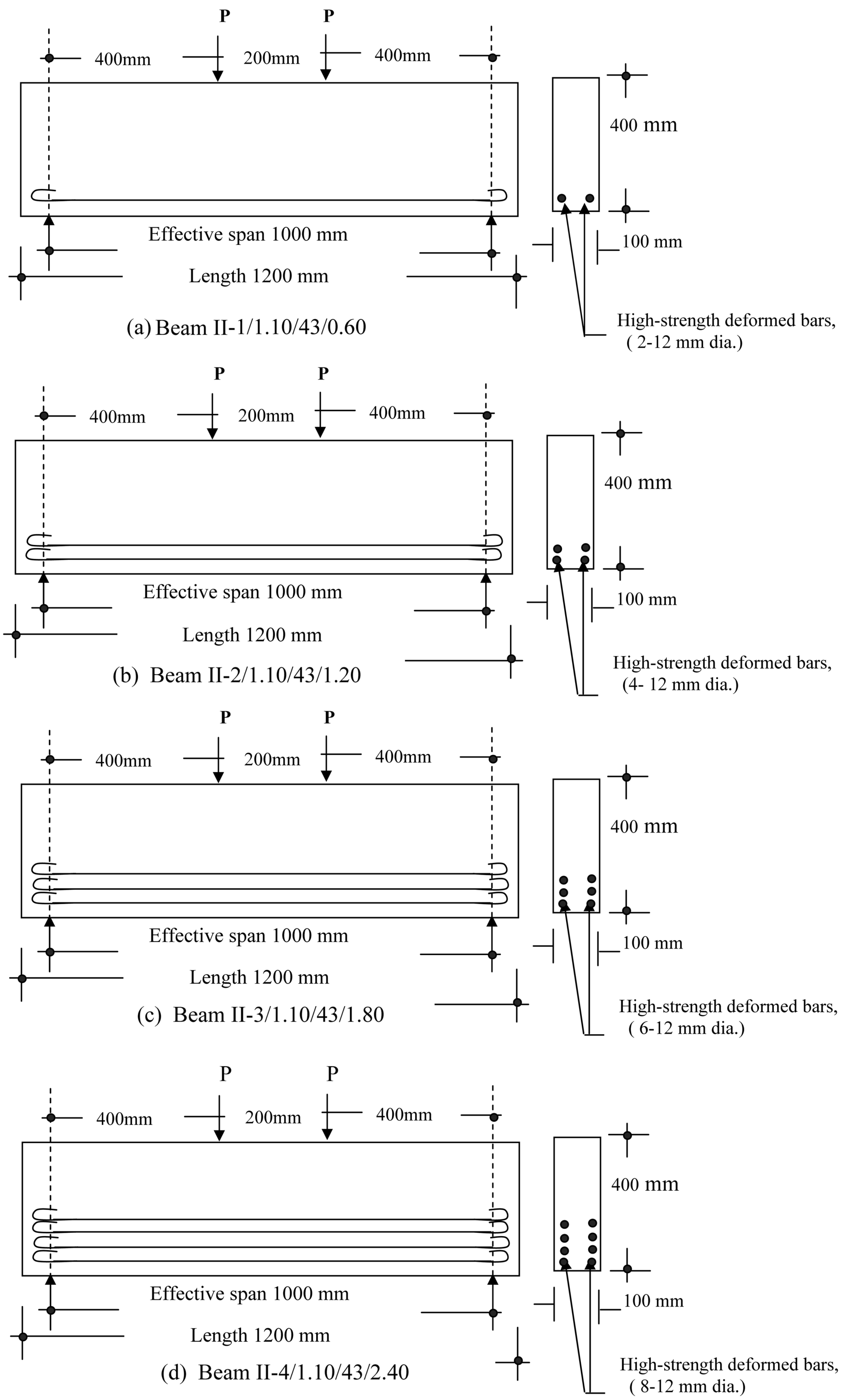


Fig. 1 (a to d) Series-II specimens

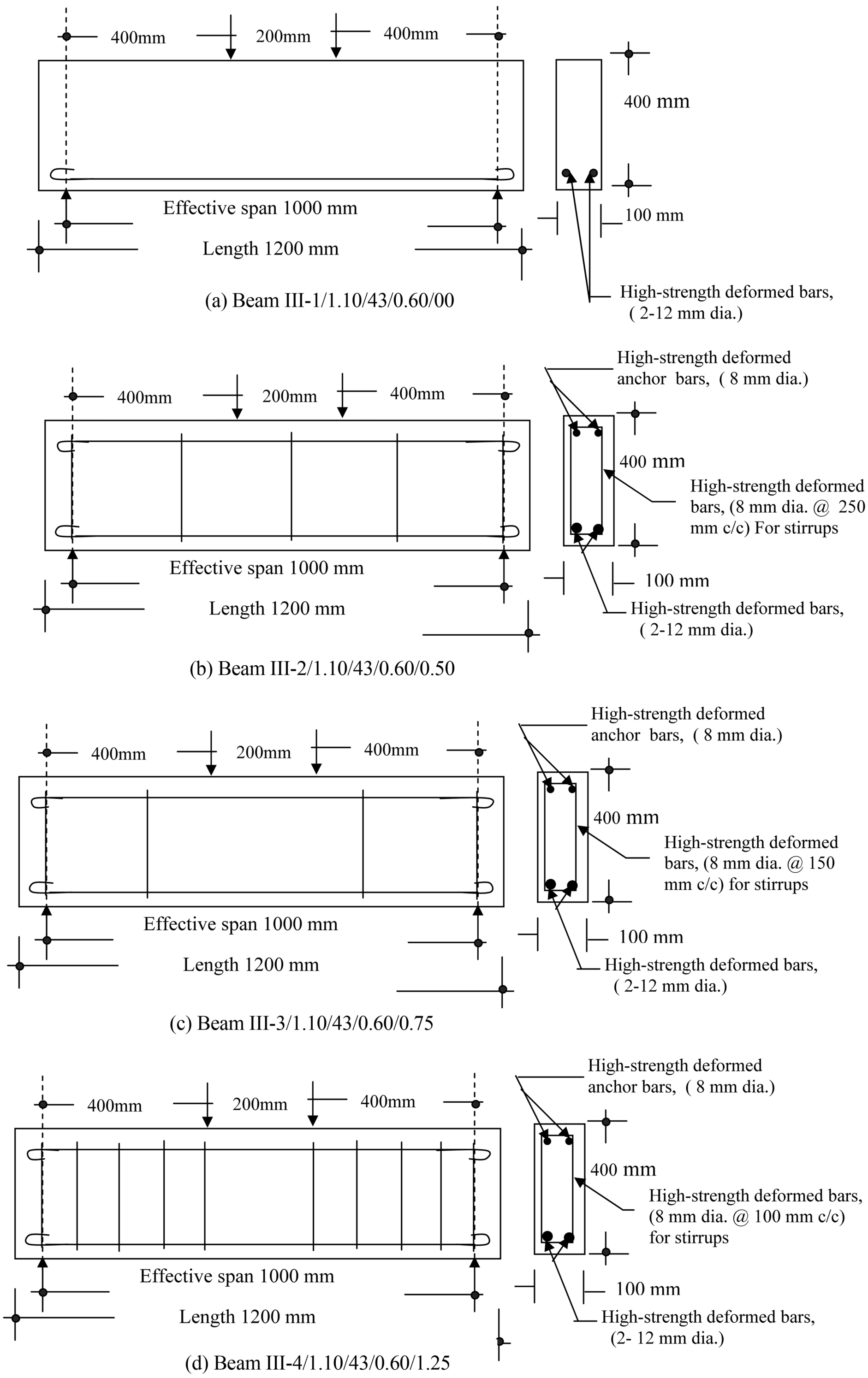
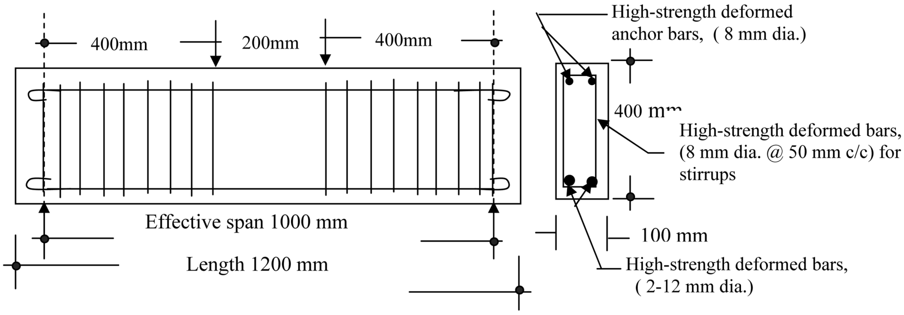
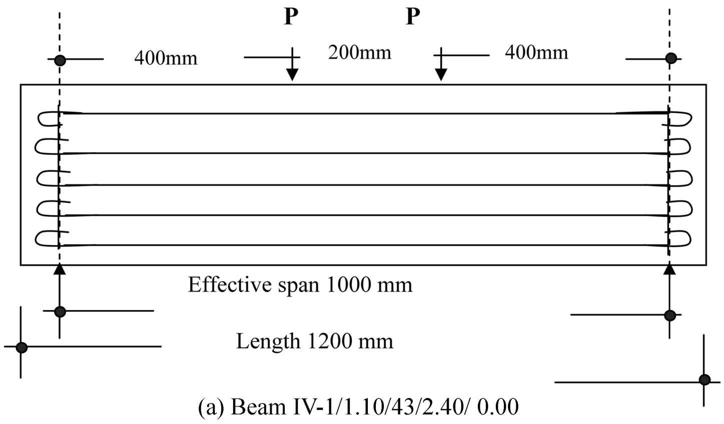


