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# EVALUATION OF THE STRENGTH OF STRUTS IN PILE CAPS USING STRUT AND TIE MODEL

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## ABSTRACT

Strut and Tie Model (STM) has been widely used for the analysis and design of disturbed, non-flexural and non prismatic members in reinforced concrete structures. The STM visualizes the disturbed members in RC structures as elasto-plastic region, where efficiency factors are applied to the compressive strength of concrete, to determine the strength of compression struts. The compressive forces are resisted by the concrete struts and the tensile forces are carried by steel bars. In typical deep members such as pile caps, the failure mainly occurs due to crushing of compression struts. Hence the exact failure strength of deep members like pile caps depends on the compressive strength of the concrete struts.

In this research six pile caps of different depths were designed on the basis of STM for the assumed external loads. The pile caps were later tested under monotonic axial loads applied at the middle of pile caps. The theoretical failure load of the pile caps was compared with the actual load carrying capacity of the pile caps. The strut strength corresponding to the failure load was worked out and compared with the theoretical strength of bottle shaped strut proposed by ACI-318. The failure loads given by Souza and Kuchma were also worked out and compared with the actual loads. The results have shown that the failure loads determined on the basis of STM according to ACI 318-06 are reasonably good predictor of strength of pile caps. The Souza *et al* model has given relatively large factor of safety as compared to ACI values. The actual strength reduction factor for bottled shaped compression struts corresponding to the failure loads were observed closer to the values proposed by ACI 318-06.

**KEYWORDS:** Disturbed; non flexural; non prismatic; pile cap; Strut and Tie Model.

## INTRODUCTION

The disturbed region sometimes referred to as “D-region” in reinforced concrete structures like deep beams, pile caps, dapped ended beams; corbels and non prismatic sections are subjected to complex stresses under external loads. Reliable analysis and design of such structures is not possible with the sectional analysis or ordinary beam theory. STM has been widely used as an alternative design tool for D-region in RC structures. Theoretically STM reduces complex states of stress within a D-region of a reinforced or pre-stressed concrete member into a truss comprised of simple, uni-axial stress paths. Each uni-axial stress path is considered as a member of the STM, which is either subjected to tensile stresses called “ties” and represent the location where reinforcement should be placed, or members subjected to compression called “struts”. The intersection points of struts and ties are called nodes. On the basis of the forces applied at the boundaries of the truss, member forces are worked out. The resultant stresses in each member are then compared with the permissible specified values by ACI 318. Selection of an appropriate STM for a structural element requires basic engineering judgment and past experience of the designer.

Historically the research on STM has been focused on evaluating the strength of three elements of STM, namely “Struts’, “Ties” and “Nodes”. The major contributions of the compression strength of struts and nodal zones in STM comes from (i) the cylinder concrete compressive strength $f_c^{'}$ (or cube concrete compressive strength $f_{cu}$); (ii) the orientation of cracks in the strut .i.e strut angle (iii) the width and the extent of cracks; and (iv) the degree of lateral confinement. The tensile forces in the “ties” are resisted by the steel reinforcement in the direction of such ties [1]. The strength reduction factor of concrete, sometimes called as efficiency factor of strut “$v$” is thus used to determine the effective compressive strength of struts. The effective compression strength of concrete struts is given by Eq(1)

$$f_c = v f_c^{'} \qquad (1)$$

Pile caps are typically disturbed region, where the shear failure is more dominant due to very small shear span to depth ratio and short moment arm; hence the ordinary beam theory based on sectional analysis cannot be used for analysis and design of pile caps.

Adebar *et al* (1990) tested six large pile caps designed by ACI-318-83 and STM for identical axial loads. Various patterns of main reinforcement and secondary reinforcement were used. From the failure patterns of the pile caps, they observed that the failure of deep pile caps don’t occurred due to crushing of concrete. Longitudinal splitting of concrete due to transverse tension caused by spreading of compressive stresses has cuased the failure rather. They recommended restricting the bearing stress of deep pile caps to 1.0 $f_c^{'}$ to prevent shear failure.

Siao (1993) proposed a simple method for predicting shear strength in deep beams and pile caps failing in diagonal splitting using STM. The proposed efficiency reduction factor of Siao [3] is given in Eq(2).

$$v = \frac{1}{1.14 + (0.64 + \frac{f_c^{'}}{470})(a/d)^2} \qquad \text{[Imperial units]} \qquad (2)$$

Adebar and Zhou (1993) proposed a simple rational design method for deep pile caps in which maximum bearing stress was considered as a better estimate for shear strength than shear stress on any prescribed section. They recommended the maximum bearing stress for deep pile caps as given in Eq. (3).

$$f_b = 0.6 f_c^{'} + \alpha\beta 72\sqrt{f_c^{'}} \qquad \text{[Imperial units]} \qquad (3)$$

Where $f_b$ denotes bearing stress in nodal zone of deep pile caps. The values of $\alpha, \beta$ are given in Eq. (4).

$$\alpha = \frac{1}{3}\left(\sqrt{A_2/A_1} - 1\right) \leq 1.0 \quad \text{and} \quad \beta = \frac{1}{3}\left(\frac{h_s}{b_s} - 1\right) \qquad \text{[Imperial Units]} \qquad (4)$$

$f_b$ and $f_c^{'}$ are in psi and $\beta$ accounts for confinement of compression strut. $A_2/A_1$ is same as used in ACI-318 and $\frac{h_s}{b_s}$ is aspect ratio (Height to width ratio) of compression struts.

