Comparative Analysis of Pile Cap Design Using Strut-and-Tie Method (ACI 318-2005) and Conventional Methods

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ABSTRACT

The design of pile caps is a critical aspect of structural engineering, particularly for transferring loads from superstructures to pile foundations. This study evaluates the effectiveness of the Strut-and-Tie Method (STM), as specified in ACI 318-2005, in comparison to conventional design methods outlined in IS 456-2000, IRC 21, and Thin Plate Theory. The analysis focuses on pile caps supported by two-pile, three-pile, and four-pile groups subjected to axial loads.

Key findings reveal that STM consistently results in higher design forces and longitudinal reinforcement requirements than IRC 21 and IS 456-2000. The deep beam action approach in IS 456-2000 underestimates reinforcement in discontinuity regions (D-regions), while the STM provides a more comprehensive representation of force flow through compression struts, tension ties, and nodal zones. For two-pile and four-pile groups, STM yields higher reinforcement demands than Beam Action methods, highlighting the significance of considering D-region behavior in these configurations. Conversely, for three-pile groups, STM results in slightly lower reinforcement requirements, reflecting the redistribution of forces due to increased redundancy.

Among conventional methods, Thin Plate Theory demonstrates the closest alignment with STM results, indicating its relative effectiveness in capturing thickness effects in pile caps. The findings emphasize the necessity of adopting STM for the design of D-regions to ensure structural safety and efficiency, particularly for complex pile cap configurations. This study advocates for revising existing design codes, such as IS 456-2000, to incorporate modern methodologies like STM for a more reliable approach to pile cap design.

Keywords: Strut and Tie Method, Pile cap, D-region, Strut and Tie Model (STM).

INTRODUCTION

In traditional design practices, pile caps are often assumed to act as beams spanning between the piles. Pile caps are critical structural elements designed to transfer the loads from a column or wall to a group of concrete piles, ensuring that the applied forces are effectively distributed to the foundation system. A pile cap's smallest dimension often classifies it as a deep pile cap, where conventional design assumptions may not accurately capture its structural behavior.

Commonly used design approaches, such as beam action, deep beam action, and thin plate theory, are frequently applied in practice. However, these methods largely ignore the complex thickness behavior of pile caps. This limitation may lead to inaccuracies in the analysis and design, potentially resulting in either overly conservative designs or insufficiently detailed reinforcement layouts.

In contrast, the Strut-and-Tie Method (STM), as permitted by ACI-318-2005, provides a more rational and comprehensive framework for pile cap design. The STM explicitly accounts for the three-dimensional thickness behavior of the pile cap, enabling the development of a truss-like model that represents the flow of forces through struts (compression members), ties (tension reinforcement), and nodes (regions where forces converge). This approach often results in more reliable and conservative designs compared to conventional methods.

This paper presents an analytical study of deep pile caps subjected to axial loads and supported by two-pile, three-pile, and four-pile group configurations. The pile caps are designed using the Strut-and-Tie Method as specified by ACI-318-2005 to determine the required longitudinal reinforcement. The results obtained are then compared with those derived from conventional design methods prescribed by IS: 456-2000.

In the study, the spacing of piles within each group is maintained as close as permitted by geotechnical considerations, in accordance with IRC-21 recommendations. By adopting a consistent pile spacing, the analysis focuses on understanding the influence of the STM and its potential advantages over traditional methods. The findings highlight the importance of incorporating the thickness behavior of pile caps into the design process and demonstrate the efficiency of STM in achieving optimized reinforcement detailing and overall structural integrity.

This study underscores the necessity of revising existing codes, such as IS: 456-2000, to include modern methodologies like STM for the design of deep pile caps, thereby improving the safety, reliability, and efficiency of such structural systems.

2. STRUT AND TIE MODEL METHOD (STM)

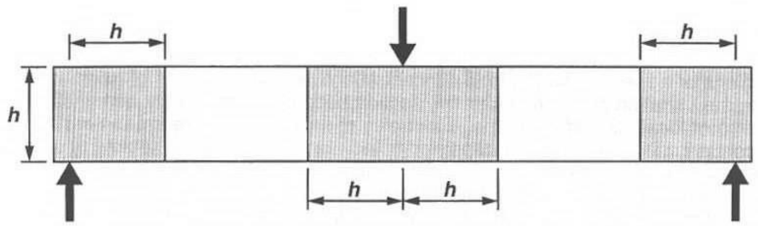
Concrete structures, whether reinforced or prestressed, can be broadly categorized into two types of regions based on their structural behavior: **B-regions** (Beam-like regions) and **D-regions** (Discontinuity regions). In B-regions, the beam-like behavior is valid, and the internal stresses and strains follow a linear distribution. This behavior is consistent with Bernoulli's hypothesis, which states that plane sections remain plane before and after bending. This simplification allows for a straightforward application of flexural design principles, including the assumption of a linear strain distribution across the depth of the section, even at ultimate flexural capacity.

