Determination of Shear Cracks For Various Aspect Ratios of Beams

Miss. Sejal Patil [1], Dr. M.N. Bajad [2]
[1]Dept of Civil Engineering
[2]Assosiate Professor, Dept of Civil Engineering
[1, 2] Sinhgad College of Engineering, Pune, India

Abstract- *The paper attempts shear strength of high strength concrete beam in shear with change shear to effective depth ratio (a/d=1, 1.5, 2, 2.5). The beams are modelled in 'ANSYS' model which is Finite Element Software. The shear capacity is evaluated using 'ANSYS' model for the beams. The paper also contains table which consists different shear strength capacity by using different codes.*

Keywords- Analytical model, High Strength Concrete, Shear Strength, Shear Span to Depth Ratio, ANSYS.

I. INTRODUCTION

The shear strength of concrete beams mainly depends on the following variables:

- Depth of member or size effect,
- Longitudinal Reinforcement,
- Shear span to effective depth a/d or moment to shear ratio,
- Axial Force,
- The tensile Strength of concrete.

Fractography is widely used with fracture mechanics to understand the causes of failures and also verify the theoretical failure predictions with real life failures. The prediction of crack growth is at the heart of the damage tolerance discipline. In linear elastic fracture mechanics (LEFM) it is assumed that all of the fracture process happens at the crack tip and that the entire volume of the body remains elastic. Under this assumption, the questions of crack propagation and structural failure can be solved by methods of linear elasticity. It is convenient to distinguish three elementary fracture modes, Modes I, II and III (Fig. 01).

There are three ways of applying a force to enable a crack to propagate:

Mode I fracture:	Opening mode (a tensile stress normal to the plane of the crack),
Mode II fracture:	Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front),
Mode III fracture:	Tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack front).

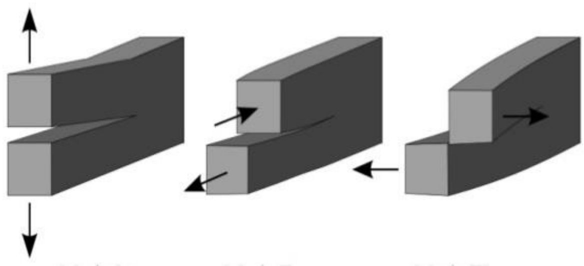


Figure. 01 Mode of Fracture

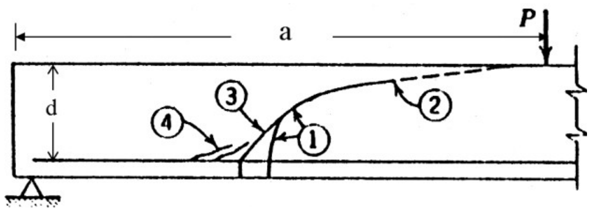


Figure. 02 Formation of Diagonal Tension Cracks

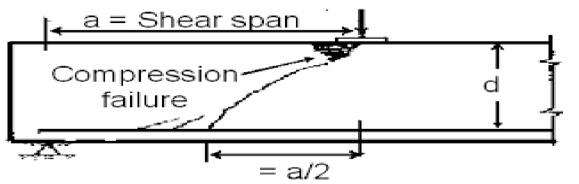


Figure. 03 Shear Compression Failure for Small Span

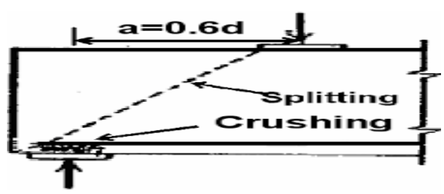


Figure. 04 True Shear Failure

Depending upon the shear span, shear failure may be classified into three types i.e. diagonal tension failure, diagonal compression failure and splitting or true shear failure (Fig. 02, 03 & 04 respectively). The shear failure of reinforced concrete beams without web reinforcement is a distinctive case of failure which depends on various parameters such as a/d, ρ, aggregate type, strength of concrete, type of loading, and support conditions, etc. To estimate the shear resistance of beams standard codes and researchers all over the world have specified different formulae considering different parameters.