Tan *et al* (2001) applied the direct STM to pre-stressed deep beams. They developed an expression for calculating the crushing strength of diagonal strut for pre-stressed deep beams on the basis of STM incorporating the combined tensile strength of longitudinal reinforcement, web reinforcement, pre-stressed tendons amount, and tensile strength of concrete. They reported that proposed STM has yielded consistent and accurate prediction of shear strength of pre-stressed deep beams.

Yun (2000) applied non linear techniques in the selection, analysis and verification of STM instead of conventional STM approach for disturbed region. He proposed that initially, the plain concrete may be modeled and analyzed nonlinearly with the help of Finite Elements Analysis (FEA). The principal stress flow may be displayed as a result, which shall assist in sketching the STM. The STM is then analyzed linearly to determine the cross sectional areas of struts and ties. The process is continued till the geometric compatibility condition of the model is satisfied. The non linear analysis and subsequent selection of the STM on the basis of stresses trajectories, helped in selection of the most appropriate STM for non linear structures.

Hwang and Lee (2002) presented the concept of softened STM for strength prediction of discontinuity region. The softened STM satisfied equilibrium, compatibility and constitutive laws of cracked concrete. They developed the softening factors of struts given by Eq(5)

$$\xi \approx 3.35\sqrt{f_c^{'}} \leq 0.52 \quad (5)$$

They further applied the proposed method to the database of 449 deep beams, walls and beam column joints and reported satisfactory correlation between the predicted and actual failure loads of these structures.

Taher (2005) applied the fundamental shear failure mechanisms for pile caps i.e. beam failure mechanism and truss mechanism for the load transfer of pile caps. Basically the ACI-318 sectional design is based on the beams mechanism and the Canadian design of pile caps is based on the truss approach. He proposed a modified STM incorporating the beam action beside the strut action of traditional STM approach. This hybrid approach accounted for the design of both shallow as well as deep pile caps. His design procedure catered for the beams mechanism as well as truss mechanism for the failure of the pile caps. The obvious advantage of the procedure given was to cover the possible failure mechanism of the pile caps. Hence a high degree of accuracy can be expected from this approach. The author analyzed six pile caps having different geometric properties, reinforcement percentage and patterns, with the help of his proposed hybrid approach which gave very reasonable estimates of actual failure loads of the pile caps.

Tjhin and Kuchma (2002) proposed Computer Aided Strut and Tie (CAST) design tool to overcome the complications and challenges faced in the STM design process. The design tools of CAST provides for STM generation, constructing of nodal zones, determining of truss member forces, and prediction of load deformation and capacity of disturbed regions.

Sergio Berna and Morrison (2007) applied STM proposed by Schlaich *et al* (1987) to the deep beams with opening and observed that the measured strength of laboratory specimen was much higher than the design strength of STM. They also identified the sources of over strength in deep beams. This increase comes from the contributions of secondary steel bars, and concrete contribution in tie strength, which is often neglected in the STM design. However further research was recommended for evaluating these contributions.

Carlos *et al* (2006) evaluated the strength reduction factor for STM applied to deep beams and compared it with the values proposed by ACI-318. They observed that the main design variable were main strut angle, amount of web reinforcement crossing the struts and concrete strength. They found that the strength factor for struts in case of Normal Strength Concrete (NSC) is adequate. For High Strength Concrete (HSC) deep beams they recommended minimum web reinforcement of 0.01 when strength factor is 0.60.

Miriam *et al* ( 2008) gave comparative analysis of the behavior of pile caps supported by three piles caps and subjected to axial loads. They used various configurations of secondary steel bars. The pile caps were designed on the basis of STM. The pile caps were tested to failure and the theoretical loads were compared with ultimate loads of pile caps. They studied the influence of diameter reduction, crack width, bases displacement, stress in the lower nodal zones, stress in the upper nodal zones, strain in concrete, strain in reinforcement, and failure modes of pile caps. They further proposed the following values for the upper nodal zones and lower nodal zones for the two depths of the pile caps tested as. The stresses in upper nodal zones for 20 cm deep pile caps are given by Eq(6).

For D= 20 cm

$$\sigma_{unz} \leq 0.40 f_{cm} \quad \text{Stress in Upper Nodal Zones} \quad (6)$$

The stresses in lower nodal zones for 20 cm deep pile caps are given by Eq(7).

$$\sigma_{Lnz} \leq 0.50 f_{cm} \quad \text{Stress for lower nodal zone pile caps.} \quad (7)$$

The stresses in the upper nodal zone of 30 cm deep pile caps are given by Eq(8)

$$\sigma_{unz} \leq 0.30 f_{cm} \quad \text{Stress in upper nodal zones.} \quad (8)$$

Taher (2006) used the concept of iterative Non Linear Finite Element Analysis for identification of the expected load path of the pile caps and subsequent load transfer mechanism. He proposed an analytical procedure for the unified design of pile caps incorporating both the Code concepts and characteristic load path. He reported that the proposed analytical method provided better agreement between the theoretical and actual failure loads of the pile caps than ACI-318 and Canadian Code.

Souza *et al* (2009) further extended the STM for the design of four pile cap supporting axial compression and biaxial bending. They simplified the earlier adaptable three dimensional truss model proposed by Souza *et al* [16] to determine the reaction on the piles, the internal angles and the forces in the struts and ties. The simplified model is shown in Fig.1. They also applied this simplified model to the experimental database of pile caps already tested with shear span to depth ratio ranging from 0.44 to 1.99. They observed that shear failure in the plies caps is generally the result of longitudinal splitting of compression strut. To avoid this sort of failure, they proposed a compressive stress less than 1.0 $f_c$ shear span to depth ratio under 1.0, which can lead to ductile failure and the yielding of longitudinal steel, can precede the splitting or crushing of compression struts.