Fig. 2 (a to e) Series-III specimens

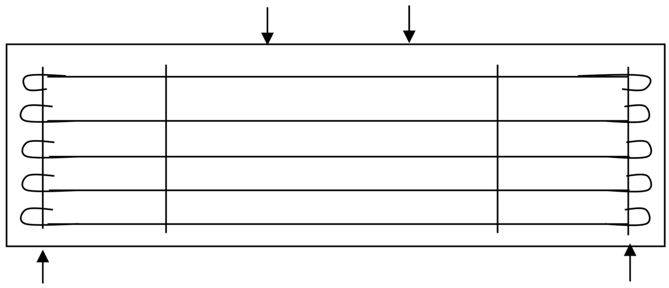


(e) Beam III-4/1.10/43/0.60/2.25

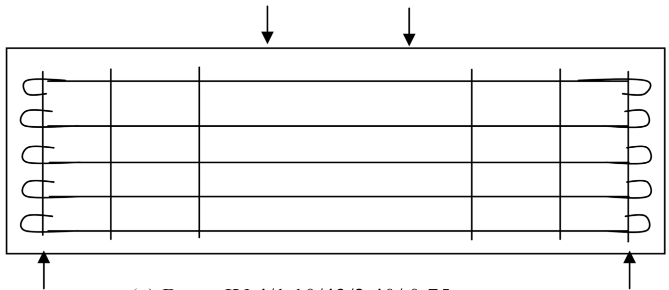
Fig. 2 Continued



(a) Beam IV-1/1.10/43/2.40/ 0.00

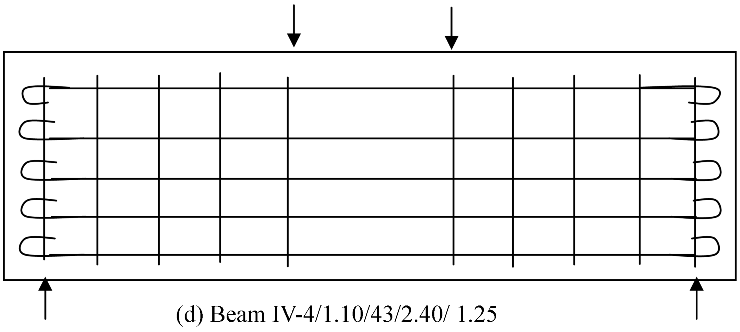


(b) Beam IV-4/1.10/43/2.40/ 0.50

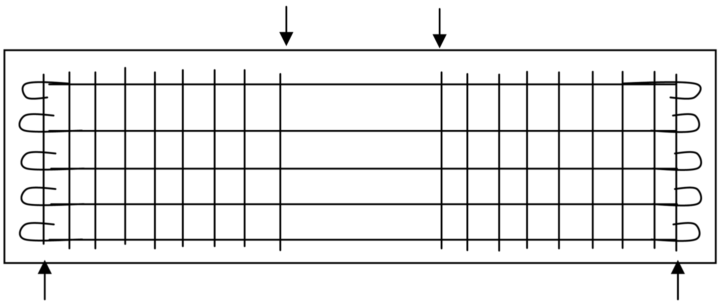


(c) Beam IV-4/1.10/43/2.40/ 0.75

Fig. 3 (a to e) Series-IV Specimens



(d) Beam IV-4/1.10/43/2.40/ 1.25



(e) Beam IV-5/1.10/43/2.40/ 2.25

Fig. 3 Continued

steel (Figs. 2(a) to (e)), Series IV specimens are beams with varying percentage vertical (transverse) steel (ρ_v = 0.50% to 2.25%) with constant percentage of horizontal steel distributed across the depth of beam (Figs. 3(a) to (e)), Series V specimens are beams with varying shear-span-to-depth ratio (*a/d*-ratio = 1.25 to 3.20) with constant percentage of longitudinal steel of 0.80% and Series VI specimens are beams with varying cube compressive strength of concrete (32 MPa to 48 MPa) with constant percentage of longitudinal steel of 0.60%.