However, in D-regions, the beam-type behavior is disturbed due to geometric or loading discontinuities. These regions are characterized by local concentrations of stresses caused by abrupt changes in geometry (such as at openings, supports, or corners) or by the application of concentrated loads. Bernoulli's hypothesis does not hold in these regions, as the strain distribution is nonlinear and the assumptions of plane sections are no longer valid. Instead, the behavior of D-regions is dominated by complex stress trajectories and requires a different analytical approach to accurately capture the structural response.

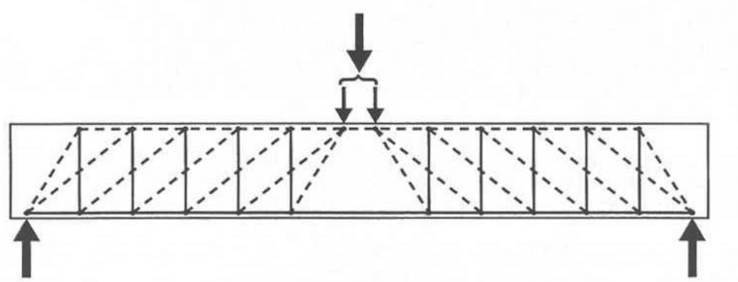
The design of D-regions is inadequately addressed in **IS: 456-2000**, which primarily focuses on beam-like behavior and relies heavily on empirical methods. This lack of specific guidance often leads to inconsistent or overly conservative designs for discontinuity regions, which may result in inefficient use of materials or even structural failures. In contrast, modern design methodologies, such as the **Strut-and-Tie Method (STM)**, provide a rational and systematic approach to designing D-regions. By representing a complex structural member with simplified truss models, STM facilitates the modelling of force transfer through compression struts, tension ties, and nodes, offering a more accurate representation of the structural behavior in D-regions.

Bernoulli's hypothesis, while pivotal for the design of B-regions, does not account for the unique challenges posed by D-regions. The reliance on this hypothesis in conventional design practices highlights the need for a paradigm shift in how discontinuity regions are analysed and designed. The adoption of advanced methodologies, such as STM, aligns with international design codes like ACI-318-2005, which explicitly address the design of D-regions and ensure a more efficient and reliable structural performance.

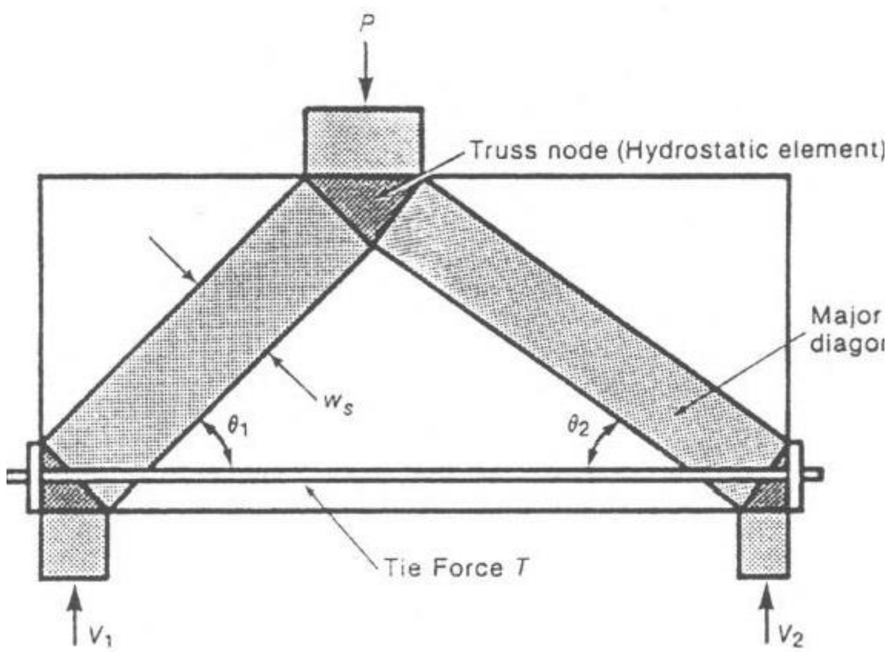
This distinction between B-regions and D-regions underscores the necessity of revising design codes, such as IS: 456-2000, to incorporate modern and rational approaches for handling the complexities of discontinuity regions. By doing so, the safety, durability, and material efficiency of concrete structures can be significantly enhanced.



