



(b) A1_FEM, (c) B1_Exp, (d) B1_FEM, (e) Damage in tension

5. Parametric study on shear provisions of Deep Beams

5.1 Response 2000

Response-2000 is a windows-based computer program designed to predict the load-deformation response of reinforced concrete sections subjected to bending moments, axial loads and shear forces. The analytical procedures in Response-2000 are based on traditional engineering beam theory, which assumes that plane sections remain plane and that the distribution of shear stresses across the section is defined by the rate of change of flexural stresses. When relating stresses and strains at various locations across the section, the program uses the Modified Compression Field Theory (MCFT). MCFT uses the modified constitutive relationships when compared to Compression Field Theory (CFT). The MCFT also considers the contribution of concrete in tension. The presence of principal tensile strain in the concrete decreases the principal compressive strength of concrete. MCFT has been successfully used in the past to predict the response of RC beams under shear dominant loading.

5.2 Parametric study

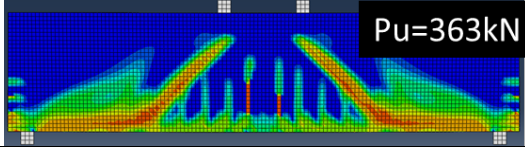
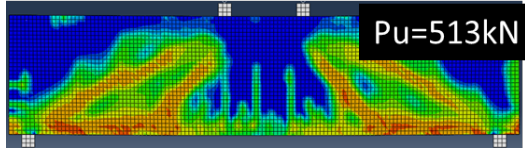
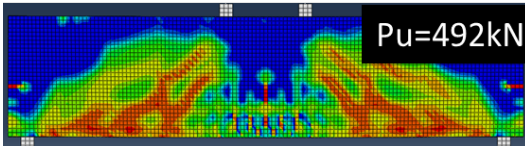
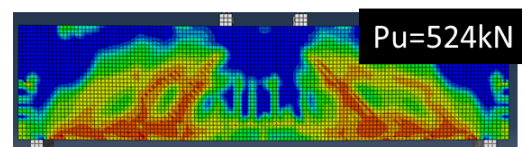
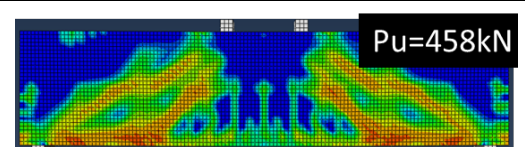
The parametric study is conducted by developing FE models of six deep beams. All developed FE models have a clear span (l_c) of 1829 mm, a depth (d) of 457 mm and a width of 203 mm. The effective depth of the modelled beams is 379 mm. The primary variable considered in the parametric study is the minimum web reinforcement and its arrangement. The deep beams with different amounts of web reinforcements as per ACI 318, AASHTO LRFD and EN 1992-1-1 are designed using STM and compared the behaviour with the FE results. The specimens were identified as DB-0.25V-0.25H, where the DB represents the deep beams, 0.25V represents the 0.25% of vertical shear reinforcement, and 0.25H represents the 0.25% horizontal shear reinforcement.

For deep beams under point loads, shear capacity can be calculated by taking the vertical component of the diagonal strut capacity, if no ties in the member have failed. Strut capacity depends upon the effective compressive strength of concrete in the strut region. The transverse tension developed in the strut region reduces the compressive strength of concrete, and this effect is considered by using a reduction coefficient. To determine the reduction coefficient, ACI 318-19 considers the effective transverse reinforcement in the strut region. Similarly, AASHTO LRFD considers the strain in the strut in the direction of tie and EN1992-1-1 considers the resistance to the total bursting force in the strut region. Detailed formulations to calculate the strut capacity and shear capacity as per ACI, AASHTO and EN1992-1-1 are summarised in Table 4 below.

Table 3. Parametric study specimen details

Specimen ID	Web reinforcement	Code
DB-0V-0V	No Web reinforcement	ACI 318-19
DB-0.25V-0.25H	0.25% orthogonal mesh in both the directions	ACI 318-19
DB-0.25V-0H	0.25% only vertical direction $0.0025/\sin^2(90-\theta)$	ACI 318-19
DB-0.3V-0.3H	0.3% orthogonal mesh	AASHTO LRFD
DB-0.2V-0.2H	0.2% orthogonal mesh	EN 1992-1-1



Reinforcement pattern	Failure Mode
No Shear Reinforcement	 Pu=363kN
ACI 318-19 (Only vertical web reinforcement)	 Pu=513kN
ACI 318-19 (Orthogonal web reinforcement)	 Pu=492kN
AASHTO-LRFD (Orthogonal web reinforcement)	 Pu=524kN
EN-1992-1-1 (Orthogonal web reinforcement)	 Pu=458kN
Figure 10. Failure modes of shear reinforced concrete deep beams	

Provision of minimum reinforcement in both horizontal and vertical directions as per ACI provisions results in higher capacity and ductile mode of failure. Due to the inclusion of shear reinforcement in both horizontal and vertical directions (B1_AC_HV_198c/c), the peak load improved by 35.5% compared to control beams (B1_No stirrups). Similarly, according to BS EN1992-1-1 code provisions, the beams were modelled using minimum shear reinforcement (EN1992-1_HV_247c/c) at 0.2% in orthogonal directions. These simulated results show that the improvement in peak load is 27.3% to that of the control beam. The minimum reinforcement provided in AASHTO provides better results in both load-carrying capacity and ductile failure mode from the detailed observations. However, according to ACI 318-19 provisions, the effective transverse reinforcement of 0.25% (170 c/c spacing) resulted in better capacity than the orthogonal mesh of 0.25%. It could be due to the reduced spacing of shear reinforcement for the same effective transverse reinforcement. From the AASHTO-LRFD and ACI 318-19 provisions, the reinforcement in orthogonal directions provides better performance in load-carrying capacity and ductility. The load deformation behaviour of beams with minimum reinforcement as per different codes is presented in Figure 11. Similarly, the failure mode of beams with different minimum reinforcement is compared in **Error! Reference source not found.**