3.4 Specimen identification

This paper addresses the effect of various influencing parameter on the shear capacity of reinforced concrete transfer (deep) beams. In the beam natations under Table 1, in series I beam specimens, the series number is given first; this is followed by beam serial number, followed by *a/d*-ratio, then cube compressive strength of concrete and then longitudinal steel percent. For example, Beam I-1/1.10/43/0.28 refers to a specimen in series I of serial number 1 with *a/d*-ratio of 1.10, cube compressive strength of concrete as 43 MPa and 0.28 percent longitudinal steel.

For series II beam specimens, the series number is given first; this is followed by beam serial number, followed by *a/d*-ratio, then cube compressive strength of concrete and then horizontal web steel percent. For example, Beam II-1/1.10/43/0.60 refers to a specimen in series II of serial number 1 with *a/d*-ratio of 1.10, cube compressive strength of concrete as 43 MPa and 0.60 percent horizontal web steel.

For series III beam specimens, the series number is given first; this is followed by beam serial number, followed by *a/d*-ratio, then cube compressive strength of concrete, constant longitudinal steel and then vertical steel percent. For example, Beam III-1/1.10/43/1.20/0.50 refers to a specimen in series III of serial number 1 with *a/d*-ratio of 1.10, cube compressive strength of concrete as 43 MPa, 1.20 percent longitudinal steel and 0.50% vertical steel.

For series IV beam specimens, the series number is given first; this is followed by beam serial number, followed by *a/d*-ratio, then cube compressive strength of concrete, constant horizontal distributed web steel and then vertical steel percent. For example, Beam IV-1/1.10/43/2.40/0.50 refers to a specimen in series IV of serial number 1 with *a/d*-ratio of 1.10, cube compressive strength of concrete as 43 MPa, 2.40 percent constant horizontal distributed web steel and 0.50% vertical steel.

For series V beam specimens, the series number is given first; this is followed by beam serial number, followed by cube compressive strength of concrete, constant longitudinal (tension) steel and then *a/d*-ratio. For example, Beam V-1/43/0.80/1.10 refers to a specimen in series V of serial number 1 with cube compressive strength of concrete as 43 MPa, 0.80% constant longitudinal (tension) steel and *a/d*-ratio of 1.10.

For series VI beam specimens, the series number is given first; this is followed by beam serial number, followed by *a/d*-ratio, constant longitudinal (tension) steel and then cube compressive strength of concrete. For example, Beam VI-1/1.10/0.60/32, refers to a specimen in series VI of serial number 1 with *a/d*-ratio of 1.10, 0.60 percent constant longitudinal (tension) steel and cube compressive strength of concrete as 43 MPa.

4. Test procedure

4.1 Test setup and loading apparatus

All beam specimens were tested under four-point loading test set-up (2-active, 2-passive) as shown in Fig. 4. The spacing between the top Point-Loads was kept constant for all the specimens at 200 mm and the shear span separating the laoding points from the supports was equal on both ends of the specimens creating a zero shear region between the laoding points. The load transfer from laoding frame to the specimens was through a proving ring by hydraulic jack placed on the top of specimens.

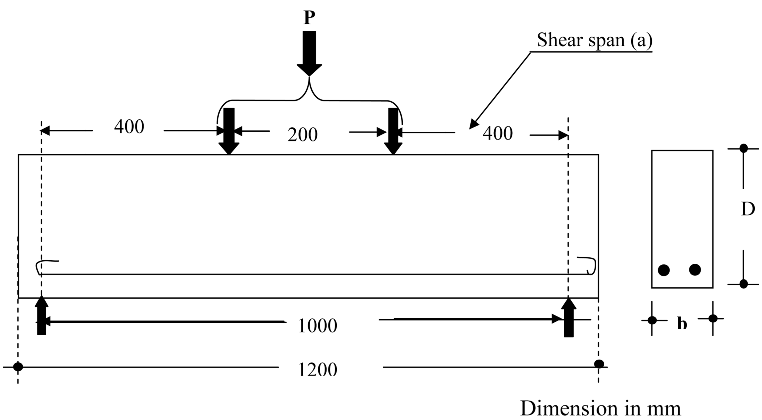


Fig. 4 Four point loading test set-up

After 28-days curing period, the beam specimens were removed from the curing tank and both sides of the beam were white-washed to aid observations of the crack development during testing. Load was applied gradually with the help of jack and deflection of proving ring was recorded to find the failure load.

4.2 Test results and discussion

The results obtained from the experimental investigation are tabulated in Table 3. From the results obtained, the effect of various parameters on shear strength of concrete are analyzed and discussed as follows.

Table 3 Test results of Series I, II, III, IV, V & VI

Test Beam Designation	*a/d* ratio	Concrete strength		Long. Reinf	Vertical Reinf.	$V_{max.}$ (kN)	$\tau = V/bd$ (MPa)	$\tau/\sqrt{f_{cu}}$	Mode of failure
		f_{cu} MPa	f_c' MPa						
I-1/1.10//43/0.28	1.10	43.69	32.19	0.28	--	60	1.60	0.24	Flexure
I-2/1.10//43/0.42	1.10	43.62	32.17	0.42	--	75	2.00	0.30	Flexure-shear
I-3/1.10/43/0.60	1.10	43.81	32.21	0.60	--	90	2.40	0.36	Shear
II-1/1.10//43/0.60	1.10	43.81	32.21	0.60	--	90	2.40	0.36	Diagonal-splitting
II-2/1.10/43/1.20	1.10	43.62	32.18	1.20	--	140	3.76	0.57	Diagonal-splitting
II-3/110/43/1.80	1.10	43.58	32.22	1.80	--	165	4.40	0.67	Diagonal-splitting
II-4/1.10/43/2.40	1.10	43.68	32.15	2.40	--	185	4.96	0.75	Diagonal-splitting
III-1/1.10/43/0.60/0.00	1.10	43.79	32.19	0.60	0.00	90	2.40	0.36	Diagonal-splitting
III-2/1.10/43/0.60/0.50	1.10	43.68	32.14		0.50	105	2.80	0.42	Shear-flexure
III-3/1.10/43/0.60/0.75	1.10	43.74	32.19		0.75	125	3.33	0.50	Flexure
III-4/1.10/43/0.60/1.25	1.10	43.81	32.20		1.25	150	4.00	0.60	Shear-compression
III-5/1.10/43/0.60/2.25	1.10	43.70	32.16		2.25	160	4.27	0.64	Shear-compression
IV-1/1.10/43/2.40/0.00	1.10	43.79	32.19	2.40	0.00	185	4.93	0.75	Diagonal-splitting
IV-2/1.10/43/2.40/0.50	1.10	43.68	32.14		0.50	292	7.79	1.18	Shear
IV-3/1.10/43/2.40/0.75	1.10	43.74	32.19		0.75	315	8.40	1.27	Flexure-shear
IV-4/1.10/43/2.40/1.25	1.10	43.81	32.20		1.25	320	8.53	1.29	Flexure-shear
IV-5/1.10/43/2.40/2.25	1.10	43.70	32.16		2.25	330	8.80	1.33	Flexure-compression
V-1/43/0.80/1.10	1.10	43.00	33.0	0.80	--	98.25	2.62	0.40	Diagonal-splitting
V-2/43/0.80 /1.23	1.23	42.50	3.3.5		--	65	2.00	0.31	Diagonal-splitting
V-3/43/0.80 /1.45	1.45	43.25	34.0		--	44	1.60	0.24	Diagonal-splitting
V-4/43/0.80 /1.78	1.78	43.50	34.2		--	29.25	1.30	0.20	Diagonal-splitting
V-5/43/0.80 /2.28	2.28	42.50	34.10		--	21	1.20	0.18	Diagonal-splitting
V-6/43//0.80 /3.20	3.20	42.75	33.21		--	14	1.12	0.17	Diagonal-splitting
VI-1/1.10/0.60/32	1.10	32.30	24.44	0.60	--	77	2.05	0.36	Diagonal-splitting
VI-2/1.10/0.60/37	110	36.48	27.43		--	80	2.13	0.35	Diagonal-splitting
VI-3/1.10/0.60/43	1.10	43.27	32.15		--	84	2.24	0.34	Diagonal-splitting
VI-2/1.10/0.60/48	1.10	47.55	36.67		--	88	2.34	0.34	Diagonal-splitting