a) B- and D-Regions



b) Strut-and-Tie Model for Entire Beam



Literature Review

Concrete structures are classified into beam-like regions (B-regions) and discontinuity regions (D-regions) based on their stress and strain behavior. This classification, introduced by Schlaich, Schäfer, and Jennewein (1987), forms the foundation for modern structural analysis. In B-regions, Bernoulli's hypothesis applies, allowing for linear strain distribution and facilitating the use of traditional flexural design methods (Hibbeler, 2017). However, in D-regions, stress distribution becomes nonlinear due to abrupt geometric changes or concentrated loads, necessitating alternative approaches for analysis and design (MacGregor & Wight, 2005).

IS 456:2000, the Indian standard for the design of concrete structures, largely focuses on beam-like behavior and lacks explicit provisions for D-region design. As highlighted by Verma and Kaushik (2012), the code primarily relies on empirical formulations, which may lead to inefficient or unsafe designs in regions with complex stress patterns. This gap in the Indian code contrasts with international standards such as **ACI 318-2005**, which incorporates the Strut-and-Tie Method (STM) for the design of discontinuity regions. STM, initially formalized by Ritter (1899) and later refined by Schlaich et al. (1987), uses truss models to represent force flow through struts (compression members), ties (tension reinforcement), and nodes (force-concentration points), offering a rational and systematic design approach (ACI Committee 318, 2005).

The limitations of traditional design methods, such as beam action, deep beam action, and thin plate theory, have been widely discussed. These methods assume simplified behavior and fail to capture the thickness effects and nonlinear strain distribution in pile caps and other D-regions (Brown et al., 2006). In contrast, STM accounts for these factors, leading to more accurate and conservative results, particularly for pile caps subjected to axial loads (Park & Gamble, 2000). Studies by Adebar et al. (1990) and Kuchma et al. (2008) have demonstrated the effectiveness of STM in predicting the structural behavior of pile caps and other D-regions, highlighting its advantages over conventional approaches.

The importance of pile cap design has also been emphasized in geotechnical contexts. Pile spacing, as governed by standards like IRC-21, plays a crucial role in force distribution and structural performance (Saran, 2010). The integration of geotechnical considerations with advanced structural design methods, such as STM, ensures the overall stability and reliability of pile-supported systems.

Given these advancements, researchers have called for updates to design codes such as IS 456 to incorporate modern methodologies like STM. By bridging the gap between empirical and rational design approaches, these updates could enhance the safety, efficiency, and durability of concrete structures, particularly in regions with complex stress patterns (Ramakrishna & Parameswaran, 2015).

In summary, while traditional design practices have served as a foundation for reinforced concrete structures, their limitations in D-regions necessitate the adoption of advanced methodologies like STM. The integration of STM into national and international codes represents a significant step forward in ensuring the structural integrity of complex concrete systems.

REVIEW OF PROVISIIONS IN CODES OF PRACTICE.

2.1 ACI-318-2005 (Strut and Tie Method)

STM design provisions consist of rules for defining the dimensions and ultimate stress limits of struts and nodes as well as the requirements for the distribution and anchorage of reinforcement. Guidelines [5, 6] for design by the STM have been developed for European practice. Provisions for the STM have been incorporated in the Canadian Concrete Design Code [7, 8] since 1984 and in the AASHTO LRFD [9, 10] code since 1994. Another specific set of provisions has been developed to be included as an alternative design procedure in the 2002 ACI code [11].