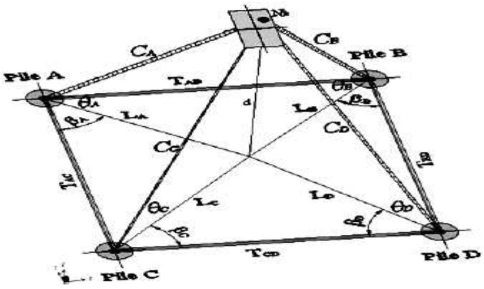


**Figure 1. Proposed STM for four-pile caps supporting rectangular columns (Souza et al,2009)**

The adoptable model of Souza *et al* (2009) tried to develop expressions for the flexural failure loads, shear failure loads and mode of failure based on the concrete and steel stresses, longitudinal steel volume and type of placement. The adaptable model was proved successful in predicting the load carrying capacity of the four pile caps on one hand and failure mode on the other hand. The tested pile caps were also analyzed with the help of Souza *et al* model. They have proposed the following expression for the loads causing flexural failure of the pile cap.

$$N_{ff} = -\frac{4\phi_y A_s D f_y d}{e} \tag{9}$$

For the load causing shear failure of the pile caps, the following equation was proposed;

$$N_s = -2.08 b d f_c^{2/3} \tag{10}$$

ACI SP208 (2000) based on the application of STM for the design of pile caps by ACI-Sub Committee 445-1 (2000), has reported the following results.

1. STM can be adopted to pile caps carrying vertical loads and overturning moment.
2. Design depends on the judgment of the truss model.
3. Assumption of square struts may be followed to simplify complex truss geometry in three dimensional analyses. The node areas must be sufficient.

4. STM design has been reported to lead to greater depth of pile caps and more quantity of longitudinal reinforcement.
5. STM design being rational may lead to better performance to avoid the brittle failure of pile caps.

Sufficient research has been carried out on the general principles of STM in last two decades. The works of Marti (1985), Collins and Mitchell (1986) and Schlaich *et al*. (1987) constitutes important building blocks for in depth research on STM. Researchers have also tried to determine the strengths for the different types of nodes and struts through both lab testing and analytical research. Though vast research has been carried out on STM, yet there seems no consensus amongst the researchers on the strength of the struts and nodes of STM. In the present work six pile caps of same square area but different depths were designed on the basis of STM. The pile caps were then tested in the laboratory to determine the failure load, the failure angles of struts. The compressive strengths of struts coinciding with the failure loads were determined and compared with the values proposed by ACI-318.

## RESEARCH OBJECTIVES

The research objectives can be summarized as follows:

i. Investigation into the failure modes, deformation and failure angle of the compression struts of six pile caps tested.
ii. Comparison of the crack patterns as well the actual angle of the strut with the theoretical inclination of struts in the proposed STM.
iii. Comparison of the actual failure loads with the theoretical load carrying capacity of the pile caps on the basis of STM according to ACI 318-06 and model proposed by Souza and Kuchma and check the suitability of the STM for design of pile caps.
iv. Determination of the theoretical strength of the compression struts and its comparison with the actual strength of struts at the failure.
v. Checking the reasonability of strength reduction factor for compression struts proposed by ACI-318 on the basis of actual failure loads.
vi. The test results will add to the limited research data of design and investigation of pile caps based on the application of STM.

## MATERIAL AND SPECIMEN DETAILS

In this experimental program, 6 piles caps in three sets of 2 pile caps each were included. The surface area of all the pile caps was kept the same as 750mmx750 mm. However the depths were kept as

220mm, 380 mm, and 460 mm respectively for three sets of pile caps. The shear span to depth ratio for the three sets of pile caps comes out to be 1.0, 0.60 and 0.50 respectively. The application of the test results to the actual pile caps in the field may be extended on the basis of the shear span to depth ratio as adopted in most of the research on pile caps and deep members in RC structures. The details of the pile caps are given in Table 1.The shear span to depth ratio for the pile caps comes out to be about 1. Coarse aggregates of 12mm down sizes, fine aggregates of fineness modulus of 2.65 and Ordinary Portland Cement of Type-1 was mixed in the nominal ratios by volume shown in Table 1. The water cement ratio was kept as 0.48. Longitudinal steel bars having specified yield stress of 414 MPa was used in the experimental work. The 28 days cylinder compressive strength of concrete is also given in Table 1.

The pile caps were designed on the basis of Strut and Tie Models, using the ACI 318-06 procedure. Since each pile cap is comprised of four pile supports, therefore four STM are assumed to develop along each face of pile cap and the load carried by each STM is ¼ $^{th}$ of the total assumed external load for which the pile cap has been designed ( Plane 2 D analysis). The closer analogy of the model can be given by 3D (Pyramid like model). For analysis of 3D model for the assumed STM, SAP-2000 was used. Further details about the analysis are given in Appendix. The details of member forces strut angle and steel reinforcement for three sets of pile caps are given in Table 2.