4.3 Ultimate strength

Shear capacity is defined as the maximum shear force that a critical section can sustain. It is widely accepted that a main contributor to shear resistance in concrete is aggregate interlock. The use of web reinforcement to carry shear force is necessary when the concrete portion alone is unable to sustain the force. The presence of sufficient web reinforcement can help to prevent the brittle failure in a transfer beam. The ultimate strengths (V_n^{TEST}) of different beam specimens are given in Table 3.

4.4 General behavior

The general behavior of all the specimens was quite similar. First, the fine flexural cracks were initiated in the pure bending region and with further increase of load, new flexural-shear cracks formed in the shear spans and subsequently, curved toward the loading points. Failure in these specimens was always sudden with loud sound at failure and in diagonal tension, shortly after diagonal shear cracks appeared.

4.5 Modes of failure

The failure modes of the specimens are indicated in the Table 3. Four failure modes are identified, i.e., diagonal splitting (shear) failure, shear-flexure failure, flexure and shear-compression failure. The diagonal-splitting failure, characterized as shear failure, is brittle, sudden and hence treacherous. A critical diagonal crack joining the loading point at the top and support point at bottom is developed. In the shear-compression mode of failure, after the appearance of the inclined crack, the concrete portion between the top load point experiences high compression and it then finally fails. This mode of failure is equally a brittle mode of failure. The shear-flexure mode of failure is the combined failure in shear and flexure. Flexural cracks are formed followed by the partly diagonal crack. This is ductile mode of failure in which the beam deflects at the centre and no explosive sound was heard at the time of failure.

4.6 Effect of percent longitudinal (tension) steel and percent horizontal web steel

Table 3 presents the measured the ultimate strength (failure load) of the transfer beams. The shear strength was observed to be increased with the increase in the percent longitudinal tension steel provided at the bottom of beams (Series-I specimens). However, a significant increase in the shear capacity was observed by longitudinal steel provided from the bottom of the beam up to 50% of total depth of beam in the web of the beam (Series-I specimens) but beyond 1.80% this increase is nominal. This fact is primarily because of longitudinal steel affects the amount of longitudinal strain and thereby affects crack width, interface shear transfer, dowel action, and thereby the shear strength. A flexure, flexure-shear, shear and diagonal splitting modes of failure are observed in this series specimens.

4.7 Effect of percent transverse steel ratio

The failure shear strength and modes of failure of beam specimens are indicated in Table 3. The addition of transverse steel improves the shear response of the transfer beams by increasing the failure shear strength and a higher ductile response in comparisons with Series-I & II specimens. A significant increase in the shear capacity was observed up to 1.25% transverse steel. Beyond 1.25 percent, the increase in shear capacity was not significant for this range of beam specimens and failure occurs in concrete compression zone, between the two-load points.

4.8 Effect of percent horizontal distributed steel

In the Series IV beam specimens, a constant percentage of horizontal steel (2.40%) distributed across the depth of beam and varying percentage vertical (transverse) steel (ρ_v = 0.50% to 2.25%). The beam specimen were cast and tested with view to see the influence of horizontal steel provided in the whole depth of the beam along with varying percentage vertical (transverse) steel. The placement of horizontal steel in the whole body of the beam, improves the shear response of the transfer beams by increasing the failure shear strength significantly and a higher ductile response in comparisons with Series-III specimens. An initially diagonal splitting mode of failure has been transformed in to flexure-compression mode of failure with increase in the percentage of transverse steel.

4.9 Effect of shear span-to-depth (a/d) ratio

The shear strength of concrete beams for different depths at 28 days curing age is given in Table 3. Fig. 11 shows the effect of shear span-to-depth ratio (or moment-shear ratio) on nominal shear stress at diagonal cracking, which is obtained by dividing measured failure load to the nominal cross sectional area ($b \times d$). As the shear span-to-depth (a/d) ratio decreases, the shear strength increases. The increase in shear strength is significant in RC beam specimens with a/d ratio less than about 1.78, because of a significant portion of the shear is transmitted directly to the support by an inclined strut. This mechanism is frequently referred to as arch action and the magnitude of the direct load transfer increases with decreasing a/d-ratio. The shear strength of RC beams with a/d-ratio less than 1.78 is higher than those of the RC beams with a/d-ratio more than 1.78. This result is due to the beneficial effect of direct load transfer to the support by arch action or so called strut-and-tie load transfer mechanism. The transition point between the arch action and beam action (or transfer beams and normal beams) lies between a/d-ratio of 1.45 to 1.78. Either side of this a/d ratio, behavior of RC beams, in terms of load resisting mechanism, failure pattern and the noise at failure, were entirely different.

4.10 Effect of cube compressive strength of concrete

The beam specimens of Series VI, were cast and tested to see the effect of cube compressive strength of concrete on shear strength of transfer beams. The specimens of this series are without any transverse steel and a constant percentage of longitudinal steel is provided. A small increase in the shear strength has been observed with increase in the cube compressive strength of concrete. As transverse steel is not provided in the beam specimens, failure is in diagonal-splitting with loud noise at failure with increase in the cube compressive strength of concrete.

4.11 The shear design models and proposed shear strength expression

Four design methods, namely, the ACI Code 318-05, the UK's CIRIA Guide-2, the BS Code: 8110-1997 and the IS Code: 456-2000 are used to estimate the ultimate shear strength of the specimens.