OBJECTIVE

- Calculate deflection for HSC with various a/d ratio for shear failures using ANSYS
- Examinefor the influence of the crack propagation path of shear stress for various a/d ratio on HSC member using ANSYS
- Study the effect of a fracture toughness of beam specimens using ANSYS
- Compare shear stress with ANSYS and shear stress with the new empirical equation for shear strength

II. METHODOLOGY

Eight reinforced high strength concrete (HSC) beams are cast and tested, under two-point loading (fig.05) (33), varying the shear span to effective depth ratio (a/d). The test specimens are divided into four series. Each series consisted of two high strength concrete beams without shear reinforcement with a/d ratio 1, 1.5, 2 and 2.5. For all the series, the parameters viz., concrete proportions and percentage of longitudinal steel are kept constant. The details of the beams cast are listed in Table 01.

Table No. 01 Details of Beam

A/D Ratio	Size of Beam for M50 And M60 Grade Concrete	No. Of Beams
1	150*150*700	2
1.5	150*150*800	2
2	150*150*1000	2
2.5	150*150*1150	2

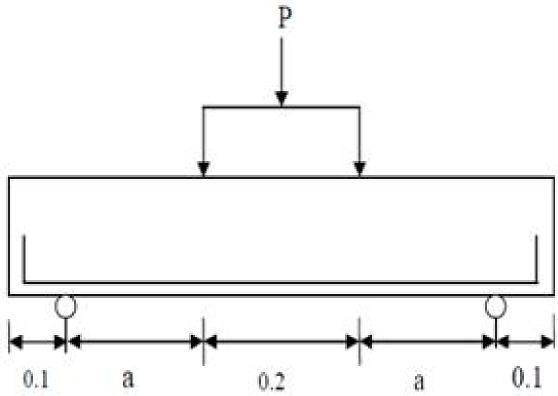


Fig.05 Shear Span to Effective Depth Ratio

About ANSYS

Finite Element Analysis (FEA) is a method used for the evaluation of structures, providing an accurate prediction of the component's response subjected to various structural loads. Finite element method is a numerical analysis method that divides the structural element into smaller parts and then simulates the loading conditions to evaluate the response of concrete. The accuracy and convergence of the solution depends on factors such as mesh density, constitutive properties of concrete, convergence criteria and tolerance values etc. The basic linear equation used to solve the static structural analysis in ANSYS is as given below in Equ-1.

$$[K]\{q\} = \{F\} \qquad (1)$$

Material Properties of Reinforced Concrete used for Beam Modeling in ANSYS

Table No. 02 Material Properties

Material	Property	Value
Structural steel	f_{sy} (MPa)	265
	f_{su} (MPa)	410
	E_s (MPa)	205×10^3
	μ	0.3
	e_t	0.25
Reinforcing bar	f_{sy} (MPa)	250
	f_{su} (MPa)	350
	E_s (MPa)	200×10^3
	μ	0.3
	e_t	0.25
Concrete	f_{sc} (MPa)	42.5
	f_{sy} (MPa)	3.553
	E_c (MPa)	32920
	μ	0.15
	e_s	0.045

Table No. 04 Details of Grade of Concrete

Grade	Grade Designation	Specified Characteristic Compressive Strength of 150mm Cube At 28 Days In N/mm^2
Ordinary Concrete	M10	10
	M15	15
	M20	20
Standard Concrete	M25	25
	M30	30
	M35	35
	M40	40
	M45	45
	M50	50
	M55	55
High strength concrete	M60	60
	M65	65
	M70	70
	M75	75
	M80	80

These values are calculated using the empirical equation of SP16 (1980)

$$\tau_c \quad \frac{0.85}{6\beta} \sqrt{} \; 0.83 f_{ck} \ldots$$

Where,

$$\beta = \frac{0.8 f_{ck}}{6.89 p_t} \qquad \ldots\ldots\ldots\ldots(4)$$

Where, but not less than 1

And $$p_t = \frac{100 A_s}{b_w d} \qquad \ldots\ldots\ldots\ldots(5)$$

Percentage steel values taken from table no. 15 in IS 456:2000. Design shear strength of concrete τc , N/mm2 (IS 456-2000 clause 40.2.1, 40.2.2,40.3 ,40.4, 40.5.3, 41.3.2, 41.3.3, 41. 4.3 and Table No. 19).