## TESTING OF PILE CAPS AND OBSERVATIONS

The pile caps resting on four circular rigid cylinders of 150 mm diameter were tested under monotonic external loads applied through a hydraulic system, attached to a calibrated proving ring. The tests were conducted at the Structural Engineering Laboratories, Engineering University Taxila-Pakistan. To measure strain of concrete inside the pile caps, sensor embedment gauges (LVDT's) were used, which has an active gauge length of 100mm, placed monolithically in 130mm rugged polymer concrete hard cover to resist mechanical damage during pouring of concrete. The polymer cover having the gauge becomes part of the concrete on hardening and any strain in the concrete after application of the load, is transferred to the gauge inside the polymer cover, which is measured by the data logging system. The schematic diagram of the concrete embedment gauge is shown in Figure 2.

Table 1. Dimensions, concrete mix proportioning and compressive strength of pile caps used.

| Pile Caps Set | Pile caps title | Pile caps dimensions ( | | | Nominal ratio of concrete | Average Compressive Strength of Concrete $f_c'$ (MPa) |
|---|---|---|---|---|---|---|
| | | Length | Width | Depth | | |
| 1 | PC1 | 750 | 750 | 220 | 1:2:4 | 21 |
| | PC2 | 750 | 750 | 220 | 1:2:4 | 21 |
| 2 | PC3 | 750 | 750 | 380 | 1:1 ½ :3 | 30 |
| | PC4 | 750 | 750 | 380 | 1:1 ½ :3 | 30 |
| 3 | PC5 | 750 | 750 | 460 | 1:1 ½ :3 | 30 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | PC6 | 750 | 750 | 460 | 1:1 ½ :3 | 30 |

Table 2. Member forces strut angle and details of main and distribution steel for pile caps.

| Pile caps Set (mm) | Total external load (kN) | Load transferred to the STM (kN) | Strut angle (degrees) | Member Forces (kN) | | | Steel reinforcement | |
|---|---|---|---|---|---|---|---|---|
| | | | | Struts | Ties | | | |
| | | | | | Force (kN) | $As_{req}$ ($mm^2$) | Main ($mm^2$) | Dist |
| 1(PC-1 and PC-2 (750X750x220) | 445 | 111.25 | 29.51 | 226 | 197 | 633 | 5#13 Bunched (663$mm^2$) | #10@150 |
| 2 ( PC-3 and PC-4) 750X750x380 | 890 | 222.50 | 51.61 | 284 | 176 | 603 | 3#16 Bunched (685 $mm^2$) | #10 @100 |
| 2 ( PC-5 and PC-6) 750X750x460 | 1065 | 266.25 | 58.27 | 313 | 164 | 530 | 3#16 Bunched (685$mm^2$) | #10 @ 75 |

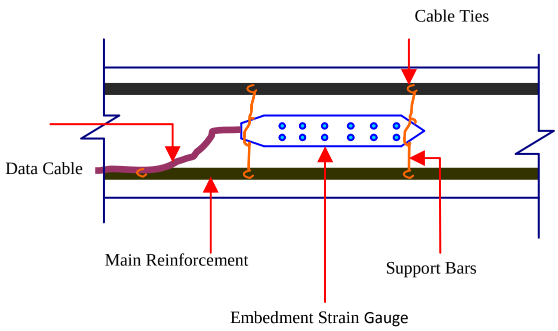


**Figure 2. Schematic diagram of concrete embedment gauge placed inside the concrete to measure the stain in steel.**

The strain gauges (LVDT's) were placed along the theoretical direction of the concrete struts and longitudinal steel bars to measure the strain of the concrete struts and steel bars respectively, inside the concrete. This also helped in assessing the failure mode of the pile caps. The location of the LVDT's is shown in the 3D hypothetical model in Figure 3.

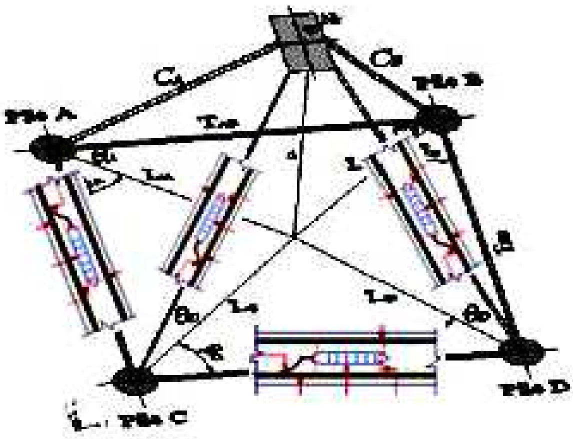

**Figure 3 Location of LVDT's (Strains gauges) placed along the struts and ties.**

The loads were gradually applied at the centre of the pile cap with the help of 150 mm circular rigid steel plate acting as a circular column. The pile caps have transferred the applied axial load to the piles in four equal parts. The monotonic load was applied at a uniform rate at 5kN increment after every 30 seconds (0.17kN/sec).

When loads were gradually increased small flexural cracks appeared in the middle third region of the pile caps. With further increase of axial loads, the number of flexural cracks increased and at the same time flexural cracks also appeared in the regions near the pile caps. Form the tips of theses cracks , diagonal cracks originated toward the centre of the pile caps, where the load was applied. In some cases two identical diagonal cracks appeared at same distance from the centre of the pile cap. When loads were enhanced further, the width of the diagonal cracks increased and ultimately caused the failure of the pile caps. Loads were marked on cracks to show the loads corresponding to certain depth of the crack. The strain of the struts and steel bars were also noted from the strain gauges through data logging system. The loads corresponding to first flexural crack are noted and expressed as $V_{cr}$ , the failure load has been expressed as $V_u$ and the theoretical load corresponding to the assumed Strut and Tie Model Souza *et al* model have been worked out and given in Table 3 for all the six pile caps.