Angles between struts and ties should be at least 45° whenever possible. Exception from this rule is when a diagonal compression strut meets two ties in orthogonal direction. Angles smaller than 30° are unrealistic and involve high compatibility strains (ACI 318 permits angles up to 25°). The stress assumed in the compression field has been elaborated in FIB Bulletin 3 which incidentally is also adopted by ACI 318: 2005. This is given by the following equation:

$f_{cd,\,eff} = \nu\,(1- f_{ck.cyl}/250)\, f_{1cd}$

where

$f_{ck.cyl}$ = characteristic cylinder strength
f_{1cd} = design strength = $0.85\, f_{ck.cyl}/1.5$
Since IS:456-2000 refer to cube strengths
$f_{cd,eff} = \nu\,(1- f_{ck,cube}/300)\; 0.45\, f_{ck,cube}$

where
ν = 1 for uncracked sections

= 0.80 for struts with cracks parallel to strut and bonded transverse reinforcement
= 0.60 for struts transferring compression across cracks with normal crack width
= 0.45 for struts transferring compression across large cracks (members with axial tension, or flanges in tension)

Table1 Stress Limits and Strength Reduction Factors According to ACI 318-05 Appendix A

Stress Limits, f_{cu}	
Struts: $f_{cu} = 0.85\beta_c f'_c$	
where:	$\beta_s = 1.00$ for prismatic struts in uncracked compression zones $\beta_s = 0.40$ for struts in tension members $\beta_s = 0.75$ struts may be bottle shaped and crack control reinforcement is included $\beta_s = 0.60$ struts may be bottle shaped and crack control reinforcement is not included $\beta_s = 0.60$ for all other cases $f'_c =$ Specified concrete compressive strength
Note:	Crack control reinforcement requirement is $\sum \rho_{vi} sin\, \gamma_i \geq 0.003$, where $\rho_{vi} =$ steel ratio of the *i*-th layer of reinforcement crossing the strut under review, and $\gamma_i =$ angle between the axis of the strut and the bars.
Nodes: $f_{cu} = 0.85\beta_n f'_c$	
where:	$\beta_s = 1.00$ when nodes are bounded by struts and/or bearing areas $\beta_s = 0.80$ when nodes anchor only one tie $\beta_s = 0.60$ when nodes anchor more than one tie
Strength Reduction Factors, Ø	
$\emptyset = 0.75$ for struts, ties, and nodes	

2.2 IS: 456-2000 (Deep beam action – clauses-29.1)

This method is allowed by the code for design of D-region structural element but the codal provisions are empirical in nature and follow sectional design procedure.

The lever arm Z for a deep beam shall be determined as below

a) For simply supported beams

$Z = 0.2 (l + 2D)$ when $l \leq l/D \leq 2$

$Z = 0.6 l$ when $l/D < 1$

b) For continuous beams

$Z = 0.2 (l + 2D)$ when $l \leq l/D \leq 2.5$

$Z = 0.5 l$ when $l/D < 1$

2.3 IS: 456-2000 (Beam action – clauses-22.6.1)

The design of structural elements in **B-regions** (beam-like regions) is typically governed by the **sectional design procedure**, which assumes linear stress distribution across the section. This method relies on **beam action** principles, where flexural behavior is predominant, and the design is based on calculating the internal forces, such as moments and shear forces, at critical sections.

According to Clause 22.6.1 of IS: 456-2000, the **critical section for flexural reinforcement** is considered at the **face of the column**. This means the maximum design moment (**Mface**) is calculated at the point where the beam or slab connects with the supporting column. This approach ensures that the flexural reinforcement is sufficient to resist the applied moments at the critical location, where stress concentrations are typically the highest.

This method is used for design of B-region structural element and follows the sectional design procedure. The critical section of design moment (M_{face}) for flexural reinforcement is at face of column. However, if column is act as floating column, then it is preferable to take critical section at the midpoint between centre line of column and face of column to obtain design moment (M_{max}).

2.4 IS: 456-2000 (Thin Plate Theory - Timoshenko and Krieger)

This theory is based on membrane action. However this theory does not consider the shear deformation behavior that is it does not consider the thickness behavior. In the present paper -Pro 2006 is use for FEM based thin plate analysis for pile cap and the flexural reinforcement is calculated based on allowable stress limit specified by IS: 456-2000.