The Griffith Theory Equation,

$$V_c = \frac{0.446\,E}{\sqrt{H}} \left(\frac{}{E_c}\right) \left(\frac{\mu(1.3)}{A_s}\right) \rho^{\frac{1}{2}} (1 - \sqrt{\rho})^{\frac{2}{3}} K_{ICD} \ldots(6)$$

Equation (6) states that, shear capacity of beams is inversely proportional to the depth of beams and directly proportional to modular ratio, longitudinal reinforcement and fracture toughness. From our experimentation, we are observing that shear capacity of beams is mainly depend upon a/d ratio, longitudinal reinforcement and grade of concrete.so by considering these parameters.

$$\tau_c = 1.1 \frac{\sqrt{E_s}}{\frac{A}{D}} K_{IC} * \rho \qquad \ldots\ldots\ldots(7)$$

Example of ANSYS Modeling of HSC Beam:

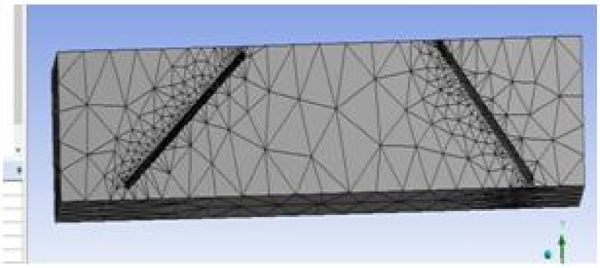


Figure. 06 Cracked Specimen of Longitudinal Reinforcement (ρ %) =1 & M50 (Length 24.2cm)