4.11.1 ACI 318-2005 design model

The shear provisions apply to both simple and continuous beams when the span to depth ratio *L/D* is less than 5. The calculations are carried out for the critical section, which is defined as follows. For concentrated load, the critical section is located midway between the load and the face of the support; for a uniformly distributed load it is at 0.15l from the support where l is the clear span. The ACI code assumes that V_c is equal to the shear strength of a beam without stirrups, which in turn, is taken equal to the load at which inclined cracking occurs, is calculated as:

The shear strength of deep beam is divided into two parts:

1. The concrete contribution (V_c) and
2. The contribution of steel (V_s)

The concrete contribution to the shear strength can be computed by Eq. (1),

In S.I. system (N, mm system)

$$V_c = \left(3.5 - 2.5\frac{M_u}{V_u d}\right)\left(0.16\sqrt{f_c'} + 17\rho_w \frac{V_u d}{M_u}\right) b_w d$$

$$\le 0.5\sqrt{f_c'}\, b_w d$$

where

$$3.5 - 2.5\frac{M_u}{V_u d} \le 2.5 \tag{1}$$

where M_u and V_u are the ultimate moment and shear at the section under consideration. f_c' is the concrete strength in MPa, ρ_w is the longitudinal reinforcement ratio ($A_S/b_w d$). And A_s is the area of longitudinal reinforcement.

The contribution of the orthogonal web reinforcement to the shear strength can be computed as by Eq. (2)

$$V_s = \frac{A_v}{S_v}\left[\frac{1 + \frac{l_n}{d}}{12}\right] + \frac{A_h}{S_h}\left[\frac{11 - \frac{l_n}{d}}{12}\right] = \frac{(\nu_v - \nu_c)}{f_y} \cdot b \tag{2}$$

f_y the strength of the web steel and should not be more than the 410 MPa

A_v = the area of vertical web reinforcement within a distance S_v in inch^2

A_h = the area of horizontal web reinforcement within a distance S_h, in inch^2

4.11.2 CIRIA Guide - 2 - "Supplementary Rules" design model

The CIRIA Guide- 2 method is applicable for the range of $0.5 \le x_e/h \le 01.25$.

In this Eqs. (3) and (4), the ultimate shear strength of deep beam is made up of two parts: the contribution of the concrete and the contribution of the web reinforcement as

$$V_n = V_n + V_s \tag{3}$$

$$V_n = \lambda_{11}\left(1 - 0.35\frac{x_e}{h_a}\right)\sqrt{f_{cu}}bh_a + \lambda_2\sum_n \frac{100A_iy_i\sin^2 a_i}{h_a} \tag{4}$$

Where
$\lambda_1 = (0.75 \times 0.52 \times C_1) / \gamma_{mc} = 0.44$ for normal weight aggregates
$= (0.75 \times 0.52 \times C_1) / \gamma_{mc} = 0.32$ for lightweight aggregates
$\lambda_2 = [(0.75 \times 0.52 \times C_2) / \gamma_{ms}]/100 = 1.95$ MPa for deformed bars
$= [(0.75 \times 0.52 \times C_2) / \gamma_{ms}]/100 = 0.85$ MPa for plain round bars
C_1 = empirical coefficient for concrete = 1.40 for normal weight concrete.
C_2 = empirical coefficient for deformed bars = 415 MPa.
γ_{mc} & γ_{ms} material safety factor for concrete & steel, respectively

In the expression of empirical coefficients for λ_1 and λ_2, CIRIA used a statistical factor of 0.75 just to convert the mean test values to characteristic values consistent with British design codes; and a factor of 0.52 to convert the cylinder splitting strength f_t to $\sqrt{f_{cu}}$. The material partial safety factors for concrete and steel (γ_{mc} & γ_{ms}) were given the standard values of 1.25 and 1.15, respectively.

4.11.3 Indian Standard: IS456: 2000

The magnitude of the design shear strength τ_c depends on various factors that are related to the grade of concrete (f_{ck}) and the percentage tension steel $p_t = 100A_{st}/(bd)$. The value given in Code (Table 19) are based on the following empirical formula given by Eq. (5)

$$\tau_c = \frac{0.85\sqrt{(0.85f_{ck})}}{6\beta}(\sqrt{(1+5\beta)}-1) \tag{5}$$

Where,
$\beta = (0.8f_{ck})/(6.89p_t)$ or 1 whichever is greater.

4.11.4 British Standard: BS 8110-1997

The value of the design shear strength of concrete given in code (Eq. (6)) is based on the empirical formula

$$v_c = \left[\frac{0.79}{\gamma_m}\left(\frac{100A_s}{b_vd}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4}\left(\frac{f_{cu}}{25}\right)^{1/3}\right] \tag{6}$$

$K = (400/d)^{1/4}$ = size effect factors and should not be less than unity and pt% should not be grater than 3.0. This formula gives values of v_c for concrete grade 25. For higher grades of concrete, values should be multiplied by $(f_{cu}/25)^{1/3}$. The value of f_{cu} should not be greater than 40.

4.11.5 Authors' proposed empirical expression for transfer beams

The Proposed Four-term formula (Eq. (7)) for shear capacity of Transfer Beam is as follows:

$$V = V_c + V_{ms} + V_{wh} + V_{wv}$$

Where

$$V_c = \alpha_1\left[\left(1-0.30\frac{a}{d}\right)\sqrt{0.80f_{ck}}bd\right] \qquad V_{ms} = \alpha_2\left(\frac{100A_s d\sin^2\theta_i}{D}\right) \tag{7a}$$

$$V_{wh} = \alpha_2\left(\sum_{i=1}^{n}\frac{100A_{iwh}y_i\sin^2\theta_i}{D}\right) \qquad V_{wv} = \alpha_2\left(\sum_{i=1}^{n}\frac{100A_{iwv}y_i\sin^2\theta_i}{D}\right) \tag{7b}$$

$$\alpha_1 = \left(\frac{0.75\times 0.50\times C_1}{\gamma_{mc}}\right) \qquad \alpha_2 = \left[\frac{0.75\times C_2}{\gamma_{ms}}\right]\frac{1}{100} \tag{7c}$$

where,

V = Total shear capacity

V_c = The concrete contribution to shear strength

V_{ms} = The contribution of the main longitudinal tension steel to shear strength.

V_{wh} = The contribution of the horizontal web steel

V_{wv} = The contribution of the vertical web steel

A_s = Area of main steel

a = Shear span

f_{ck} = Characteristics compressive strength of concrete

b and d = width and effective depth of beam

θ_i = Angle of reinforcement with notional splitting line

y_i = Distance from top as shown in Fig. 5

α_1 & α_2 = empirical coefficient for concrete and reinforcing steel bars respectively

C_1 = empirical coefficient for concrete = 1.40 for normal weight concrete.

C_2 = empirical coefficient for deformed bars = 415 MPa.