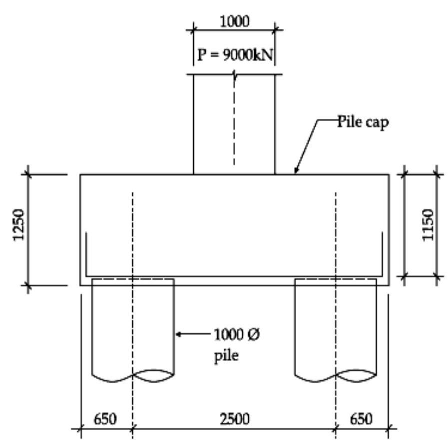
3. NUMERICAL RESULTS

3.1 Description of the Problem - Pile spacing, depth of pile.

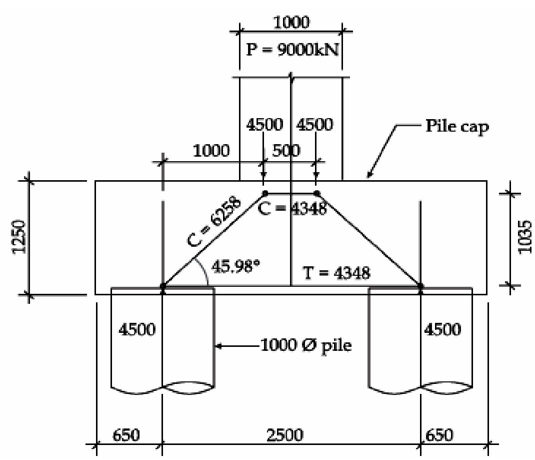
Piles are spaced as close as permitted by geo technical considerations (2.5 times the diameter for end bearing piles or 3.0 times the diameter for piles transmitting the load by skin friction). When bending moments are large it may become more economical to increase the spacing of the piles. Indian Road Congress, IRC-21, specifies that if STM approach is used for design of pile caps the thickness of the pile cap should not be less than 0.5 times the pile spacing. And if the piles are spaced more than three pile diameters, IRC 21 recommends that only the reinforcement placed within 1.5 pile diameters shall be considered to constitute a tension member. Also 80% of the tension member reinforcement shall be concentrated in strips linking the pile heads. No check for shear is required to be carried out for pile caps designed and detailed according to STM methods.

3.2 Problem: 1 Pile cap with two piles groups.

The STM modal with minimum dimension as per IRC-21 are as shown in figure-1. The finite size of the column can be considered by splitting the vertical load in to two equal parts. The effective depth of the truss is assumed to be 1.035m. Tensile force can be estimated by resolving forces. Width of pile cap is assumed to be 1.3 m.



(a) Dimensions of pile cap and pile group



(b) STM Model

Figure-1 Pile Cap with Two pile group

Table:2 Design force for pile cap in two pile group (longitudinal reinforcement).

	Design Methods	Design Forces	Ast

Sr No.		Tensile force (kN)	Moment (kN m)	(mm²)
1	Cantilever beam action			
	M_{face} (IS:456-2000)	3264 (eq)	3375	9041
	M_{max} (IS:456-2000)	4348 (eq)	4500	12043
2	Thin plate (STAAD)	4376 (eq)	4529	12121
3	STM			
	IRC 21	4348	4500 (eq)	12043
	ACI 318-2005	5845	6050 (eq)	16189
4	Deep beam action	3492 (eq)	3038	9672