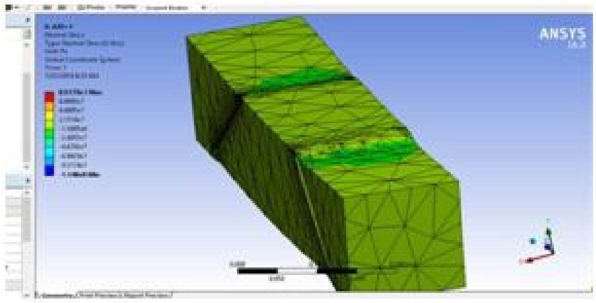


Figure. 07 Normal Stress a/d =1

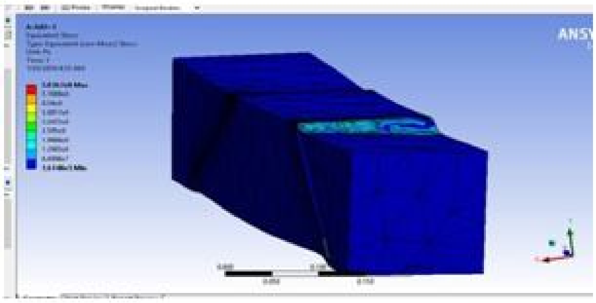


Figure. 08 Equivalent Stress a/d =1

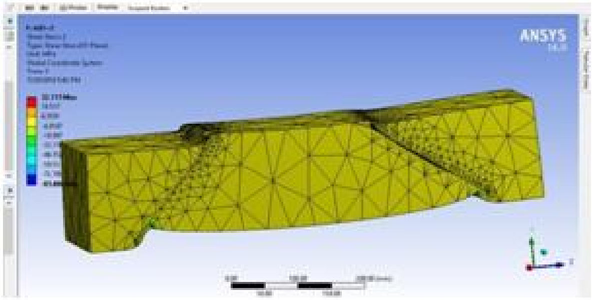


Figure. 09 Shear Stress at Ratio a/d =2

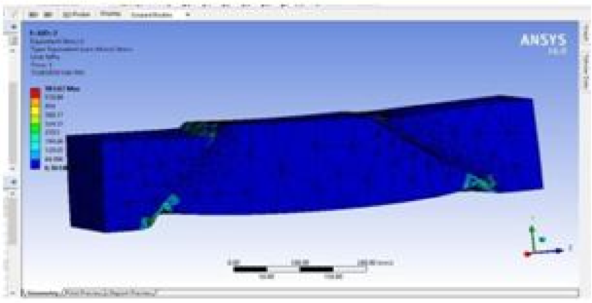


Figure. 10 Equivalent Stress a/d =2

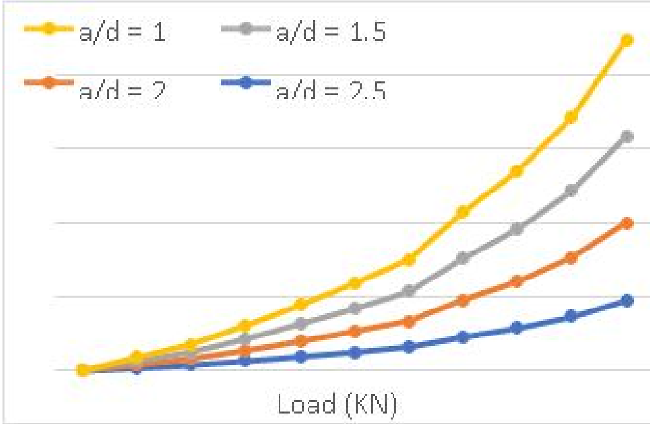
III. RESULTS

- Effects of Loads on HSC Beam with Various a/d Ratio

Table No. 05 and Graph. 01 shows the results of deflection for M50.

Table No. 05 Load v/s Deflection for M50

Load KN	a/d=1	a/d=1.5	a/d=2	a/d=2.5
0	0	0	0	0
5000	0.10482	0.09434	0.08490	0.07641
10000	0.20972	0.18875	0.16987	0.15289
15000	0.35371	0.31834	0.28651	0.25786
20000	0.51563	0.46407	0.41766	0.37589
25000	0.68861	0.61975	0.55777	0.50200
30000	0.87613	0.78852	0.70967	0.63870
35000	1.24860	1.12374	1.01137	0.91023
40000	1.57170	1.41453	1.27308	1.14577
45000	1.99380	1.79442	1.61498	1.45348
50000	2.60390	2.34351	2.10916	1.89824

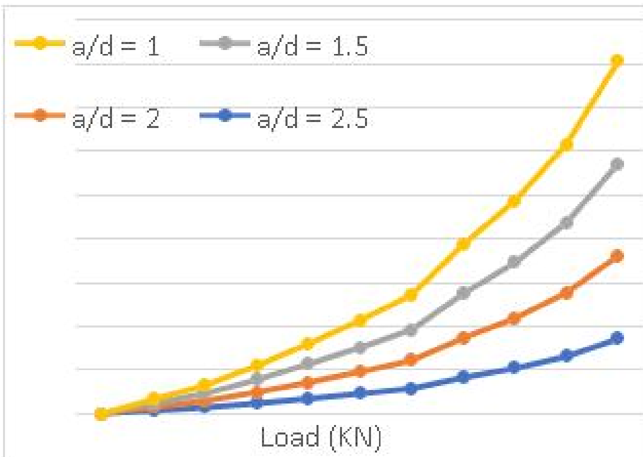


Graph. 01 Load v/s Deflection for M50

Table No. 06 and Graph. 02 shows the results of deflection for M60.

Table No. 06 Load v/s Deflection for M60

Load KN	a/d=1	a/d=1.5	a/d=2	a/d=2.5
0	0	0	0	0
5000	0.09434	0.08490	0.07641	0.06877
10000	0.18875	0.16987	0.15289	0.13760
15000	0.31834	0.28651	0.25786	0.23207
20000	0.46407	0.41766	0.37589	0.33831
25000	0.61975	0.55777	0.50200	0.45180
30000	0.78852	0.70967	0.63870	0.57483
35000	1.12374	1.01137	0.91023	0.81921
40000	1.41453	1.27308	1.14577	1.03119
45000	1.79442	1.61499	1.45348	1.30813
50000	2.34351	2.10916	1.89824	1.70842



Graph. 02 Load v/s Deflection for M60

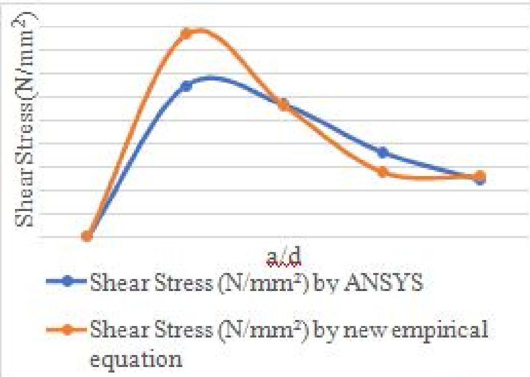
Calculation of shear stress by ANSYS and by new empirical equation

Table No. 08 and Graph. 04 shows the results error of shear stress values for M50 by ANSYS software and by new empirical equation for a/d = 1, 1.5, 2, 2.5. It showed that values of shear stress with% error are varying; (i.e. 2.531792%, -0.035587%, - 3.010753%, 0.542636%, respectively).

