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DESIGN AND EVALUATION OF THE SHEAR STRENGTH OF DEEP BEAMS BY STRUT AND TIE MODEL (STM)*

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Abstract– Strut and Tie Model (STM) has been widely applied for the design of non flexural and deep members in reinforced concrete structures in the last few decades. Experimental research on STM is underway to further rationalize the method for the analysis and design of disturbed regions in reinforced concrete structures. In this research six deep beams with a shear span to depth ratio (a/d) of 0.64, 0.76 and 0.94 have been designed against the external assumed loads. The beams were later tested under monotonic two point loads and the actual shear strength of the deep beams was determined at the failure loads of the beams. The load carrying capacity of the deep beams was also calculated on the basis of the actual strengths of the compression struts and nodes with the help of guidelines given by ACI-318-06, for the use of STM. The observed failure loads were compared with the load carrying capacity of beams worked out from the strengths of the struts. The failure loads were also compared with the provisions of EC-02. It has been observed that both STM based on ACI 318-06 and EC-02 have given a reasonable prediction of the shear strength of deep beams.

Keywords– Strut and Tie Model, deep beams, shear span, shear strength

1. INTRODUCTION

Deep beams are structural elements loaded as beams, but having small shear span to depth ratios, typically less than 2. These have useful applications in many structures, such as tall buildings, foundations, bridges, offshore structures, and several others [1].

The traditional sectional design approaches based on "Linear Strain Variation" utilize a parallel chord truss model which is not applicable for the design of deep beams. Due to the small shear span-depth ratio of a deep beam, a large portion of the supported loads is directly transmitted to the supports. Therefore, the shear strength of deep beams is experimentally observed to be significantly greater than that of slender beams. For such beams, failure is generally caused by shear compression, in which the concrete between the supports and the point of application of load fail in compression. Strut-and-Tie modeling (STM) is a useful design tool when applied to structural elements, where plane sections do not remain planar after the application of load. These elements are sometimes referred to as disturbed region (D-region) in reinforced concrete structures. The behavior of such elements is not dominated by flexural deformations and hence the ordinary beam theory is not applicable to such structures. The typical disturbed regions in concrete include corbels (brackets), deep beams, dapped-end beams, pile caps, non prismatic members and post-tension anchorage zones [2].

Foster and Gilbert [3] tested 16 deep beams designed on the basis of the Sectional Design Model of ACI318-89 and the plastic truss model. The deep beams having concrete compressive strength in the range

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of 50 MPa (3250psi) to 120 MPa (17400psi) and shear span to depth ratio from 0.5 to 1.32 were tested under concentrated load at the mid span. The Finite Element Analysis (FEA) was also used for the analysis of deep beams and it was observed that the FEA model gave less conservative results by an average of 15%.

Foster and Malik [4] evaluated the validity of several proposed expressions to determine the efficiency factor for concrete struts. They evaluated the models proposed by Vecchio and Collins [5], Marti [6], Chen *et al* [7], Batchelor, George, and Campbell [8], Collins and Mitchell [9] and Foster and Gilbert [3] and showed that the inclination of the strut relative to the axis of the concrete member is the principal variable in determining strut efficiency. They further observed that the Modified Compression Field Theory (MCFT) of Vecchio and Collins [5] has given the best correlation when compared with the experimental data.

Matamoros and Wong [10] proposed a method for determining the capacity of a deep beam based on the strength of the struts. They tried to determine the efficiency node-strut interface for deep beams and developed a method by which the presence of horizontal and vertical reinforcement can be used with the help of STM.

Wight and Montesinos [11] provided step-wise details for the design of deep beams by Strut and Tie Model, using the basic design guidelines given by ACI318-02 Appendix-A.

Quintero *el al* [12] evaluated the strength factors given by ACI 318-02 Appendix-A on the basis of tests of 12 RC deep beams with the main design variables such as the strut angle, web reinforcement crossing the strut and concrete strength. They observed that the strut strength factors given by ACI318-02 are adequate for use in normal strength concrete bottle-shaped struts crossed by either no reinforcement or minimum web reinforcement.

The recent software based solutions incorporating STM allows a significant reduction in analysis time, allowing designers to evaluate different strut-and-tie models for the design of a structure [13].

Park and Kachma [14] developed a method for calculating the strength of deep beams on the basis of the Strut and Tie Model (STM). The proposed method considers constitutive laws for cracked reinforced concrete strain compatibility, and uses a secant stiffness formulation. In this method, the failure of deep beams due to crushing of the nodal compression zone at the top of the diagonal strut, yielding of the longitudinal reinforcement, as well as that of strut crushing or splitting was considered. It was observed that the calculated capacities by the proposed method were both accurate and conservative with little scatter or trends for deep beams with different concrete strengths including high-strength, various combinations of web reinforcements and the *a/d* ratio ranging from 0.35 to 2.34 [14] .