γ_{mc} & γ_{ms} material safety factor for concrete & steel, respectively

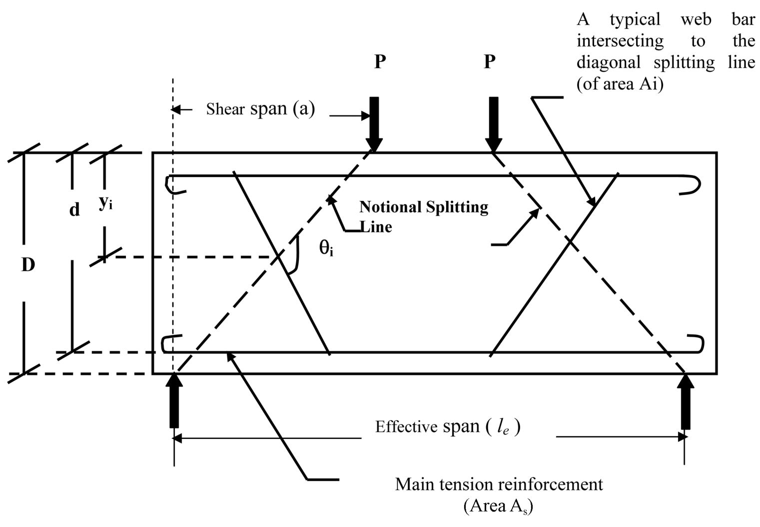


Fig. 5 The meaning of the symbols in the proposed formula

4.12 Comparison of test results with proposed equation and shear design equations

Four design methods, namely, the ACI Code, the CIRIA Guide Code, the BS8110 Code and IS 456 Code are used to estimate the ultimate shear capacity. The Tables 4 to 8 and Figs. 6 to 10 compares effect of various influencing parameters on shear strength.

Table 4 Shear strength of RC transfer beams without transverse steel: effect longitudinal (tension) steel (%)

Test Beam Designation	Shear strength (kN)						Shear strength ratio				
	V_{ACI}	V_{CIRIA}	V_{BS}	V_{IS}	V_{TEST}	$V_{EQ.}$ Eq. (7)	V_{TEST}/ V_{ACI}	V_{TEST}/ V_{CIRIA}	V_{TEST}/ V_{BS}	V_{TEST}/ V_{IS}	V_{TEST}/ V_{EQ}
I-1/1.10//43/0.28	84	81	34	28	60	68	0.71	0.74	1.76	2.14	0.88
I-2/1.10//43/0.42	87	86	39	33	75	75	0.86	0.87	1.92	2.27	1.00
I-3/1.10/43/0.60	92	94	44	38	90	83	0.78	0.75	1.61	1.82	1.10

Table 5 Shear strength of RC transfer beams without transverse steel: effect of horizontal web steel (%)

Test Beam Designation	Shear strength (kN)						Shear strength ratio				
	V_{ACI}	V_{CIRIA}	V_{BS}	V_{IS}	V_{TEST}	$V_{EQ.}$ Eq. (7)	V_{TEST}/ V_{ACI}	V_{TEST}/ V_{CIRIA}	V_{TEST}/ V_{BS}	V_{TEST}/ V_{IS}	V_{TEST}/ V_{EQ}
II-1/1.10//43/0.60	92	94	44	38	90	83	0.98	0.96	2.00	2.37	1.10
II-2/1.10/43/1.20	110	110	55	51	140	106	1.27	1.27	2.55	2.75	1.32
II-3/110/43/1.80	110	125	64	59	165	124	1.50	1.32	2.58	2.80	1.33
II-4/1.10/43/2.40	110	137	70	65	185	138	1.68	1.35	2.64	2.85	1.34

Table 6 Shear strength of RC transfer beams with transverse steel: effect of vertical web steel (%)

Test Beam Designation	Shear strength (kN)				Shear strength ratio		
	V_{ACI}	V_{CIRIA}	$V_{EQ.}$ Eq. (7)	V_{TEST}	V_{TEST}/ V_{ACI}	V_{TEST}/ V_{CIRIA}	V_{TEST}/ $V_{EQ.}$7
III-2/1.10/43/0.60/0.50	140	105	74	105	0.79	1.00	1.42
III-3/1.10/43/0.60/0.75	140	110	81	125	1.10	1.14	1.54
III-4/1.10/43/0.60/1.25	140	116	90	150	1.14	1.30	1.67
III-5/1.10/43/0.60/2.25	140	118	95	160	1.18	1.36	1.68

Table 7 Shear strength of RC transfer beams without transverse steel: effect of shear span-to-depth ratio

Test Beam Designation	Shear strength (kN)						Shear strength ratio				
	V_{ACI}	V_{CIRIA}	V_{BS}	V_{IS}	V_{TEST}	$V_{EQ.}$ Eq. (7)	V_{TEST}/ V_{ACI}	V_{TEST}/ V_{CIRIA}	V_{TEST}/ V_{BS}	V_{TEST}/ V_{IS}	V_{TEST}/ V_{EQ}
V-1/43/0.80/1.10	92	94	44	38	90	83	0.98	0.96	2.00	2.36	1.10
V-2/43/0.80 /1.23	90	82	33	29	60	74	0.67	0.73	1.82	2.10	0.81
V-3/43/0.80 /1.45	88	72	24	21	40	64	0.44	0.56	1.67	1.90	0.63
V-4/43/0.80 /1.78	86	53	18	14	30	52	0.34	0.57	1.67	2.14	0.58

Table 8 Shear strength of RC transfer beams without transverse steel: effect of cube compressive strength of concrete

Test Beam Designation	Shear strength (kN)						Shear strength ratio				
	V_{ACI}	V_{CIRIA}	V_{BS}	V_{IS}	V_{TEST}	$V_{EQ.}$	V_{TEST}/V_{ACI}	V_{TEST}/V_{CIRIA}	V_{TEST}/V_{BS}	V_{TEST}/V_{IS}	V_{TEST}/V_{EQ}
VI-1/1.10/0.60/32	82	84	37	38	77	77	0.94	0.92	1.99	2.00	1.00
VI-2/1.10/0.60/37	87	89	41	38	82	80	0.94	0.92	2.02	2.18	1.02
VI-3/1.10/0.60/43	92	94	41	38	90	84	0.98	0.96	2.10	2.34	1.10
VI-2/1.10/0.60/48	97	98	41	38	98	88	1.01	1.00	2.25	2.55	1.11

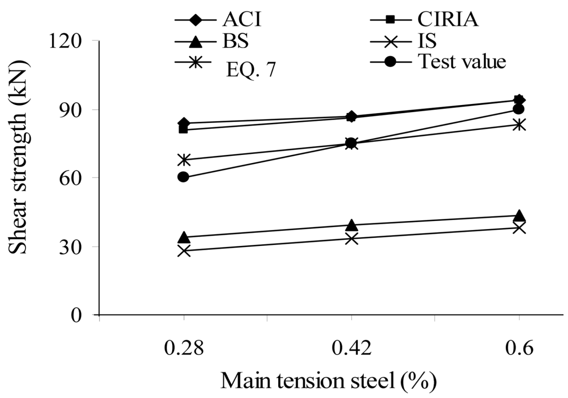


Fig. 6 Transfer beams without transverse steel: effect of main steel on shear strength

