10th International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-X
G. Pijaudier-Cabot, P. Grassl and C. La Borderie (Eds)
https://doi.org/10.21012/FC10.235531

EXPERIMENTAL INVESTIGATION ON STRUT EFFICIENCY FACTORS FOR DESIGN OF REINFORCED CONCRETE DEEP BEAMS

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Key words: Deep beam, Bottle-shaped strut, Strut efficiency factor

Abstract: Deep beams are encountered in structural systems as transfer girders, pile caps, pier caps, etc., which are critical in shear. After initial flexural cracking, load directly transfers to supports in deep beam through tied arch mechanism. The strength of deep beams depends on capacity of diagonal struts. The strut capacity is estimated by reducing the uniaxial compressive strength of concrete by a factor known as strut efficiency factor. The strut efficiency factor accounts for the effect of diagonal splitting tension (bottle-shaped strut). In the present study, the strut efficiency factors developed for bottle-shaped struts are validated with the experimental results on isolated concrete struts. The width of loading plate and height of strut are the variables for the experimental investigations. Total twelve unreinforced concrete struts were tested. It has been found that there seems no reduction in strength of bottle-shaped strut as compared to uniaxial compressive strength.

1 INTRODUCTION

ACI 318 [1] defined the deep beams are the structural members loaded and supported on different faces so that the compression strut develops between load and support. The clear span of deep beam shall be less than four times the overall depth of beam or concentrated forces shall be acting within a distance equal to two times the overall depth from supports. Due to small span-to-depth or shear span-to-depth ratio of deep beam, stress trajectories are disturbed and conventional simple beam design procedures are not applicable. ACI 318-14 states that, the deep beams shall be designed considering either the nonlinear strain distribution or Strut-and-Tie Model (STM). The non-linear strain distribution is very difficult to excersie in day-to-day design practices, whereas STM based design is simple to apply. Cracked disturbed-regions are modelled using struts-and-ties by representing principal compressive stress field as a strut and principal tensile stress field as a tie.

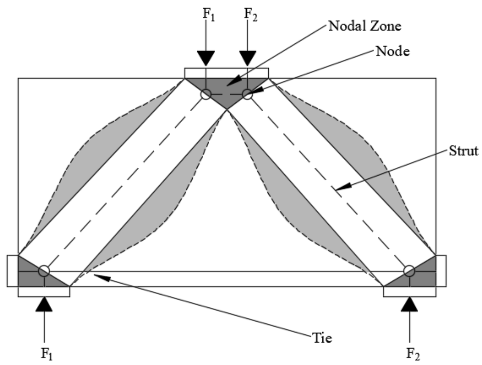

Figure 1: Strut-and-tie model for Deep beam.

The continuous stress fields are condensed to discrete struts and ties. These struts and ties are interconnected at discrete nodes. Capacity of struts, ties, and nodal zones is calculated either using code recommendation available or popular equations from literature. The capacity is checked against the demand estimated from the truss model. The accuracy of results from STM depends on accurate estimate of capacity of struts, ties and node zones.

2 CONCRETE STRUTS

Concrete struts represent the concrete compressive stress field and the centre line of struts will coincide with the resultant compression. Three different strut types are identified.

Prismatic struts are idealised struts that are subjected to axial compression without any transverse tensile forces. These struts will have a uniform width along the length of struts.

In most cases, the load flows from a smaller area (column) to wider (beam). Therefore, the width of strut is not be uniform, and the boundary of strut is not parallel to stress field (bottle-shape). The change in direction of compression introduces transverse tensile forces to satisfy the equilibrium. Due to transverse tension, the load carrying capacity of bottle-shaped strut is lesser than other type of struts.

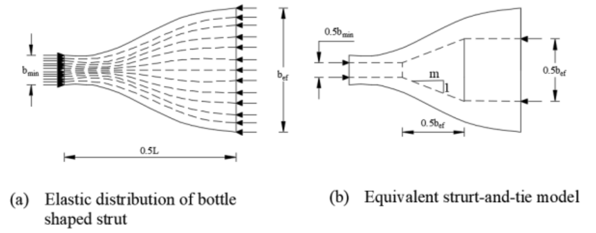

Figure 2: Transverse tension in bottle-shaped strut

Fan type struts are idealised stress field with negligible curvatures. These struts are used to idealise the compressive stress fields of a deep beam subjected to uniformly distributed load. These struts do not develop any transverse tension.