Negative indicates decreasing values.

Table No. 08 Shear Stress (N/mm2) for M50 with % error

A/D	Shear Stress (N/mm^2) by ANSYS	Shear Stress (N/mm^2) by new empirical equation	% Error between Shear Stress (N/mm^2) by ANSYS and by new empirical equation
1	6.46	8.65	2.531792
1.5	5.64	5.62	0.035587
2	3.63	2.79	3.010753
2.5	2.44	2.58	0.542636



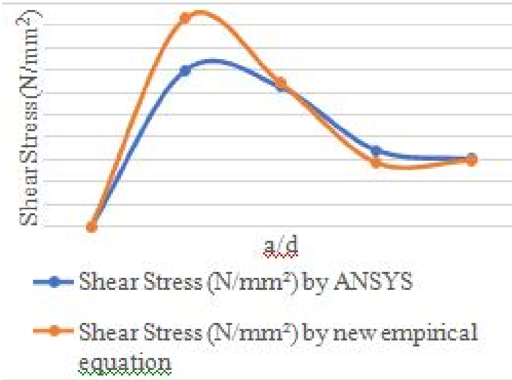
Graph. 04 Values of Shear Stress (N/mm^2) for Grade M50

Table No. 09 and Graph. 05 shows the results error of shear stress values for M60 by ANSYS software and by new empirical equation for a/d = 1, 1.5, 2, 2.5. It showed that values of shear stress with % error are varying; (i.e. 2.500000%, 0.280374%, - 1.909722%, -0.168350%, respectively).

Negative indicates decreasing values.

Table No. 09 Shear Stress (N/mm^2) for M60 with % error

A/D	Shear Stress (N/mm^2) by ANSYS	Shear Stress (N/mm^2) by new empirical equation	% Error between Shear Stress (N/mm^2) by ANSYS and by new empirical equation
1	7.02	9.36	2.500000
1.5	6.24	6.42	0.280374
2	3.43	2.88	1.909722
2.5	3.02	2.97	0.168350



Graph. 05 Values of Shear Stress (N/mm2) for Grade M50

- Effects on various beam specimen's length with crack length values

Table No. 10 shows the results of crack length in various specimens. It showed that length decreased.

Table No. 10 Crack Length of Beams of M50

Sr No	Beam Specimens of M50	Cracked Length in "Cm"
1	150*150*700	24.2
2	150*150*850	31.42
3	150*150*1000	40.2
4	150*150*1150	45.2

Table No. 09 Crack Length of Beams of M60

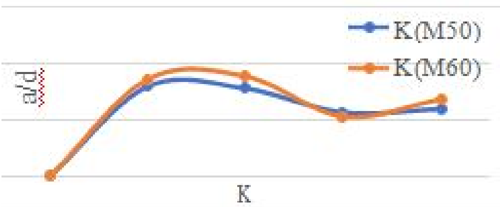
Sr No	Beam Specimens of M60	Cracked Length in "Cm"
1	150*150*700	22.2
2	150*150*850	32.4
3	150*150*1000	39.8
4	150*150*1150	46.1

- Determination of Fracture Toughness of Beams

Table No.10 and Graph. 06 shows the results of fracture toughness of beams for M50 and M60 grade concrete calculated by using Griffith Irwin's equation.

Table No. 10 Stress Intensity Factor of M50 & M60 Grade Specimens

A/D	Beam Specimens	K (M50)	K (M60)
1	150*150*700	3.2	3.46
1.5	150*150*850	3.12	3.56
2	150*150*1000	2.27	2.13
2.5	150*150*1150	2.39	2.74



Graph. 06 Fracture Toughness Factor (K) v/s a/d ratio

IV. DISCUSSION ON TEST RESULTS

The test results are discussed under different categories as follows,

- Effects of loads on HSC Beam with various a/d ratio

  An increasing in the load was observed with an increasing in deflection for M50 and M60. It is due to the shear span to depth ratio (a/d).

- Calculation of shear stress by ANSYS and by new empirical equation

  An increasing in the shear span to depth ratio (a/d) was observed with a decreasing shear stress of HSC. It is due to the ANSYS software. It is also due to the new empirical equation

- Effects on various beam specimen's length with cracked length values

  A decreasing in the length of beam was observed with change with various beam specimens. It is due to the various loads.