Zangha and Hai [15] proposed a Modified STM for determining shear strength of RC deep beams. The modified model for simply supported deep beams (SSDBs) was evaluated using 233 test results, which gave better agreement than the original model.

Wang and Meng [16] proposed a Modified Strut and Tie Model (MSTM) for simply supported pre-stressed RC beams. Based on the test results of 56 pre-stressed and post tensioned beams, they observed that MSTM based predictions are accurate, consistent and conservative.

Breña *et al* [17] concluded that the conservative nature of STM is well documented, but the existing margin of safety of the structure designed using STM is not currently known. The sources of the over strength of structures designed using strut-and-tie models have not been critically examined. Experimental testing is required to provide designers and researchers with tools to evaluate the models used for design. This information is necessary for future calibration of design parameters to achieve relatively uniform reliability of structures designed using strut-and-tie models.

The structures designed on the basis of STM can fail in a number of ways such as strut or compression, shear or diagonal failure, flexural failure, bearing failure and anchorage failure etc.

Arabzadeh [18] developed a simple method for the design of deep beams on the basis of truss analogy and applied it to the 18 simply supported deep beams. The proposed method was able to reliably predict the failure mode and load for the deep beams.

Later Arabzadeh *at al* [19] further improved this simple STM for the prediction of the ultimate shear strength of deep beams, and applied the proposed method to the results of a database of 324 beams. They reported that the proposed model more accurately predicted the shear strength of deep beams.

In this research, 6 RC deep beams in three sets of a/d values of 0.64, 0.78 and 0.94 were designed on the basis of STM for assumed applied loads and material stresses, which were later tested under two point loads to determine the shear strength of deep beams. The strength of the beams was then worked out on the basis of the strengths of the most critical compression struts and nodes for the STM, while using the equations given by ACI-318-06 [20]. The shear strength of the deep beams was also determined with the equation proposed by EC-02 [21].

The actual results were then compared with the theoretical strength capacities of the RC deep beams given by STM and EC-02. The failure modes of the beams were also observed.

2. MATERIAL AND TEST SETUP

Concrete in a nominal ratio of cement, sand and coarse aggregates as (1:1 ½ :3) was used to achieve the specified strength 34.5 MPa (5000 psi). The actual cylindrical compressive strength of concrete was, however, obtained as 37.25MPa (5400 psi). The longitudinal steel of a specified yield strength of 414 MPa (60,000 psi) and transverse steel of a specified strength of 275 MPa (40,000 psi) was used. The actual yield strength of the steel bars has been given in Table 1.

Table 1. Details of reinforcing bars used in the deep beams

Nominal sizes		Nominal areas		Average yield stress		Average ultimate stress		% elongation
US	Metric	In^2	mm^2	psi	MPa	psi	MPa	
#2	#6	0.05	32	45200	310	60312	416	12.39
#5	#16	0.310	200	67400	465	107500	741	13.64
#6	#19	0.44	248	68500	472	108400	748	12.89

Linear Variable Displacement Transducers (LVDT) were installed to measure the deflections of specimens at the mid span. To check the yielding of the main steel, protected linear strain gauges were tied to the steel bars at mid span. The beams were tested under symmetric two point loading, applied at the centre lines of the bearing plates. The loads were applied through the hydraulic system, transferring the load through a calibrated proving ring to the bearing plates. A schematic plan of the load application has been shown in Fig.1.

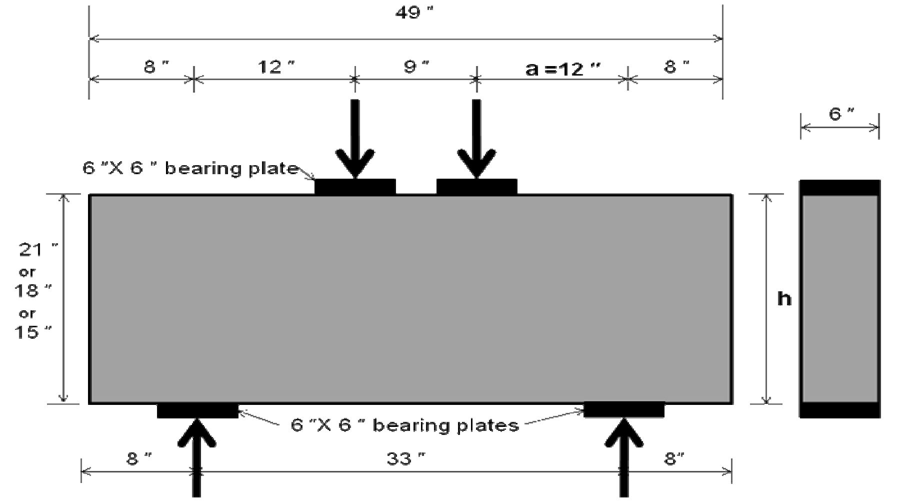
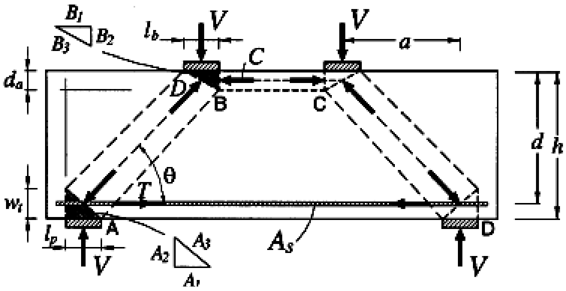