3 STRUT EFFICIENCY FACTOR

The capacity of struts depends on the stress condition, angle between strut and tie, confinement and distribution of reinforcements. Effect of these parameters on the strut capacity shall be investigated to arrive at accurate capacity of struts. The effect of all these parameters and uncertainties in truss model are lumped into single factor called strut efficiency factor *(v)*. The effective compressive stress in concrete strut *(f_{ce})* is defined as,

$$f_{ce} = v f_c{'} \quad (1)$$

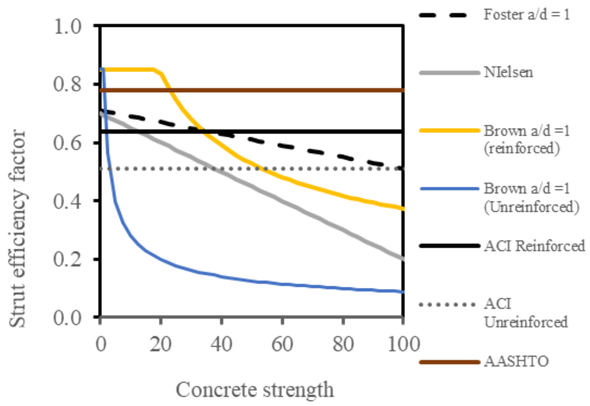

Figure 3: Strut efficiency factor vs. concrete strength

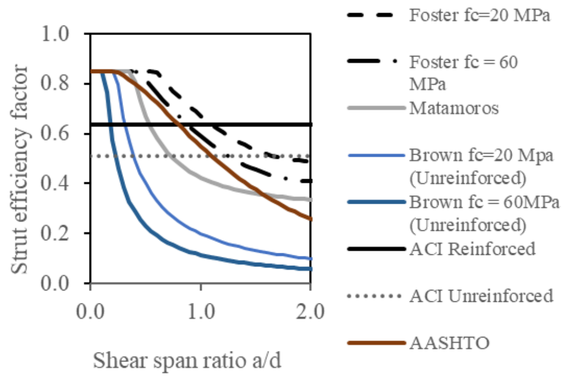

Figure 4: Strut efficiency factor vs. shear span-to-depth ratio

Strut efficiency factors for different types of struts are reported in ACI 318 [1], AASHTO LRFD [2], CSA [3], EC-2 [4], and fib model code [5]. The strut efficiency factors are not consistent and uniform among various national codes. AASHTO and Canadian standards adopted Vecchio and Collins model [6]. ACI 318-14 is proposed single value of strut efficiency factor for different struts. Quintero-febres et al. [6] found that strut efficiency factors proposed in ACI 318 for normal strength concrete was conservative, whereas, unconservative in case of high strength concrete. Quintero-febres et al.[7] recommended that the value of v = 0.60 shall be used for high strength bottle-shaped strut only for the struts having transverse reinforcement equal to 0.01. Many researchers proposed expression for strut capacity based on the experimental results of deep beams. The proposed strut efficiency factor v found in the literature always remains less than 1.0. However, the experimental studies [8]-[12] on isolated struts revealed that the strut efficiency fator reached 1.0 even for unreinforced isolated bottle-shaped strut.

3 DATABASE ON CONCRETE STRUTS

A total 97 test results of unreinforced isolated concrete struts have been collected from literature [8-12].

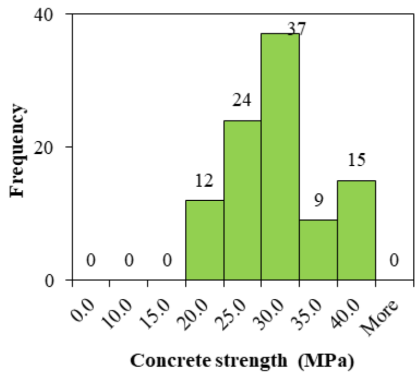

Figure 5: Histogram of concrete strength

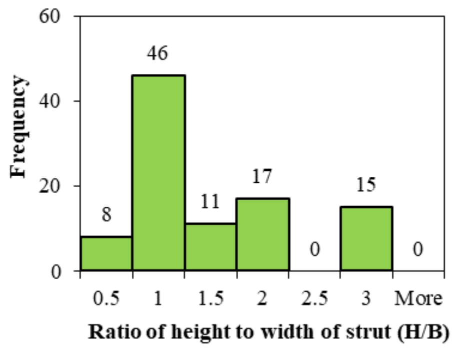

Figure 6: Histogram of ratio height to width of strut

Brief description of existing experimental studies on isolated concrete struts can be found in [12]. Characteristics of parameters are shown as histograms in Figures 5-7.