- Determination of Fracture Toughness Factor of Beams
  Fracture toughness factor of beams varies with the various beam specimens. It is due to the shear span to depth ratio (a/d).

V. CONCLUSION

Based on the results of this experimental investigation, the following conclusions are drawn

- The load increases in interval of 5000KN as the deflection increased for a/d = 1, ,1.5, 2, 2.5.
  Hence, it is recommended that increase in deflection for various a/d ratio is beneficial.
- The shear stress for HSC reduced or increase by varying % error (i.e. for M50 = 2.531792%,-0.035587%, -3.010753%, 0.542636%; and for M60 = 2.500000%, 0.280374%, -1.909722%, -0.168350%) as the 50% shear span to depth ratio (a/d = 1, 1.5, 2, 2.5, respectively) increased.
  Hence, it is recommended that variation in shear stress for HSC with a/d ratio is beneficial.
- The length reduced as cracked length for M50 and M60 as the change with various beam specimens.
  Hence, it is recommended that cracked length for shear stress for HSC is beneficial.
- The shear span to depth ratio (a/d = 1, 1.5, 2, 2.5) increased by 50% interval as the fracture tough- ness factor of beams varies for various beam spec- imens.
  Hence, it is recommended that beam specimen variation is beneficial for fracture toughness factor.

REFERENCES

[1] A. R. Marí, Antoni Cladera, 'Shear strength in the new Eurocode 2. A step forward?', *Structural Concrete*, Vol. 8, No. 2, (2007), pp. 57-66.

[2] A. Shah∗a and S. Ahmadb, 'An Experimental Investigation into Shear Capacity of High Strength Concrete Beams', *Asian Journal of Civil Engineering (Building and Housing)*, Vol. 8, No. 5, (2007), pp. 549-562.