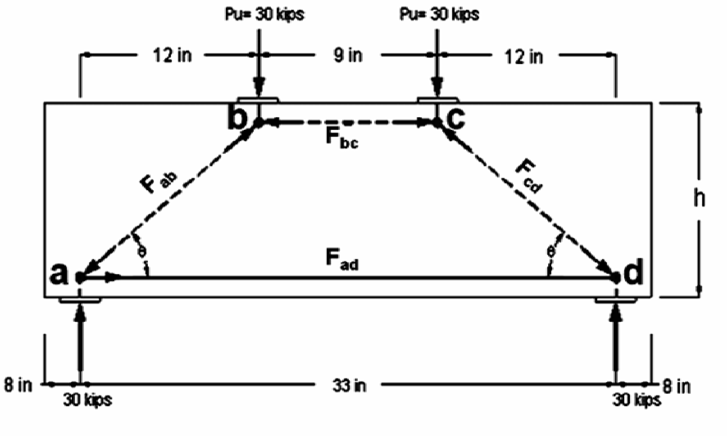
Fig. 1. Schematic diagram for application of loads at the deep beams

3. DESIGN OF DEEP BEAMS USING STRUT AND TIE MODEL

The beams were designed against an external total load of 266 kN (60Kips), applied at the deep beams in two equal loads symmetrically. There can be many possible truss models for the given loading and geometry of the deep beams. However, the assumed theoretical STM for the applied loads is shown in Fig. 2a, which has been based on the model proposed by Gaetano Russo *et al* [22]. The assumed truss under the applied loads has a trapezoidal shape as shown in Fig. 2b. In STM the nodes are dimensionless points where the compression struts and tie are assumed to intersect and must not be compared with the joints or pins of ordinary trusses. Hence the proposed STM for deep beams is an acceptable solution since the nodes are not true pins, and instability within the plane of the truss is not a concern in a Strut-and-Tie Model.



a) Strut and Tie Model for deep beams under given loading adapted from Ref. [22]



b) Assumed trapezoidal Strut and Tie model under applied load.

Fig. 2. Conceptual and actual Strut and Tie Model for the applied loads

The following steps were adopted for the design of deep beams as per guidelines of ACI318-06.

a) Checking Bearing Capacity at Loading and Support Location

The applied stress on the bearing plates must not exceed the value given by ACI-318 as follows;

b) Checking the truss geometry

To ensure that the proposed truss lies within the deep beam, as shown in Fig. 3. The strut and tie capacities are also checked.

c) Resolving the assumed truss to determine member forces

The member forces of truss for the external applied loads are given in Fig. 4. The compressive forces in the struts are carried by the concrete and the tensile forces in the ties shall be the tensile reinforcement.

For compressive forces, it is necessary to check the allowed maximum strength of the strut and the strength of the nodal zones, where member forces intersect.

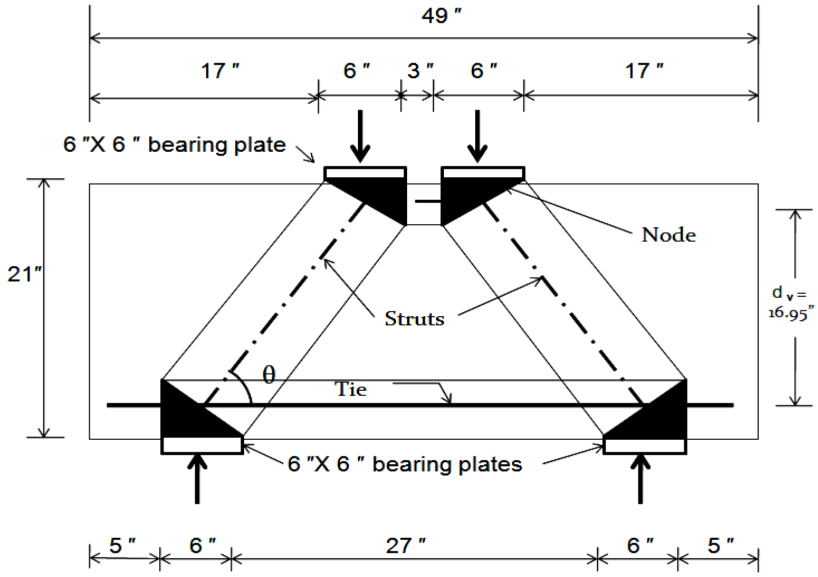


Fig. 3. Truss geometry of the assumed STM under applied load

d) Verifying the strut capacities

The horizontal strut is assumed of uniform cross section, whereas the diagonal struts are assumed as bottle shaped, because of the greater width available for later. The strut capacities were checked against the forces in the respective members.