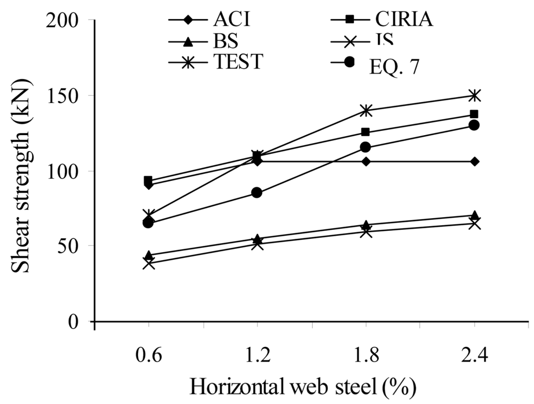


Fig. 7 Transfer beams without transverse steel: effect of horizontal web steel (%) on shear strength

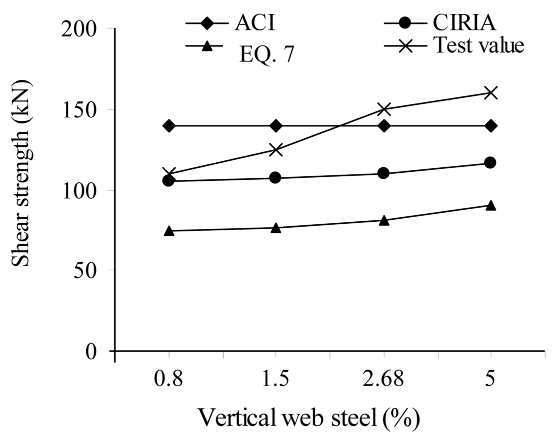


Fig. 8 Transfer beams with transverse steel: effect of vertical web steel (%) on shear strength

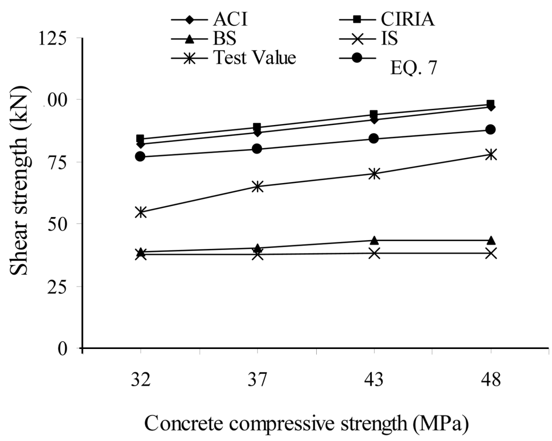
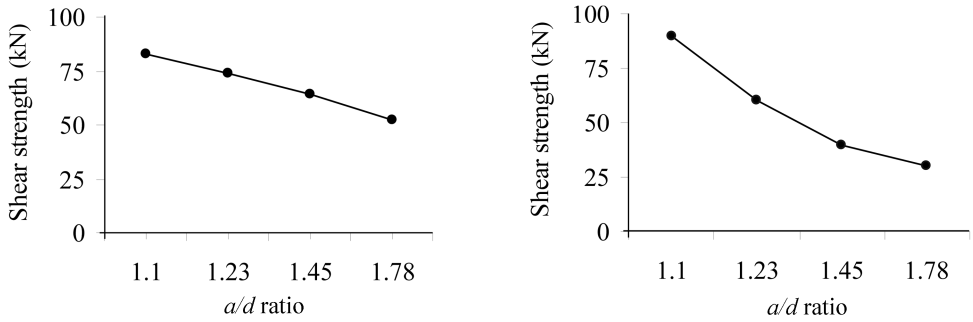


Fig. 9 Transfer beams without transverse steel: effect of compressive strength of concrete on shear strength



(a) Shear strength prediction by proposed expression

(b) Experimental shear strength

Fig. 10 Transfer beams without transverse steel: effect of shear span-to-depth ratio on shear strength predictions

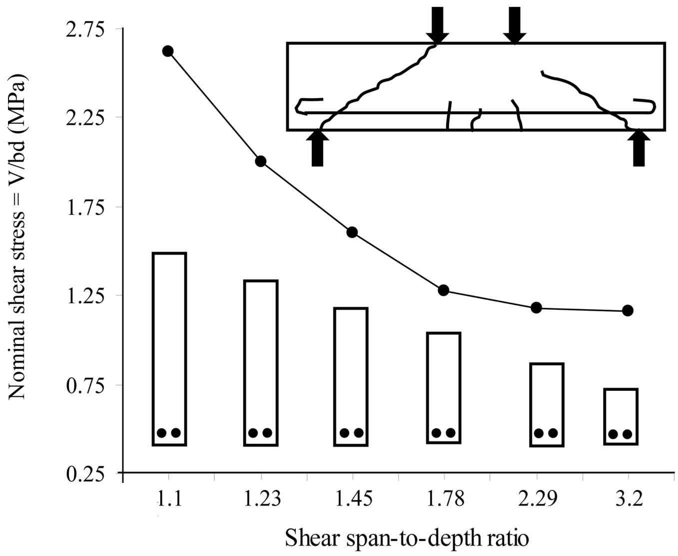


Fig. 11 The effect of shear span-to-depth ratio (or moment-shear ratio) on nominal shear stress

5. Conclusions

Based on the experimental and analytical studies on transfer (deep) beam in high-rise building, The addition of longitudinal beyond 1.80% and transverse steel beyond 1.25% improves the shear response of the transfer beams by increasing the failure shear strength and a higher ductile response, represents a practical upper limit in maximizing the longitudinal steel to augment the shear strength. Moreover, a significant increase in the shear capacity is observed by providing orthogonal web reinforcement and a desired mode of ductile failure can be achieved through orthogonal web reinforcement. It is evident that the shear span-to-depth (*a*/*d*-ratio) ratio is a significant influencing parameter of the shear strength. For shear span-to-depth (*a*/*d*-ratio) ratio < 1.8, the load transfer mechanism of beams is observed to be altogether different primarily because of the tied arch action/

truss action, than the shear span-to-depth (*a/d*-ratio) ratio > 1.8. Thus *a/d*-ratio of 1.8 is a differentiating line between the normal and transfer (deep) beams.

Based on the study of different design codes of deep beams (Transfer beams), it is concluded that that no design code has given complete guidelines for the design of the Transfer beam except ACI Code. The CIRIA Guide-2 gives some useful guidelines for design procedures but warns that there is no experimental evidence to substantiate these procedures. The suitability of the proposed empirical expressions was studied by comparing the shear strength predictions from test data and four design methods viz. ACI, CIRIA Guide-2, BS Code and IS Code through parametric studies and it shows vary good agreements among the other design methods considered for all percentage of tension reinforcement, all grades of concrete and three *a/d* ratios, indicating the consistency of the proposed expressions.