[3] Abdul Ghaffar1, Afzal Javed2, Habib ur Rehman2, Kafeel Ahmed2 and M Ilyas2, 'Development of Shear Capacity Equations for Rectangular Reinforced Concrete Beams', *Pak. J. Engg. & App.l. Sci.*, Vol. 6, (2010), pp. 1-8.
[4] Adam S. Lubell, Evan C. Bentz, and Michael P. Collins, 'Shear reinforcement spacing in wide members', *ACI Structural Journal*, Vol. 106, No. 2, (2009), pp. 205-214.
[5] Ahmad S.H., Khaloo A.R. and Poveda A., 'Shear Capacity of Reinforced High Strength Concrete Beams', *ACI Journal*, Vol. 83, No. 2, (1986), pp. 297-305.
[6] Alejandro Pérez Caldentey, Patricio Padilla, Aurelio Muttoni and Miguel Fernández Ruiz, 'Effect of Load Distribution and Variable Depth on Shear Resistance of Slender Beams without Stirrups', *ACI Structural Journal*, Vol. 109, No. 5, (2012), pp. 595-603.
[7] Amer M. Ibrahim and Mohammed Sh. Mahmood, 'Finite Element Modeling of Reinforced Concrete Beams Strengthened with FRP Laminates', *European Journal of Scientific Research*, Vol.30, No.4, (2009), pp. 526-541.
[8] Aruna Munikrishna, Amr Hosny, Sami Rizkalla, and Paul Zia, 'Behavior of Concrete Beams Reinforced with ASTM A1035 Grade 100 Stirrups under Shear', *ACI Structural Journal*, Vol. 108, No. 1, (2011), pp. 34-41.
[9] Bashir H. Osman, Erjun Wu, Bohai Ji, Suhaib S. Abdulhameed, 'Effect of reinforcement ratios on shear behavior of concrete beams strengthened with CFRP sheets', *HBRC Journal*, Vol. 14, No. 1, (2018), pp. 29-36.
[10] Bazant Z.P. and Kim J. K., 'Size Effect in Shear Failure of Longitudinally reinforced beams', *ACI Journal Proceedings*, Vol. 83, No. 2, (1986), pp. 456-468.
[11] Berg F. j., 'Shear Strength of Reinforced Concrete Beams without Web Reinforcement', *Journal of ACI*, Vol. 59, No. 11, (1962), pp. 1587-1599.
[12] D.K. Kayathri and C. D. R. Balaji, 'Experimental and Analytical Study on Flexural Behavior of Curved Beams', *International Journal of Science and Engineering Applications*, Vol. 4, No. 3, (2015), pp. 146-152.
[13] Ehab M. Lotfy, Hassan A. Mohamadien, Hussein Mokhtar Hassan, 'Effect of web reinforcement on shear strength of shallow wide beams', *International Journal of Engineering and Technical Research (IJETR)*, Vol. 2 No. 11, (2014), pp. 98-107.
[14] Faizan Abid, R C Patil, Rakesh Sakale, 'Development of high-performance concrete', *International Journal of Trend in Scientific Research and Development (IJTSRD)*, Vol. 2, No. 2, (2011), pp. 1465-1479.
[15] G. App.a Rao∗ And R Sundaresan, 'Evaluation of size effect on shear strength of reinforced concrete deep beams using refined strut-and-tie model', *Indian Academy of Sciences*, Vol. 37, No. 1, (2012), pp. 89-105.
[16] I. A. Bukhari*, R. L. Vollum†, S. Ahmad* and J. Sagaseta†, 'Shear strengthening of reinforced concrete beams with CFRP', *Magazine of Concrete Research*, Vol. 6, No. 1, (2010), pp. 65- 77.
[17] Imran A. Bukhari* and Saeed Ahmad** 'Evaluation of Shear Strength of High-Strength Concrete Beams Without Stirrups', *The Arabian*
[18] *Journal for Science and Engineering*, Vol. 33, No. 2B, (2008), pp. 321-336.
[19] Jafar Amani and Ramtin Moeini, 'Prediction of shear strength of reinforced concrete beams using adaptive neuro-fuzzy inference system and artificial neural network', *Scientia Iranica Transactions A: Civil Engineering*, Vol. 19, No. 2, (2012), pp. 242-248.
[20] Jin-Keun Kim and Yon-Dong Park, 'Prediction of Shear Strength of Reinforced Concrete Beams without Web Reinforcement', *ACI Materials Journal*, Vol. 93, No. 3, (1996), pp. 213-222.
[21] Junho Song, J. Kim, J.M. LaFave, 'Joint shear behavior of RC beam-column connections', Magazine of Concrete Research, Vol. 61, No. 2, (2009), pp. 119-132.
[22] Junho Song†, Won-Hee Kang‡, Kang Su Kim‡†, Sungmoon Jung‡‡, 'Probabilistic shear strength models for reinforced concrete beams without shear reinforcement', *Structural Engineering and Mechanics*, Vol. 34, No. 1, (2010), pp. 15- 38.
[23] K. Adinkrah-App.iah1, M. Adom-Asamoah2 and R. O. Afrifa2, Herbert Abeka1, 'Evaluation of Shear Strength of Reinforced Concrete Deep Beams', *Engineering, Science, Technology & Entrepreneurship*, (2015), pp. 116-133.
[24] Keun-HyeokYanga, Heon-Soo Chunga, Eun- TaikLeea, Hee-ChangEunb, 'Shear characteristics of high-strength concrete deep beams without shear reinforcements', Engineering Structures, Vol. 25, No. 10, (2003), pp. 1343-1352.
[25] Mohammed Shukri Al-Zoubi, 'Simplified Model for Diagonal Cracking Shear Capacity of Slender RC Beams without Web Reinforcement', *Jordan Journal of Civil Engineering*, Vol. 11, No. 1, (2017), pp. 103-116.
[26] N. Humnabad and P. B. Autade, 'Experimental Evaluation Shear Strength of Steel Fibre Reinforced Concrete Deep Beam', *International Journal of Engineering Research & Technology (IJERT)*, Vol. 5, No. 5, (2016), pp. 97-106.
[27] Ozawa K., Maekawa K., Okamura H.1, 'Development of high-performance concrete', *Journal of the Faculty of Engineering*, Vol. 41, No. 3B, (1992), pp. 381-439.
[28] Prof. R.S. Chavan*, Dr. P.M. Pawar **, 'Shear Strength of Slender Reinforced Concrete Beams without Web Reinforcement', *Journal of Engineering Research and Applications*, Vol. 3, No. 6, (2013), pp. 554-559.

[29] R. Butterfield, 'Dimensional analysis for geotechnical engineers", *Geotechnique*, Vol. 49, No. 3, (1999), pp 357-366.