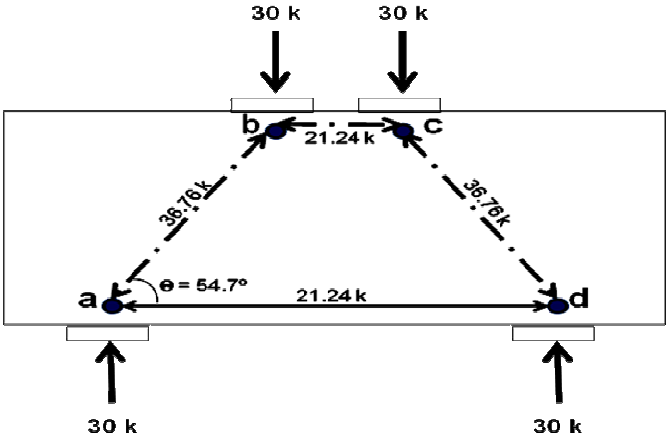


Fig. 4. Member forces in the assumed truss under applied loads

e) Checking the strength of nodal region

The nodal capacities of struts and ties are checked for both nodal points “a” and “b” against the member forces.

f) Design of ties and anchorage

The tensile forces resisted by the longitudinal steel and the corresponding area of steel is worked out as

$A_{st} = F_{tie} / (\Phi f_y)$, *where*

$A_{st;}$ *Area of longitudinal steel*

F_{tie}; Tensile force in ties.
Φ; Strength reduction factor taken as 0.7
f_y; Specified yield stress of longitudinal steel.

The minimum longitudinal steel as per ACI 318-05 Clause 10.5.1, must satisfy the following equation: $A_{st.\min} = \frac{3\sqrt{fc'}}{fy} b_w d.$

To check the anchorage of the tie, the following equation for developing the length must be satisfied.

$$l_{dh} = \frac{.02\beta\lambda fy}{\sqrt{fy}} \times d_b \geq 8d_b$$

According to ACI Code provision 12.5.4, closed stirrups along the full development length is required to prevent the bearing failure and bond failure. For vertical reinforcement the equation $\sum \frac{A_{si}}{b_{si}} \sin y_i > 0.003,$ must be satisfied. The details of the beam finally designed is shown in Fig. 5.