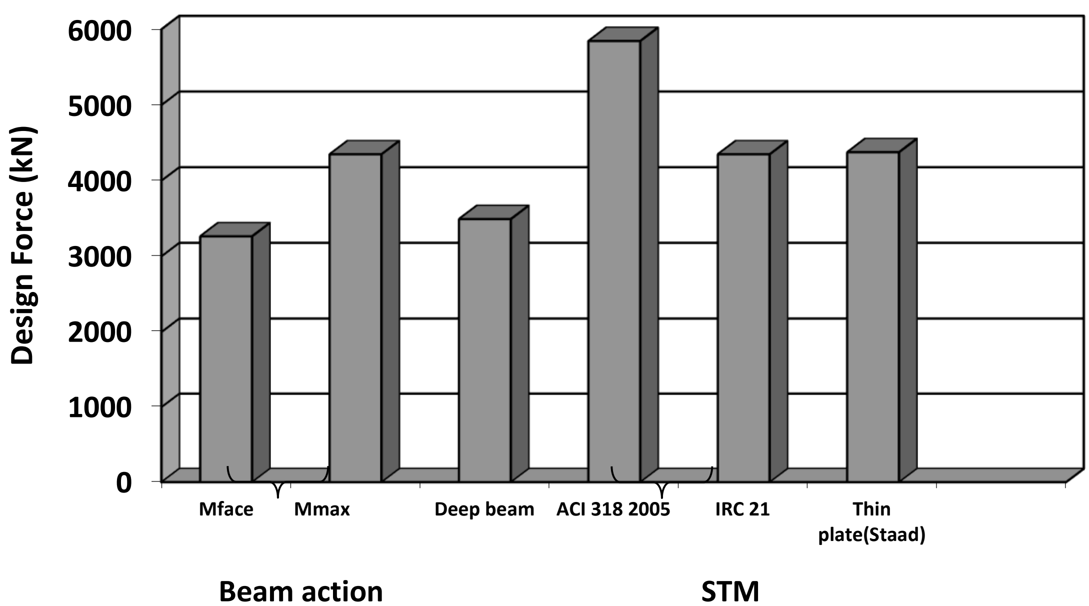


Figure-2 Comparison chart of Design Tensile force (longitudinal reinforcement) for pile cap in two pile group by various methods.

3.3 Problem: 2 Pile cap with three piles groups.

Consider a three-pile group supporting a factored axial column load of 13500 KN as shown in figure 3. Assuming the pile cap to be 1250 mm deep, column diameter as 1200 mm and assuming effective depth to be 1.035 m, then the angle of strut will be 41.1^0 if the size of the column is neglected. However, considering the finite size of the column the angle of inclination of compressive strut to the horizontal plane will be equal to 42.9^0.

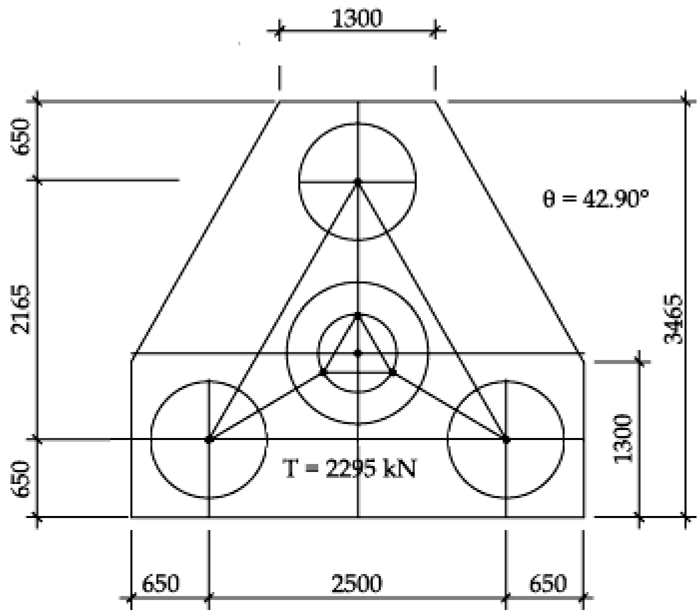


Figure-3 STM modal for three pile group

Table: 3 Design force for pile cap in three pile group (longitudinal reinforcement)

Sr No.	Design Methods	Design Forces		Ast
		Tensile Force (kN)	Moment (kN-m)	(mm^2)
1	Cantilever beam action			
	M_{face} (IS:456-2000)	3666 (eq)	3794	10154
	M_{max} (IS:456-2000)	4971 (eq)	5144	13769
2	Thin plate (STAAD)	3445 (eq)	3565	9542
3	STM			
	ACI 318-2005	3777	3650 (eq)	10462
	IRC 21	2796	2894 (eq)	7745
4	Deep beam action	1759 (eq)	1715	4872