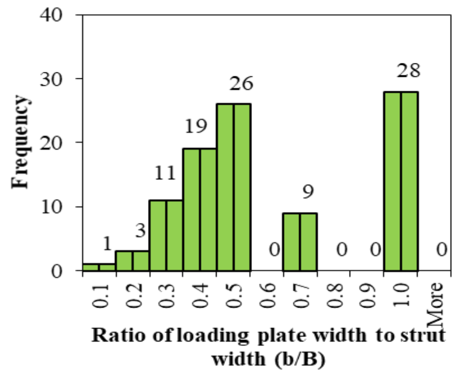

Figure 7: Histogram of ratio loading plate width-to-width of strut

The strut efficiency factor has been estimated from experimental peak loads as per Eq. [2]

$$\nu_e = P_u / (0.85 f_c' bd) \qquad (2)$$

where P_u is peak load, f_c' is cylindrical compressive strength of concrete, b and d are width and depth of loading plate respectively. Histogram of strut efficiency factor evaluated from experimental results is shown in Figure 8

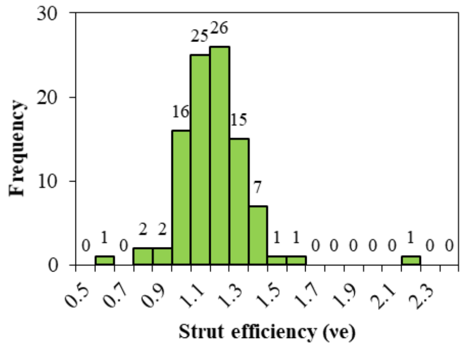

Figure 8: Histogram of strut efficiency factor

The minimum and maximum values of experimentally calculated strut efficiency are 0.59 and 2.10 respectively. The mean value of strut efficiency factor is 1.12 with coefficient of variation of 15.8%.

4 EXPERIMENTAL INVESTIGATION

The compressive strength of concrete was varied from 17.4 MPa to 38.8 MPa in past experiments. Hence, an experimental study on concrete strut with high grade concrete has been conducted to add to the gap in database. Height of strut (H), width of bearing plate (b) and concrete strength have been varied in this study. Width (B) and thickness (D) of all the concrete struts is 300 mm and 150 mm respectively. Steel bearing plate of 25 mm thick was used. The ratio of height-to-width of the strut (H/B) was varied from 1.0 to 3.0 with interval of 1.0. The ratio of width of panel-to-width of bearing plate was varied from 0.25 to 1.0 with interval of 0.25. All the struts were loaded through full width of struts i.e., 150 mm. Total 12 struts were cast and cured in wet condition for 28 days. The compressive strength of concrete used in the struts is 71 MPa, which is an average value on three 150mm x 150mm x 150mm concrete cubes. Conversion factor of 0.8 was used to convert the cube strength to cylinder strength. Summary of experimental test results and parameters are given in Table 1.

Table 1: Summary of experimental result

Strut	Height (mm)	Loading Width, (mm)	Peak load (kN)	β_e
S1-1	300	75	387	0.71
S1-2	300	150	868	0.80
S1-3	300	225	1328	0.81
S1-4	300	300	2018	0.93
S2-1	600	75	579	1.1
S2-2	600	150	907	0.80
S2-3	600	225	1499	0.92
S2-4	600	300	2247	1.0
S3-1	900	75	763	1.40
S3-2	900	150	942	0.87
S3-3	900	225	1841	1.13
S3-4	900	300	2040	0.94

4.1 Experimental results and discussion

All the concrete struts were tested under load controlled 600 ton capacity compression testing machine. Axial and transverse strains in struts were measured using Linear Variable Differential Transducers (LVDT) placed at different locations along the height of struts as shown in Figure 9. Applied load to the specimen was measured using 500 ton capacity load cell.