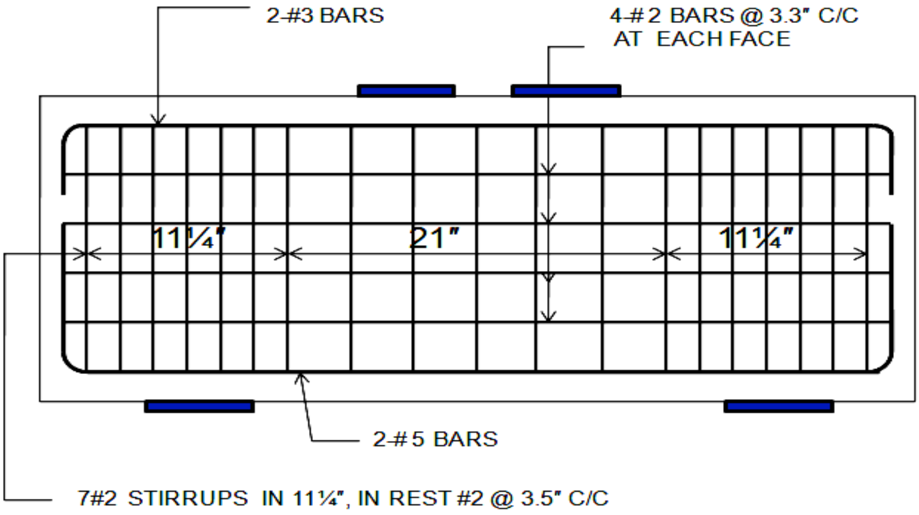


Fig. 5. Final details of beam designed on the basis of STM

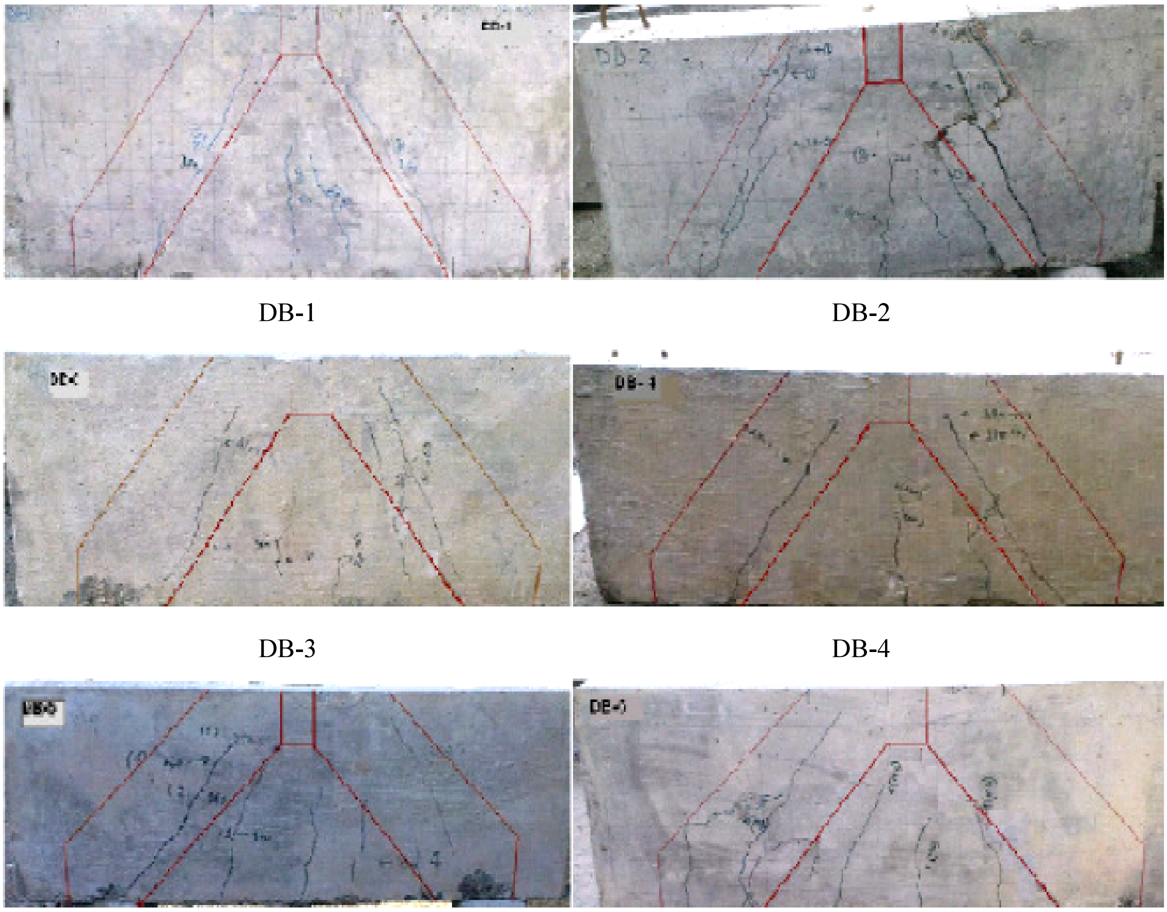
All three of the beams were designed for the assumed external loads and their final details are shown in Table 2.

4. TESTING OF SPECIMEN AND OBSERVATIONS

The beams designed on the basis of STM for the external assumed loads were tested under two point loads. Monotonic loads were gradually applied to the deep beams and the cracking pattern was closely observed. To record the strain at the mid span, the observation of LDVT was obtained through a data logging system. When loads were increased, vertical cracks appear in the beams at the mid span region and the support region. With further increase in the loads, the flexural cracks in the support region changed into diagonal cracks, extending towards the point of load application. This is sometimes called secondary crack as well. With further increase of loads, the diagonal cracks extended to the point of application of the concentrated loads and finally caused the failure of the beams. The shear strength of the beams is determined at the failure loads of the beams. The typical compression shear failure of the beam is shown in Fig. 6, where the failure plane along the diagonal compression is very clear. The theoretical and actual members forces of the asumed truss, loads at first flexural loads and first diagonal loads, as well as the final failure loads deep beams have been compared in Table 3.

Table 2. Details of deep beams, longitudinal and lateral reinforcement based on design by STM for external assumed load

Beam title (No.)	***h***(in.)	***fc'*** (psi)	Span (in.)	Shear Span **"a"**(in.)	**d** (in.)	Tension reinforcement		Web reinforcement		a/h	a/d
						A_{st} (in^2)	ρ (%)	longitudinal bars	transverse stirrups		
DB-1 and DB-2	21	5000	27	12	18.7	2 #5 (0.612)	0.49	# 2 @3.3″	# 2 @ 3.5″	0.57	0.64
DB-3 and DB-4	18	5000	27	12	15.75	2 #5 (0.612)	0.57	# 2 @2.7″	# 2 @ 3″	0.67	0.76
DB-5 and DB-6	15	5000	27	12	12.75	2 #6 (0.882)	0.98	# 2 @ 2.1″	# 2 @ 2.5″	0.8	0.94



DB-1 DB-2

DB-3 DB-4

DB-5 DB-6

Fig. 6. Typical shear compression failures of deep beams. (DB1 toDB6)

Table 3. Comparison of theoretical and actual cracking loads of deep beams based on STM