The first crack has normally occurred in the range of 50-60 % of the failure loads. The strain in the main steel has shown that none of the main steel bars have been yielded in the testing and rather the compressive strain in the struts has caused the failure of the pile caps. This fact has been further explained in next section. Failure of the pile caps is caused due compression failure of struts. The actual failure load of the pile caps were observed at an average of 14% more than the theoretical values of failure loads worked out on the basis of assumed STM proposed by ACI and 28% more than proposed by Souza and Kuchma (2009) . This shows that STM provides a factor of safety at an average of 14% for the tested six pile caps, which is quite reasonable.

**Table 3. Comparison of loads at first craks, theoretical and actual failure loads of pile caps.**

| Pile caps title | $V_{cr}$ (kN) | $V_{STM}$ (kN) | V (Souza et al) (kN) | $V_u$ (kN) | $V_u/V_{cr}$ | $V_u$ / $V_{STM}$ (ACI) | $V_u$ / $V_{STM}$ (Souza et al) | Strut angle | | Failure mode as predicted by | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | STM | Act | **STM** | **Souza** |
| PC-1 750X750x2 | 65.5 | 106.6 | 99 | 125 | 1.91 | 1.17 | 1.26 | 29 | 30 | Strut Failur | Flexural Failure |
| PC-2 750X750x2 | 87.5 | 106.6 | 99 | 123 | 1.4 | 1.15 | 1.24 | 29 | 32 | Strut Failur | Flexural |
| PC-3 750X750x3 | 136.5 | 250.9 | 193 | 260 | 1.91 | 1.04 | 1.34 | 51 | 54 | Strut Failur | Flexural |
| PC-4 750X750x3 | 112.8 | 250.9 | 193 | 258 | 2.30 | 1.02 | 1.33 | 51 | 58 | Strut Failur | Flexural |
| PC-5 750X750x4 | 145.6 | 279.2 | 238 | 306 | 1.82 | 1.09 | 1.28 | 58 | 62 | Strut Failur | Flexural |
| PC-6 750X750x4 | 151.2 | 279.2 | 238 | 302 | 2.0 | 1.08 | 1.27 | 58 | 68 | Strut Failur | Flexural |
| | | | | Mean | 1.89 | 1.09 | 1.28 | | | | |

The comparison of actual and theoretical failure values are given by ACI and Souza *et al* is given in Figure 4.

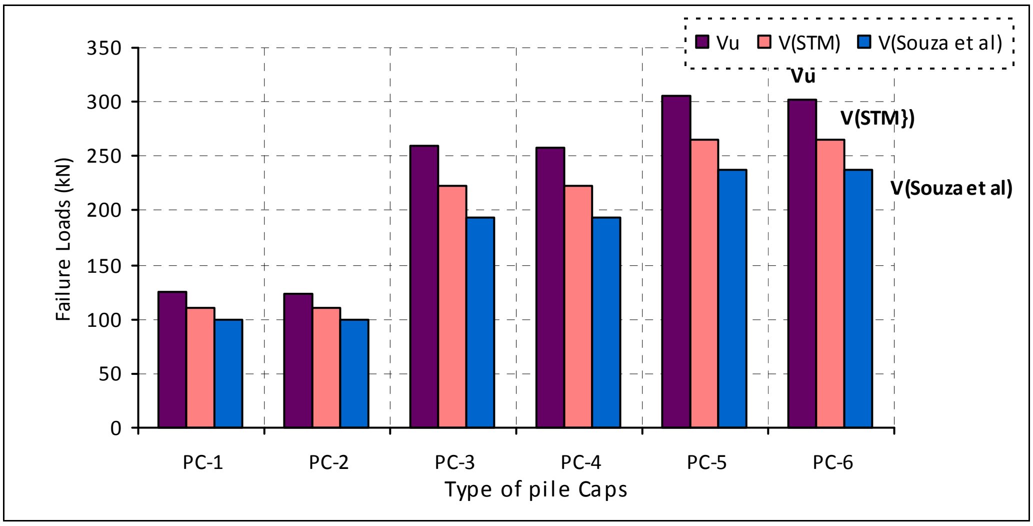


**Figure 4 Comparison of actual failure loads of pile caps and values given by STM (ACI) and Souza et al Model**

Some of the cracking patterns of pile caps are given in Figure 5. Initially some flexural cracks have appeared in the pile caps, but with further increase in the loads, diagonal shear cracks initiated from the face of the pile cap and extended towards the centre of the pile caps, where the external loads are applied. These diagonal cracks have finally caused the failure of the pile caps. The failure angle was roughly measured from the inclination of the crack causing the failure of the pile caps and was compared with the theoretical value of the strut angle. The illustrations in Fig. 3 show that diagonal cracking is the major failure mode of deep pile caps.


**Figure 5. Failure modes of pile caps under external axial loads.**

## COMPARISON OF STRUTS AND NODES STRENGTH WITH THE FAILURE LOADS OF PILE CAPS.

In design of pile caps by STM, the member forces under external axial loads in the struts and nodes are compared with the allowable strengths of the struts and nodes given by ACI318. It is assured that at no section the ACI318-06 limits are exceeded. For the pile caps tested, the strengths of struts are determined and the theoretical failure load corresponding to this strength is worked out as shown in Table 4.