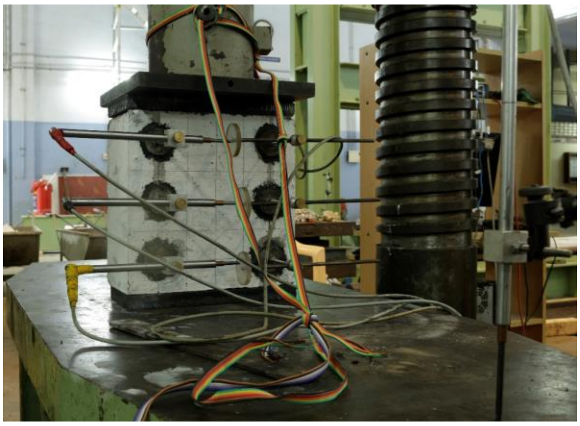

Figure 9: Experimental test set-up for strut S1-4

Axial strain vs. applied load for the struts S3-1 to S3-4 is shown in Figure 10. The axial stiffness of all the struts is the same. Softening behaviour was noticed from axial strain response in the struts S3-2 and S3-4, which had strut efficiency factor less than 1.0. Axial strain response in struts S3-1 and S3-3 is linear and had strut efficiency factor greater than 1.0. Possible reason for this behaviour may be due to inherent variability in concrete strength.

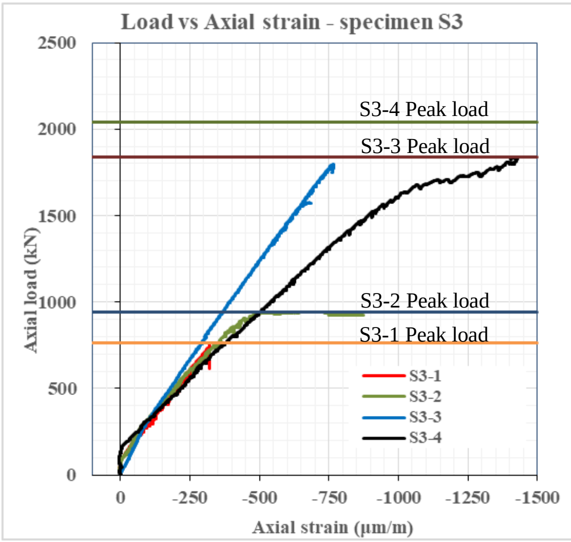

Figure 10: Axial strain plot for specimen S3-1 to S3-4.

For struts with loading plate less than 150 mm, crack initiated along centre line of struts and extended throughout the height of strut. Crack initiated from edge of the loading plate and extended to other end of strut for the struts with loading plate more than 150mm width. The failure mode of struts S1-1 to S1-4 is shown in Figure 11.

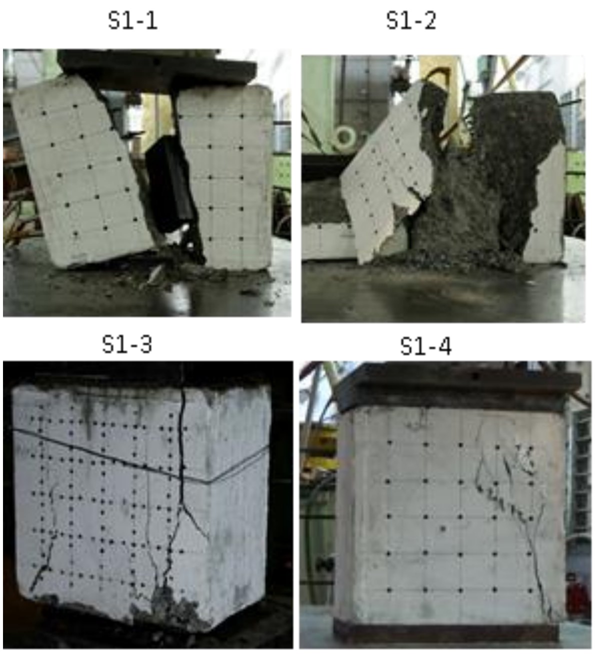

Figure 11: Failure mode of struts S1-1 to S1-4

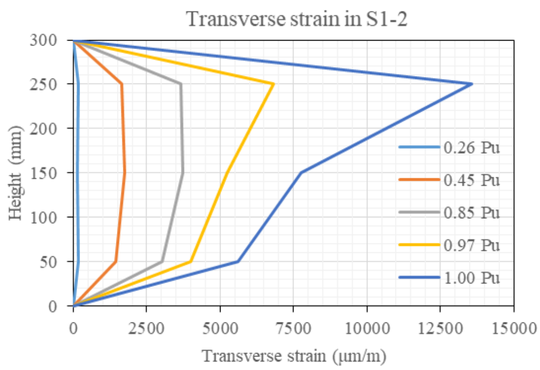

Figure 12: Transverse strain distribution of S1-2

Transverse strain along height of the strut is measured using LVDT's placed at specified gauge length. The transverse strain response for the struts S1-2, S2-2 and S3-1 are shown in Figures 12-14. Strut S3-1 is compared with struts S1-2 and S2-2, since cracking occurred outside the gauge length in strut S3-2. Transverse tensile strain is high in strut S1-1 compare to struts S2-2 and S3-1. Maximum tensile strain occurred in mid height whereas for struts S2-2 and S3-1 maximum strain occurred at the proximity of loading end.