Beams title	a/d	Steel			Design loads (kips)	Load at 1st flexural crack $(V_u)_{FL}$ (kips)	Load at 1st Diagonal crack (V_{cr}) (kips)	Load at failure V_{ult}	Strut angle degrees		Failure mode
		Main	Web steel						STM based	Actual	
		ρ (%)	Skin	Shear							
DB-1 6inx21in	0.64	2 #5 0.49	# 2 @3.3″	# 2 @ 3.5″	30	49.1	61.17	101.1	57	60	Strut comp failure
DB-2 6inx21in	0.64	2 #5 0.49	# 2 @3.3″	# 2 @ 3.5″	30	59.1	71.40	104.6	55	61	Strut comp failure
DB-3 6inx18in	0.76	2 #5 0.57	# 2 @2.7″	# 2 @ 3″	30	44.6	68.87	97.60	49	56	Strut comp failure
DB-4 6inx18in	0.76	2 #5 0.57	# 2 @2.7″	# 2 @ 3″	30	51.3	69.07	101.6	49	58	Strut comp failure
DB-5 6inx12in	0.94	2 #6 0.98	# 2 @ 2.1″	# 2 @ 2.5″	30	49.10	64.60	99.60	42	50	Strut comp failure
DB-6 6inx12in	0.94	2 #6 0.98	# 2 @ 2.1″	# 2 @ 2.5″	30	33.6	56.80	94.20	42	52	Strut comp failure

5. DETERMINATION OF DEEP BEAMS STRENGTH ON THE BASIS OF COMPRESSIVE STRENGTH OF STRUTS AND NODES AS PER ACI-318

The widths of the struts and ties are worked on the basis of the STM proposed by ACI 318-05
The width of the horizontal strut *bc* = 3.6 in for deep beam DB-1. The load carried by the strut is given as:
$(0.85)\ \beta_s f_c']\ [b.\ w_{bc}]$ =(0.85) (1) (5) (6) (3.6) = 91.8 Kips.
The strut angle is 54.7 degrees. Hence the vertical loads = P= 91.8/tan 35.3 = *129.65 K*
The width of the diagonal strut = 7 as per details given in Appendix-A. The capacity of
$F_{ns(ab)} = [\ (0.85)\ \beta_s f_c']\ [\ b.\ w_s]$=(0.85) (0.75)(5)(6)(7.0) = 133.84 kips
The vertical load can be carried by the strut P = 133.84*sin54.7= *109.26 K*
Similarly, from the nodes capacity, the capacity of strut *ab* at node a
$F_{nn(a)} = 0.85\ \beta_n f'_c]\ [\ b.\ w_s]$ =(0.85) (0.8) (5) (6) (7.5)= *153 K*
Here, $\beta_n = 0.8$ for CCT node and, $w_{ab\ (a)}$ = 7.5″
Similarly, the nodal end capacity of strut *ab* at node b $= \Phi\ F_{nn(b)}$
= (0.85) (1.0) (5) (6) (7.0)= *178.5 Kips where* β_n = 1.0 for CCC node and, $w_{ab\ (a)}$ = 7.0″

Thus, from the above four values of vertical loads, the minimum can be selected as *109 K* on the basis of the assumed STM and using the ACI 318-05 provisions. The actual failure load of the DB-1 as shown in Table 3 is *101 K*, which is very reasonably close to the strength of the beam on the basis of STM. The slight changes may be due to the actual strength of the compressive strength of concrete than what was specified. The above procedure is followed for all the deep beams and predicted STM values are compared with the failure loads in Table 4.

Table 4. Details of struts dimensions and comparison of the actual and STM predicted failure loads of deep beams

predicted failure loads of deep beams	a/d	Strut dimensions (in)				Strut Angle (degrees)	Failure load (K)		V_{ult}/V_{STM}
		Diagonal		Horizontal					
		Middle (w_{ab})	Node (*a*)	Middle (w_{bc})	Node (*b*)		STM V_{STM}	Actual V_{ult}	
DB-1 6inx21in	0.64	7.5	7.5	3.6	7	54.7	109	101.1	0.92
DB-2 6inx21in	0.64	7.5	7.5	3.6	7	54.7	109	104.6	0.95
DB-3 6inx18in	0.76	6.9	7.48	3.6	6.9	49.3	100	97.60	0.97
DB-4 6inx18in	0.76	6.9	7.48	3.6	6.9	49.3	100	101.6	1.01
DB-5 6inx12in	0.94	6.7	7.37	3.6	6.7	42.4	86.40	99.60	1.15
DB-6 6inx12in	0.94	6.7	7.37	3.6	6.7	42.4	86.40	94.20	1.09
								Mean	1.008

6. COMPARISON OF THE STM RESULTS WITH THE PROVISIONS of EC-02

According to EC-02 , the nominal shear resisting force of the plain concrete ;

$$V_c=\left(3.5-2.5\frac{Mu}{Vud}\right)\left(1.9\sqrt{f'c}+2500\rho w\frac{Vud}{Mu}\right)bwd\le 6.0\sqrt{f'c}\,bwd \qquad (1)$$

Where, $1.0 < 3.5 - 2.5\,(M_u / V_u\, d) \le 2.5$,
The force resisted by the shear reinforcement is given as;

$$Vs=\left[\frac{A_v}{s_v}\left(\frac{1+l_{n/d}}{12}\right)+\frac{A_{vh}}{sh}\left(\frac{11-l_{n/d}}{12}\right)\right]f_y\,d \qquad (2)$$

Here A_v = total area of vertical reinforcement spaced at s_v in the horizontal direction at both faces of the beam.