The results have shown that the theoretical load carrying capacity of pile caps on the basis of the strength of compression struts as per ACI318-06 is at an average 9% more than the actual failure loads of the tested pile caps, which signifies the reliability of the STM for design of tested pile caps. This has also verified the failure modes of the pile caps tested, which have failed due to failure of compression struts, as the controlling value of load carrying capacity of pile caps comes from the values of the diagonal struts. The reading of concrete embedment gauges have shown that none of the main steel bars bunched along the piles has yielded and the pile caps have failed without yielding of the steel bars. This further supports the existing observations by many researchers cited in the earlier parts, that failure in deep pile caps is mostly occured due to compression failure of the diagonal concrete struts. The strength reduction factors for compression struts $\beta_s$, were worked out for all the six pile caps tested and shown in Table 5.

Table 5. Details of struts dimensions strut strength, theoretical load carrying capacity of pile caps as per STM and its comparison of actual failure loads.

| Pile caps title, sizes and $f_c'$ | Strut area (mm$^2$) $Ws.b_w$ | $\phi f_{cu\,(1\text{-}2)} = 0.85.\beta_S \cdot f_c'$ (MPa) | Strut strength $\phi f_{cu}$ $Ws.b_w$ (kN) | Strut Angle (degrees) | Node strength $\phi f_{cn}$ $Ws.b_w$ (kN) | Failure load ( kN) | | $V_{ult}/V_{STM}$ |
|---|---|---|---|---|---|---|---|---|
| | | | | | | STM ($V_{STM}$) | Actual ($V_{ult}$) | |
| PC-1 750x750x2 | 146x150 | 13.4 | 219.9 | 29 | 234.55 | 106.6 | 125 | 1.17 |
| PC-2 750x750x2 | 146 x150 | 13.4 | 219.9 | 29 | 234.55 | 106.6 | 123 | 1.15 |
| PC-3 750x750x3 | 150x150 | 19.1 | 322.7 | 51 | 344 | 250.9 | 260 | 1.04 |
| PC-4 750x750x3 | 150x150 | 19.1 | 322.7 | 51 | 344 | 250.9 | 258 | 1.03 |
| PC-5 750X750x4 | 153x150 | 19.125 | 329.20 | 58 | 350.88 | 279.2 | 306 | 1.10 |
| PC-6 750x750x4 | 153x150 | 19.125 | 329.20 | 58 | 350.88 | 279.2 | 302 | 1.08 |
| | | | | | | | **Mea** | **1.09** |

Note: The final strength of the STM is controlled by strut strength rather than nodal strength

The average value of $\beta_s$ comes out to 0.83, which is slightly more than proposed value of 0.75 for bottled shaped CCC strut by ACI-318-06.

## LOAD DEFORMATION CHARACTERISTICS OF THE PILE CAPS.

The load deformation characteristics of the pile caps were studied with help of deflection gauges and strain gauges. Deflection gauges were placed at the mid span of the pile caps to measure the mid span deflection of the pile caps under various levels of loads, where as the strain gauges were placed along the theoretical inclination of the struts and steel bars inside the concrete to measure the strain of the compression strut and steel bars. The load deformation curves are given in Fig 6.

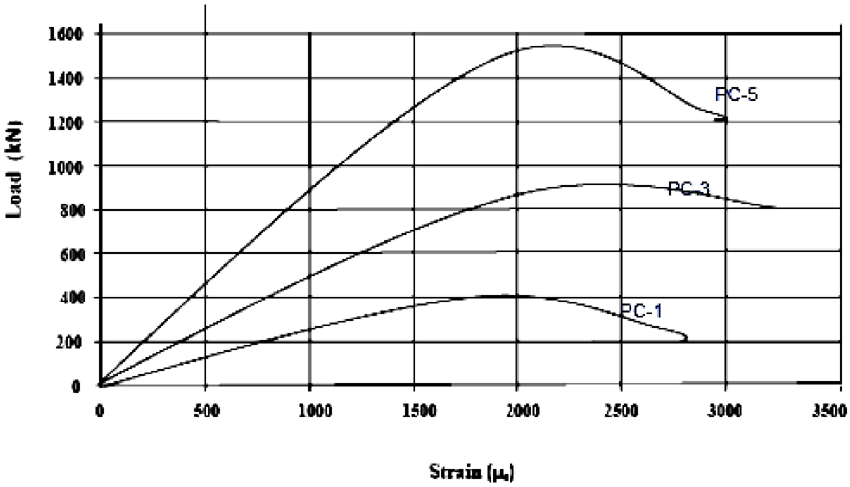


**Figure 6 Load strain curves for three groups of pile caps.**

Table 5. Strut strength reduction factors on the basis of actual failure loads of the pile caps

| Pile caps | Load at Failure ($V_u$) (kN) | Strut angle (degrees) | Force carried by diagonal strut $V_u / \sin\theta_1$ (kN) | $\phi 0.85\ f_c'\ w.b$ | $\beta_s$ |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6=4÷5 |
| PC-1 750x750x220 | 125 | 29 | 258 | 293 | **0.88** |
| PC-2 750x750x220 | 123 | 29 | 253 | 293 | **0.86** |
| PC-3 750x750x380 | 260 | 51 | 339 | 429 | **0.79** |
| PC-4 750x750x380 | 258 | 51 | 336 | 429 | **0.78** |
| PC-5 750X750x460 | 306 | 58 | 365 | 438 | **0.83** |
| PC-6 750x750x460 | 302 | 58 | 360 | 438 | **0.82** |
| | | | | Mean | **0.83** |

The typical load deformation curve for one of the pile caps (PC-5) has been given in Fig.5. The Figure shows that the strain of the compression struts has reached the admissible values of 0.003 at total load of about 1200kN. Initially concrete behaved like elastic material up to total applied load of about 1065 kN and compressive strain of 0.001. The softening of concrete has started after this point and it continues to behave more like a plastic region, as there is no sizeable increase in the external load and the strain reaches to 0.0022 at 1350kN. Thus with a very small increase in the total axial load (1350-1065 = 285 kN) ,the strain has almost doubled. The crushing of concrete occurs at about 1200kN of total load. The failure load for the pile cap was taken as 1065, which corresponds to the value of axial load, where the concrete more behaves like elastic material. Since the STM is a lower bound solution and the stresses within the elastic limits are considered for analysis and design of RC structures, the loads corresponding to the plastic region are neglected. This is one of the basic underlying assumptions of the STM, which brings relatively more degree of safety for the structures designed on the basis of STM and enhances the confidence level of designers.