References

American Concrete Institute Committee (2005), "Building code requirements for structural concrete (ACI 318-05) and commentary (ACI 318R-05)", *American Concrete Committee*, Detroit, Michigan, USA.

Ahmad, S. and Shaha, A. (2009), "Evaluation of shear strength of high strength concrete corbels using strut and tie model", *Arab. J. Sci. Eng.*, **34**(1), 27-35.

Ashor, A. and Yang, K.H. (2008), "Application of plasticity theory to reinforced concrete deep beams: a review", *Mag. Concrete Res.,* **60**, Special Issue, 657-664.

Bakir, P.G. and Boduroglu, M.H. (2002), "A design equation for predicting the shear strength of short beams", *Proceedings of the Sixth Conference on Computational Structures Technology*, Edinburgh, UK.

BS 8110 (1997), "Structural use of concrete-part 1: code of practice for design and construction", *British Standard Institution*, Milton Keynes, London.

Construction Industry Research and Information Association, CIRIA Guide 2 (1977), "The design of deep beams in reinforced concrete", Ove Arup and Partners and CIRIA, London.

European Committee for Standardization, EN1992-1-1:2004 NO002 (2002), "Design of concrete structures, Part 1: General rules and regulations for buildings", *English Edition, British Standards Institution,* London.

Foster, S.J. and Gilbert, R.I. (1998), "Experimental studies on high-strength concrete deep beams", *ACI Struct. J.*, **95**(4), 383-391.

Hwang, S.J., Lu, W.Y. and Lee, H.J. (2000), "Shear strength prediction for deep beams", *ACI Struct. J.*, **97**(3), 367-377.

IS 456 (2000), "Indian standard code of practice for plain and reinforced concrete for general building construction", *Bureau of Indian Standards*, New Delhi, India.

Kong, F.K. (1990), *Reinforced Concrete Deep Beams*, Van Nostrand Reinhold, New York.

Leong, C.L. and Tan, K.H. (2003), "Proposed revision on CIRIA design equation for normal and high strength concrete deep beams", *Mag. Concrete Res.*, **55**(3), 267-278.

Ley, T.M., Riding, K.A., Widianto, Bae, S.J. and Breen, J.E. (2007), "Experimental verification of strut-and-tie model design method", *ACI Struct. J.,* **104**(6), 749-755.

Londhe, R.S. (2007), "Experimental studies in transfer Beams for high-rise buildings", *Thesis Submitted to Roorkee for Ph.D.*, Dept. of Civil Engineering, Indian Institute of Technology, Roorkee, India.

Oh, J.K. and Shin, S.W. (2001), "Shear strength of reinforced concrete deep beams", *Struct. J.*, **98**(2), 164-173.

Pendyala, R.S. and Mendis, P. (2000), "Experimental study on shear strength of high-strength concrete beams", *ACI Struct. J.*, **97**(4), 564-571.

Russo, G., Somma, G. and Angeli, P. (2004), "Design shear strength formula for high-strength concrete beams", *Mater. Struct.*, **37**, 680-688.

Russo, G., Somma, G. and Mitri, D. (2005), "Shear strength analysis and prediction for reinforced concrete beams without stirrups", *J. Struct. Eng.,* **131**(1), 66-74.

Tan, K.H. and Cheng, G.H. (2006), "Size effect on shear strength of deep beams: Investigation with strut-and-tie

model", *J. Struct. Eng.,* **132**(5), 673-685.
Tan, K.H., Cheng, G.H. and Zhang, N. (2008), "Experiment to mitigate size effect on deep beams", *Mag. Concrete Res.,* **60**(10), 709-723.
Vecchio, F.J., Collins, M. and Aspoitis, J. (1994), "High strength concrete elements subjected to shear", *ACI Struct. J.*, **91**(4), 423-433.
Yang, K.H., Chung, H.S. and Eun, H.C. (2003), "Shear characteristics of high-strength concrete deep beams without shear reinforcements", *Eng. Struct.*, **25**(10), 1343-1352.
Yang, K.H., Chung, S.H. and Ashour, A.F. (2007), "Influence of section depth on the structural behaviour of reinforced concrete continuous deep beams", *Mag. Concrete Res.,* **59**(8), 575-586.
Yang, K.H. and Ashor, A.F. (2008), "Code modeling of reinforced concrete deep beams", *Mag. Concrete Res.,* **60**(6), 441-454.
Zarris, P.D. (2005), "Discussion of shear compression failure in reinforced concrete deep beams", *J. Struct. Eng.*, **131**(6), 988-991.
Zhang, N. and Tan, K.H. (2007), "Size effect in RC deep beams: Experimental investigation and STEM verification", *Eng. Struct.*, **29**(12), 3241-3254.

Notaions

a	: shear span
a_v	: distance of a section from support
$A_i = a_i$	: area of a typical transverse bar intersecting to a notional splitting line
A_s	: area of a main longitudinal tension steel intersecting to a notional splitting line
A_v	: area of a vertical steel
A_{iwh} and A_{iwv}	: area of horizontal and vertical web steel respectively cutting to notional splitting line as shown in Fig. 5
b	: width of beam (mm)
b_w	: width of web of beam (mm)
d	: effective depth of beam (mm)
C_1	: empirical coefficient for concrete = 1.40 for normal weight concrete
C_2	: empirical coefficient for deformed bars = 415 MPa
D	: overall depth of beam
h	: overall depth of beam
h_a	: active height of beam
f_{ck}	: characteristics compressive strength of concrete
f_{cu}	: concrete cube compressive strength
f_c'	: concrete cylinder compressive strength
f_{cu}	: concrete cube compressive strength
f_y	: yield strength of reinforcement
l_n	: clear span measured face-to-face of supports
M_u	: factored bending moment
p_t	: longitudinal tension steel (%)
τ_c	: shear strength of concrete MPa
s_h	: spacing of horizontal web reinforcement
s_v	: spacing of vertical web reinforcement
V	: total shear capacity
$V_c = V_n$	: calculated nominal shear strength of concrete
V_{ms}	: the contribution of the main longitudinal tension steel to shear strength.
V_s	: the contribution of the vertical web steel
V_u	: factored shear force
V_{wh}	: the contribution of the horizontal web steel
V_{wv}	: the contribution of the vertical web steel

$Y_i = y_i$	: distance from top as shown in Fig. 5
x_e	: clear shear span measured from inside edge of bearing block at support to outside edge of bearing block at loading point
θi	: angle of reinforcement with notional splitting line
α_1 & α_2	: empirical coefficient for concrete and reinforcing steel bars respectively
γ_{mc} & γ_{ms}	: material safety factor for concrete & steel, respectively, 1.50 and 1.15
λ_m	: material factor of safety of concrete
υ_c	: shear strength of concrete MPa
υ_v	: nominal shear strength of concrete MPa
λ_1 and λ_2	: empirical coefficient for concrete and steel
ρ_l	: longitudinal (main) steel percentage ($100A_s/(bd)$)
ρ_v	: vertical steel ratio ($A_v/(bs_v)$)