A_{vh} = total area of horizontal reinforcement spaced at s_h in the vertical direction at both faces of the beam. The theoretical shear capacities of deep beams worked out on the basis of EC-02 have been compared with actual shear at cracking in Table 5.

Table 5. Comparison of actual shear strength of deep beams with the EC-02

Beams	d (in)	$\frac{M_u}{V_u d}=\frac{7.5}{d}$	$\rho_w=\frac{A_{st}}{bd}$	V_c kips	A_v (in^2)	s_v (in)	A_{vh} (in^2)	s_h (in)	V_s kips	$V_n = V_c+V_s$ (kips)	V_{ult}	V_{cr}/V_{EC02}
1	2	3	4	5	6	7	8	9	10	11=5+10	12	13
DB-1	18.75	0.40	0.0054	48.7	0.098	3.5	0.098	3.3	22.0	70.7	101.12	1.44
DB-2	18.75	0.40	0.0054	48.7	0.098	3.5	0.098	3.3	22.0	70.7	104.6	1.47
DB-3	15.75	0.48	0.0065	37.6	0.098	3.0	0.098	2.7	22.3	59.9	97.60	1.63
DB-4	15.75	0.48	0.0065	37.6	0.098	3.0	0.098	2.7	22.3	59.9	101.60	1.68
DB-5	12.75	0.59	0.0115	29.1	0.098	2.5	0.098	2.1	22.6	51.7	99.60	1.92
DB-6	12.75	0.59	0.0115	29.1	0.098	2.5	0.098	2.1	22.6	51.7	94.20	1.82
											Mean	1.66

7. DISCUSSION OF RESULTS

For a smaller a/d ratio, where the depth of the beams is maximum for DB-1 and DB-2 a/d=0.64, the shear compression failure is more prominent and the shear strength of the beams is also maximum. The struts take the maximum loads and transfer these to the supports. The shear failure of the beams is mostly due to resistance offered by the struts. The actual strut angles are in the range of 60-61 degrees, which is measured roughly from the inclination of the diagonal crack, passing the strut region, whereas the theoretical strut angle of the diagonal strut is 54.7 degrees. The actual failure strength of beams having a/d = 0.64 is slightly smaller than the actual strength of the deep beams worked out on the basis of STM. EC-02 has also reasonably estimated the shear strength of the deep beams DB1 and DB-2 for a/d 0.64.

For deep beams with a/d =0.76 and a depth of 15in (DB-3 and DB-4) the deviation between the actual and theoretical strut angles is almost the same, as the theoretical truss angle for the applied loads is 49.3 degrees, whereas the actual inclination of the struts is in the range of 56-58 degrees. The STM estimate of the deep beams is reasonably closer to the actual failure loads. EC-02 has, however, safely estimated the shear strength of deep beams more conservatively for a/d=0.76 (DB-3 and DB-4).

For deep beams with a/d =0.94 and depth of 12in (DB-5 and DB-6), the shear failure is again due to compression failure of the diagonal struts as verified from the cracks in the beams. The STM estimate in such cases is on the higher side as compared to the actual failure loads. This increase in the shear strength in relatively shallower beams is due to the fact that the longitudinal steel might have also contributed to the strength of the beams, which has been neglected in the STM. The deviation of the actual and theoretical values of strut angles is the same i.e., actual values of 50-52 degrees against theoretical values of 42.4 degrees. The EC-02 estimates for such beams are conservative.

In all of the three sets of beams, the failure has been caused by the compression of the struts and none of the main longitudinal steel bars has been observed as yielded at the failure of the beams. Hence strut compression failure can be one of the major reasons for failure of the deep beams. Furthermore, the provision of longitudinal skin reinforcement in deep beams has also contributed to the flexural strength of the deep beams and, as a result, the concrete struts have failed in compression before yielding of the longitudinal steel.