## LIST OF ABBREVIATIONS

$\alpha$ Angle of the strut , $a/d$ Shear Span to effective depth ratio.
$\beta_n$ The capacity reduction factor or efficiency factor of nodes. $\xi$ Softening factor of struts.
$f_b$ Bearing stress in nodal zone of deep pile caps. $f_c'$ 28 days cylinder concrete compressive strength .
$f_{cu}$ 28 days cube concrete compressive strength or Effective compressive strength of a node.
$f_c$ Effective compressive strength of struts, $F_{x::}$ Horizontal component of trust forces
$F_y$ Vertical component of strut forces. ,$F_{ns}$ Capacity of struts at node.
$\frac{h_s}{b_s}$ Height to width ratio of compression struts, $P_u$ Theoretical design load.
$v$ The capacity reduction factor or efficiency factor of struts., $V_u$ Ultimate shear strength.
$V_n$ Nominal shear strength.

**CONCLUSIONS**

The following conclusions are drawn on the basis of observations of the six tested pile caps:

1. The STM based design of pile caps for assumed external has given reliable results when compared with the actual failure loads in the laboratory.

2. The failure of the pile caps tested was more controlled by the failure of the compression struts rather than the yielding of the longitudinal steel bars. Hence the shear capacity of the pile caps may be checked on the basis of the actual strength of compression struts as the compression failure is more dominant mode in pile caps.

3. The ACI-318 method of STM predicted the failure load of the tested pile caps with more accuracy as compared to the proposed model of *Souza et al*

4. The strength reduction factors for diagonal struts of pile caps given by ACI 318-06 have been observed as slightly conservative for the tested pile caps, however further experimental work is recommended to justify this observation.

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## APPENDICES

### Design of Pile caps with the help of STM for assumed external loads

The three sets of pile caps were designed against the external loads of 100 Kips (445kN), 200 Kips (890kN), and 240 Kips (1065kN). For detailed design steps involved, piles caps of set 2 (PC-3 and PC-4) are considered having size of 750mmx750mmx380mm.

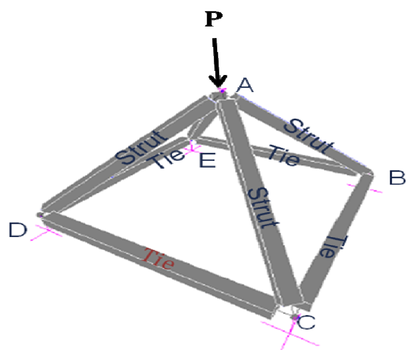


**Figure A-1. Assumed STM for the Pile Cap of size**

The pyramid shaped model of STM (3D) is exhibited in Figure A-1. The assumed 3D model was analyzed with SAP-2000. The details of bottom node after resolving the 3D model by SAP 2000 are shown in Figure A-2. The details of top node are shown in Figure A-3. The member forces in the assumed truss model are given in Table A-1.

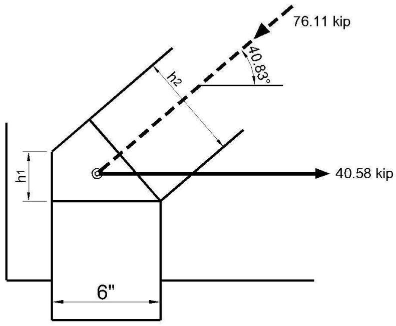


**Figure A-2 Details of bottom node of pile caps using 3 D analysis.**

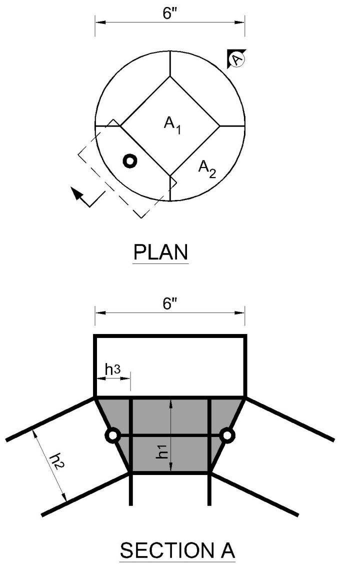


**Figure A-3: Details of top node of the pile caps in 3D analysis.**

**Table A-1 details of member forces in 3D analysis, required and provided steel reinforcement in pile caps**

| Pile caps Set | Assumed Total external load (kN) | Load transferred to the STM (kN) | Strut angle (degrees) | Member Forces (kN) | | Steel reinforcement | |
|---|---|---|---|---|---|---|---|
| | | | | Struts ( Comp) | Ties ( Tension) steel *As* eq ($mm^2$) | Main steel | Dist steel |
| 1 ( PC-1 and PC-2) 750X750x220 | 445 | 111.25 | 29.51 | 266 | 196.82<br>(633 $mm^2$) | 5#13 Bunched (663$mm^2$ | #10@150 |
| 2 ( PC-3 and PC-4) 750X750x380 | 890 | 222.50 | 51.61 | 335 | 176.5<br>603$mm^2$ | 3#16 Bunched (685 $mm^2$) | #10 @100 |
| 3 ( PC-5 and PC-6) 750X750x460 | 1065 | 266.25 | 58.27 | 355 | 164.4<br>530 $mm^2$ | 3#16 Bunched (685$mm^2$ | #10 @ 75 |

Compression force along the strut = 75 kip.(335 KN).
Tension force along the tie = 39.5 kip.(176.5 KN).
Now $\phi P_{nt} = \phi A_{st} f_y \geq P_u$ .