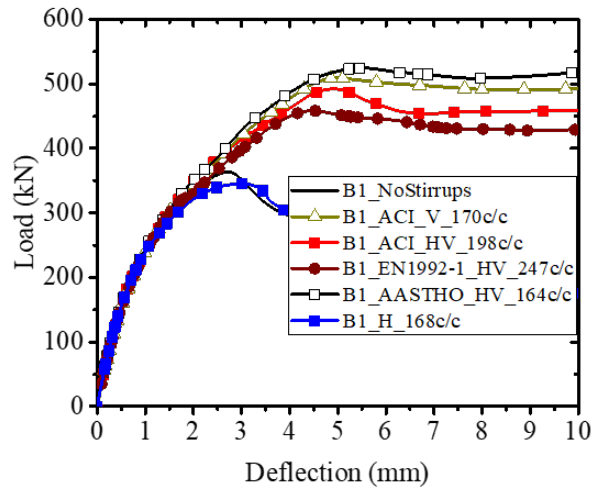


Figure 11. Load-deflection behaviour of shear reinforced concrete deep beam

Table 4. Summary of results from parametric study

Specimen ID	FE Model	ACI-318-19	BS EN-1992-1-1	AASHTO-LRFD
DB-0V-0V	363.5	211.8	309	-
DB-0.25V-0.25H	492.4	397.1	515	-
DB-0.25V-0H	512.7	397.1	515	-
DB-03V-0.3H	524.6	397.1	515	530
DB-0.2V-0.2H	458.3	211.8	515	-

Table 5. Code provisions on the shear capacity of deep beams

	Equations
ACI 318-19[5]	$V_n = f_{ce} \sin \theta_s b_w w_s$ where $f_{ce} = 0.85 \beta_s f'_c$ $w_s = \text{minimum of } (w_t \cos \theta_s + w_b \sin \theta_s), (h_c \cos \theta_s + w_b \sin \theta_s)$ $\beta_s = 0.75$ for bottle-shaped struts with minimum reinforcement $\beta_s = 0.4$ for bottle-shaped struts without minimum reinforcement <u>Minimum distributed reinforcement</u> 0.25% in each direction – orthogonal grid $\frac{0.0025}{\sin^2 \theta}$ - Reinforcement in one direction crossing strut at angle θ
AASHTO LRFD[6]	$V_n = f_{cu} \sin \theta_s b_w w_s$ where $f_{cu} = \frac{f'_c}{(0.8 + 170 \varepsilon_1)} \leq 0.85 f'_c$



	$\varepsilon_1 = \varepsilon_s + \frac{(\varepsilon_s + 0.002)}{\tan^2 \theta_s}$ <p>α_s = the smallest angle between the compressive strut and adjoining tension ties (degrees)</p> <p>ε_s = the tensile strain in the concrete in the direction of the tension tie</p> $w_s = w_t \cos \theta_s + w_b \sin \theta_s$ <p><u>Minimum reinforcement</u> 0.3% in both directions as orthogonal grids</p>
BS EN1992-1-1[7]	$V_n = f_{ce} \sin \theta_s b_w w_s$ <p>where $f_{ce} = 0.6v' f_{cd}$ for unreinforced strut,</p> $v' = 1 - \frac{f_{ck}}{250}, f_{cd} = 0.85 \frac{f_{ck}}{1.5}$ <p>$f_{ce} = 1.0v' f_{cd}$ if reinforcement provided to resist bursting force T developed normal to strut axis</p> $T = F \left[\frac{1 - 0.7 \frac{a}{H}}{4} \right]$ <p>Where F = Force in the strut</p> $w_s = \text{minimum of } (w_t \cos \theta_s + w_b \sin \theta_s), (h_c \cos \theta_s + w_b \sin \theta_s)$ <p><u>Minimum reinforcement</u> 0.2% in both directions as orthogonal grids</p>

6. Summary and Conclusions

Finite element models of deep beams were created and validated with test results. The primary variable considered in the parametric study is the minimum web reinforcement and its arrangement. The deep beams with different amounts of web reinforcements as per ACI 318, AASHTO LRFD and EN 1992-1-1 are designed using STM and compared the behaviour with the FE results. The following conclusions can be drawn based on the parametric study,

1. The FE modelling approach used in this work closely predicted the load-deflection and failure modes of reinforced concrete deep beams.
2. The parametric study on the variation of shear reinforcement shows that the AASHTO-LRFD code is conservative than both the ACI-318-19 and EN-1991-1 in predicting the ultimate load.
3. The minimum shear reinforcement provisions based on the AASHTO-LRFD gives higher capacity than the ACI-318-19 and BS EN1991-1 provisions.

Acknowledgements

This research work was sponsored by “IMPRINT Scheme- Order # IMP/2018/000846” funded by the Ministry of Human Resource Development and Department of Science and Technology, Ministry of Tribal



Affairs India through Award No: 201920-NFST-TEL-01354 for supporting the research scholar. The authors would like to thank the funding agency for their generous support.

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