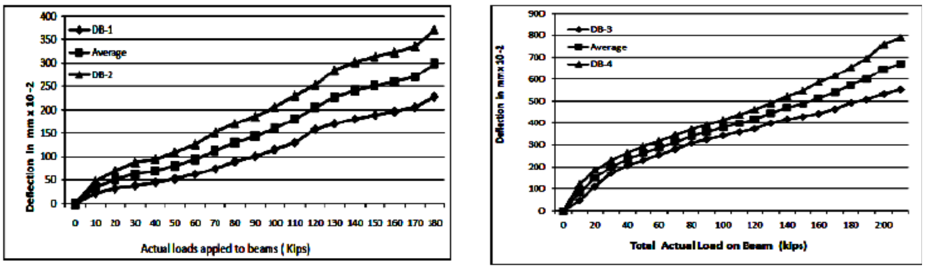
The STM based solutions mostly rely on the capacity reduction factor of nodes and struts (.i.e. β_s , β_n), for the given strength of the concrete (f_c'). The values for the β_s have been worked out both for horizontal strut (β_{sh}) and diagonal struts(β_{sd}) at the failure load by equating nominal strut capacities and the forces in struts at failure loads. These factors are given in Table 6. The assumed value of β_s as per ACI-318 is 0.75, whereas some of the values of β_s for diagonal struts are less than 0.75, as in the case of DB-1, DB-2 and DB-4. The average value of β_s for diagonal struts is 0.72, which is reasonably closer to the assumed value of 0.75 as per ACI-318. The observed values of β_s for horizontal struts are relatively higher than the assumed value of 0.75. The lower capacities of the diagonal struts have thus caused the compression of failure of the deep beams, before yielding of the main steel.

Table 6. Actual values of capacity reduction factor β_s on the basis of $\theta = \tan^{-1}(d_v/a)$, and $F_{ns\,(ab)} = F_{ab}$ and $F_{ns\,(bc)} = F_{bc}$ at failure loads of deep beams

Beams	Load at Failure (V_n) (kips)	Diagonal Strut "ab"			Horizontal Strut "bc"		
		F_{ab} = (V_n) / sin θ_1 (kips)	$F_{ns\,(ab)}$ (kips)	$\beta_{sd} = \frac{(0.75)F_{2b}}{F_{ns}(ab)}$	F_{bc} = F_{ab} cos θ_1 (kips)	$F_{ns\,(bc)}$ (kips)	$\beta_{sh} = \frac{(1.0)F_{bc}}{F_{ns}(bc)}$
1	2	3	4	5	6	7	8
DB-1	101.1	123.8	144	0.64	71.3	99	0.72
DB-2	104.6	128.2	144	0.67	74.1	99	0.75
DB-3	97.60	143.2	142	0.76	93.4	99	0.94
DB-4	101.6	134.0	142	0.70	87.4	99	0.88
DB-5	99.60	147.7	138	0.80	109.0	99	0.90
DB-6	94.20	142.1	138	0.77	105.3	99	0.79
			Mean	0.72			0.83

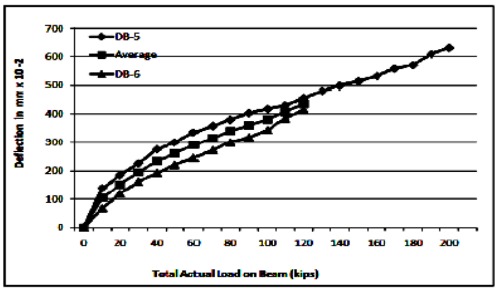
V_u: Failure loads of deep beam, $F_{ab;}$ load transferred to diagonal strut *ab*.
$F_{ns(ab)}$: Strength of Node at end *a* , β_{sd} =Strength reduction factor for diagonal strut on the basis of actual failure loads ,
$F_{bc;}$ load transferred to horizontal strut *bc*
$F_{ns(bc)}$: Strength of Node at end *b*, β_{sh} : Strength reduction factor for horizontal strut.

The load deflection curves for the three sets of deep beams have been given in Fig.7

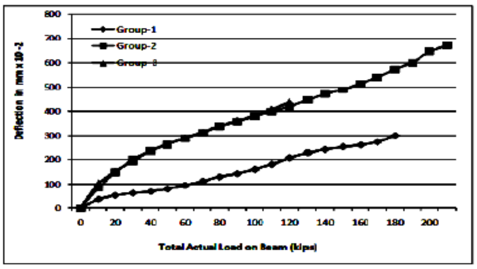


a. Deep beams of group-1 (DB-1 and DB-2)

b. Deep beams of group-2 (DB-3 and DB-4)



c. Deep beams of group-3 (DB-5 and DB-6)



d. Comparison of mid span deflections of three groups of beams

Fig. 7. Load Deflection curves and their comparison for three sets of deep beams

8. CONCLUSION

1. Strut and Tie Model (STM) has given reasonable estimates of the load carrying capacity of the deep beams when compared with the actual failure loads.
2. The failure of the beams has been caused mainly by compression failure of the diagonal concrete struts as the yielding of the longitudinal bars has not been observed in the beams. The diagonal struts have failed in all cases. This fact is also verified from the STM calculation as the capacity of the diagonal strut is minimum as compared to the horizontal struts and strengths of the nodes.
3. The provision of CE-02 for the shear strength of deep beams also gives reasonably good prediction.
4. The capacity reduction factors for strut strengths at failure loads were observed quite closer to the values recommended by ACI 318. However, the actual capacity reduction factors for the diagonal struts were relatively less than the values proposed by ACI, which may require further verification by experimental work.

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