[30] R. S. Londhe 'Experimental Investigation on Shear Strength of SFRC Beams Reinforced with Longitudinal Tension Steel Rebars', *Asian Journal of Civil Engineering (Building and Housing)*, Vol. 11, No. 3 (2010), pp. 385-395.

[31] Reddy L.1, Ramana Rao N. V.2 and Gunneswara Rao T. D.3'Evaluation of Shear Resistance of High Strength Concrete Beams Without Web Reinforcement Using ANSYS February 2011

[32] Shilang Xu., Zhang Xiufang., Reinhard Hans W., 'Shear Capacity Prediction of Reinforced

[33] Concrete Beams without Stirrups Using Fracture Mechanics App.roach', *ACI Structural Journal*, Vol. 109, No. 5, (2012), pp. 706-713.

[34] Shuaib H. Ahmad, S.F.A.Rafeeqi, Shamsoon Fareed*, . 'Shear Predictions of Eurocode EC2', *American Journal of Civil Engineering and Architecture*, Vol. 1, No. 2, (2013), pp. 43-46.

[35] Sudheer Reddy L.1, Ramana Rao N. V.2 and Gunneswara Rao T. D.3, 'Evaluation of Shear Resistance of High Strength Concrete Beams Without Web Reinforcement Using Ansys', *ARPN Journal of Engineering and App.lied Sciences*, Vol. 6, No. 2, (2011), pp. 1-7.

[36] Tarun R. Naika,*, Rakesh Kumara,1, Bruce W. Rammeb, Fethullah Canpolatc, 'Development of high-strength, economical self-consolidating concrete', *Construction and Building Materials*, Vol. 30, (2012), pp. 463-469.

[37] Theodore Zsutty, 'Shear Strength Prediction for Separate Categories of Simple Beam Tests', *Architecture Civil Engineering Environment Journal*, Vol. 68, No. 2, (1971), pp. 138-143.

[38] Vinu R. Patel1, Dr. I. I. Pandya2, 'Evaluation of Shear Strength of SFRC Moderate Deep Beams Using Strut-and-Tie Models', *International Journal of Modern Engineering Research (IJMER)*, Vol. 1, No. 1, (2011) pp.-15-20.

[39] Zhang Z. and Hsu T., 'Shear strengthening of reinforced concrete beams using carbon-fiber- reinforced polymer laminates', *Journal of Composites for Construction*, Vol. 8, No. 5, (2005) 158–169.

[40] Dr.ir. P.J.G. Schreurs, 'Fracture Mechanics' Mechanical Engineering, 2014.

[41] Charles Herbert Hamblin Jr. 'Development of High-Performance Concrete for Use on Tennessee Bridge Decks and Overlays', University of Tennessee – Knoxville, 2004.

[42] Guillermo A. Riveros, Vellore S. Gopalaratnam, Amos Chase, 'User's Guide: Fracture Mechanics Analysis of Reinforced Concrete Beams (FMARCB)', Information Technology Laboratory (U.S.) and Engineer Research and Development Center (U.S.), 2008.

[43] Jaehong Kim and James M. LaFave, 'Joint Shear Behavior of Reinforced Concrete Beam-Column Connections subjected to Seismic Lateral Loading', NSEL Report Series Report, 2009.

Nomenclature

Latin upper-case letters:

A_{st} = Area of steel

B = Width

C = Crack length

E = Young's modulus (MPa)

E_c = Young's modulus for concrete (MPa)

E_s = Young's modulus for Steel (MPa)

{F} = Nodal vector force

H = Depth

K = Stress intensity factor

[K] = Stiffness matrix

K_I = stress intensity factor

V_c = Shear force capacity in concrete

Latin lower-case letters:

(a/d)	=	Shear span to effective depth ratio
b_w	=	Width of web
d	=	Effective depth
f_{ck}	=	Characteristics strength
f_{sy}	=	Yield stress for steel (MPa)
f_{su}	=	Ultimate strength (MPa)
e_t	=	Ultimate tensile strain
f_{sc}	=	Compressive strength (MPa)
f_{sy}	=	Tensile strength for concrete (MPa)
e_s	=	Ultimate compressive strain
pt	=	Percentage steel
{q}	=	Nodal displacement vector

Greek lower-case letters

β	=	Geometry factor
μ	=	Poisson's ratio
ρ	=	Longitudinal tension steel ratio
σ	=	Applied stress
τ_c	=	Toughness stress