- ⇨ (0.85)( $A_{st}$)(60) ≥ 50 kip.
- ⇨ $A_{st} \geq 0.98$ in$^2$. (639mm$^2$)
- ⇨ Provided steel 3#16 bunched bars ( As=685mm$^2$)

The strengths of struts and nodal zones were determined with the help of ACI procedure and compared with the member forces under external loads. The finally designed pile caps are shown in Figure A-4. The detailed calculations of the design are provided due to limitation of space.

## CALCULATION OF THE STRUT STRENGTH UNDER THE FAILURE LOADS AS PER ACI318-09 PROCEDURE

For pile caps of set 2 (PC-3 and PC-4), we have worked out the compressive strength of strut $_{(1-2)}$
$= \phi F_{ns(1-2)} = \phi\, f_{cu\,(1-2)}\, Ws_{(1-2)}\, b_w = 322.73kN$ ( already calculated)
The strut angle is 51 degrees. The vertical load for the strength of strut = 322.73xSin51=**250 kN**
The capacity of the strut at node$_{-1}$ above the pile is given as $F_{nn(1-2)} = [\ \phi\ 0.85\ \beta_n\ \ f_c'\ ]\ \ [\ b.\ w_s\ ]$
For CCT node $\beta_n = 0.8$ and strut strength at node is given as ;
$F_{1-2}$= 0.75x0.85x0.8x30x150x150=**344kN**

Capacity of strut 1-2 at node-2 = $\phi F_{ns(1-2)} = \phi\ f_{cu(2)}\ \ Ws_{(1-2)}\ b_w$ = 25.5x1.0x150x150= **573 kN**

The minimum value of these is **250kN** controls**.** This is the load which can be carried by pile cap for the assumed STM through its compression strut. The actual failure load carried by the PC-3 and PC-4 is 260kN and 258 kN respectively, which is slightly more than the theoretical load carrying capacity of STM. In similar ways the theoretical load carrying capacities of other two sets of pile caps were also worked out on the basis of the strength of compressive struts using ACI 318-06 procedure.

## CALCULATION FOR CAPACITY REDUCTION FACTOR OF COMPRESSION STRUTS

The actual capacity reduction factors for struts and nodes have been worked out by equating the failure load to the strut capacity. For example continuing with the earlier calculations for PC-3, the failure load = 260kN and the angle is 51 degrees. The strut force= 260/sin51= 334kN

The strut strength is given by $\phi F_{s(1-2)} = \phi 0.85\ \beta_s\ f_C'\ \ w.b$
$= 0.75x0.85x30x150x150\ \beta_n l1000 = 430\ \beta_s$

By equating the two values we get $\beta_s = 0.78$

The values of $\beta_s$ are calculated for all six pile caps.

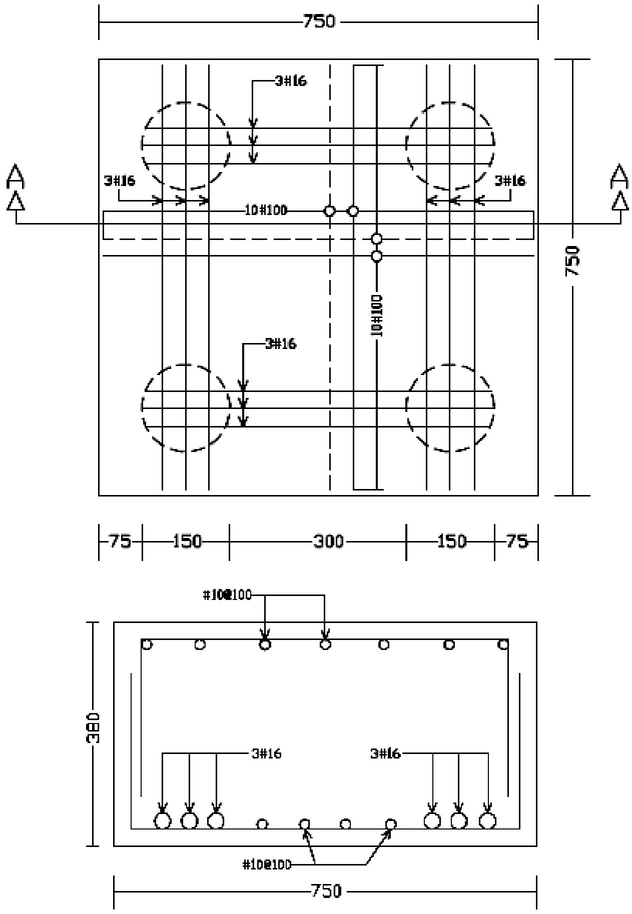


**Figure A-3. Details of main steel and distribution steel provided in pile caps PC3 and PC-4**