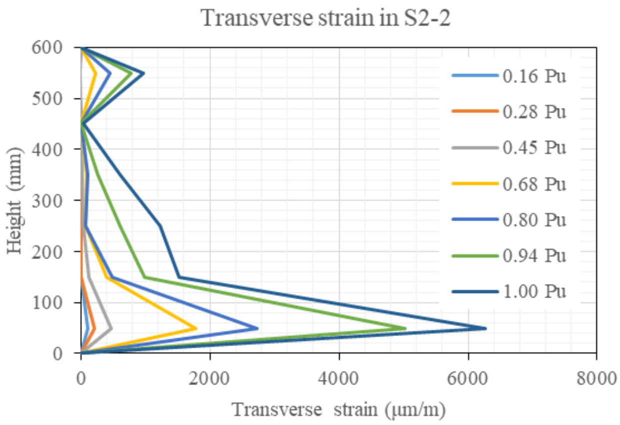

Figure 13: Transverse strain distribution of S2-2

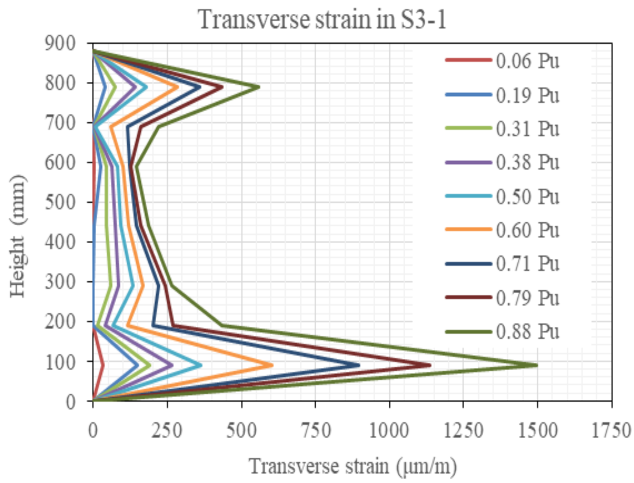

Figure 14: Transverse strain distribution of strut S3-1

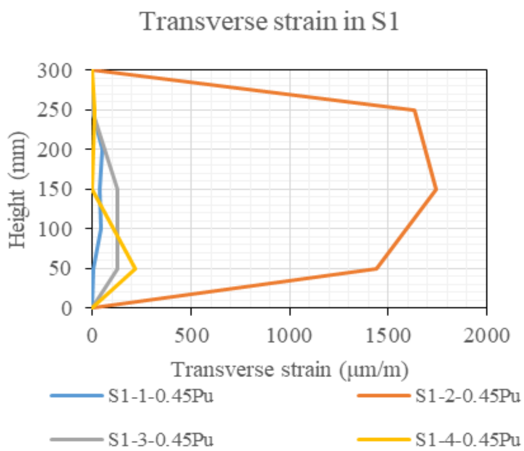

Figure 15: Transverse strain distribution in strut S1 at given axial load

Transverse tensile stress distribution is matching with the idealised strut model used for bottle-shaped struts [9]. For the given strut S1 under a particular loading, strut S1-2 had higher tensile strain. There is no reason found for this due to limited experimental data availability in this experimental study. The strut efficiency factor evaluated from experiments is less than 1.0 for struts in S1 group and its value increased for strut group S2 and S3. The mean value of strut efficiency factor is 0.95 with coefficient of variation of 20 %.

5 SUMMARY AND CONCLUSION

Bottle-shaped strut capacity has been estimated by reducing the uniaxial compressive strength by strut efficiency factor. Capacity has been reduced to take care of transverse tension that developed due to dispersion of compression stress trajectories. Unreinforced concrete isolated struts with different loading plates have been tested in this study. Transverse tension develops when the struts are loaded with loading plate width less than the strut width. There is no reduction in strength for bottle-shaped struts. Existing studies also found that the strength of struts is not reduced when its loaded plate width is less than strut width compared to fully loaded prismatic strut. From the experimental investigations, it has been found that the strut capacity is not influenced much by the width of the loading plate. The reduction in strength of the concrete strut is negligible as strut height increases. Hence, the strut efficiency factor recommended for the bottle-shaped struts in ACI 318 needs a revision.

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