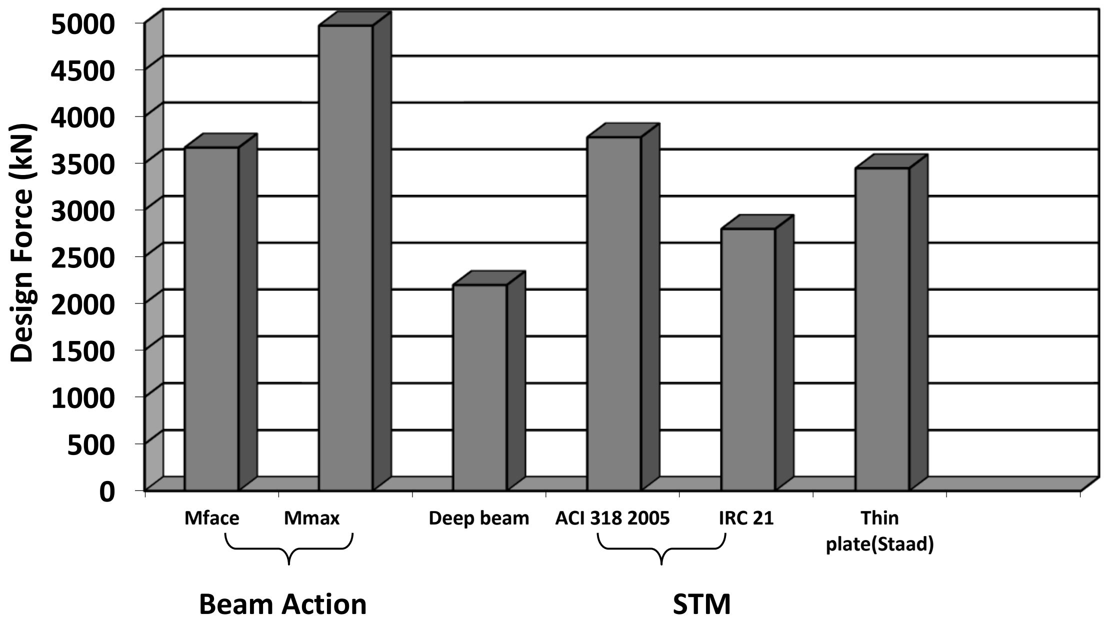
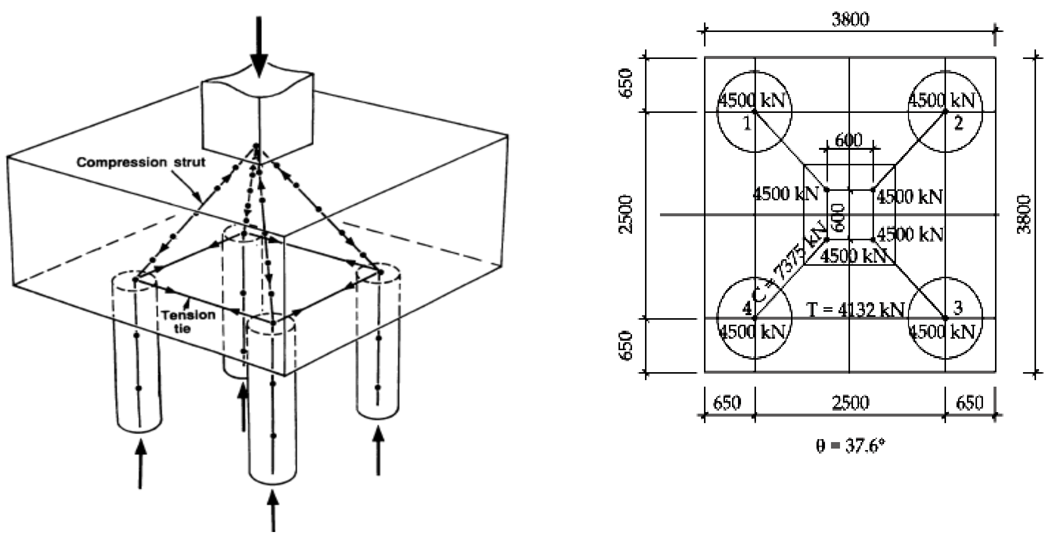


Figure-4 – Comparison chart of Design Tensile force (longitudinal reinforcement) for pile cap in three pile group by various methods.

3.4 Problem: 3 Pile cap with four piles groups.

Consider a four-pile group supporting a column load of 18000 KN as shown in fig.5. Let us assume a column size of 1200 mm and divide the load in to four equal parts for a 1250 mm deep pile cap. The effective depth is taken as 1.035 m and angle of inclination of compressive strut to the horizontal plane will be equal to 37.6^0.



(a) 3D view of load transfer mechanism **(b) STM Model**

Figure-5 Pile Cap with Four pile group

Table: 4 Design force for pile cap in four pile group (longitudinal reinforcement).

Sr No.	Design Methods	Forces		Ast
		Tensile (kN)	Moment (kN-m)	(mm^2)
1	Cantilever beam action			
	M_{face} (IS:456-2000)	2827(eq)	2925	7830
	M_{max} (IS:456-2000)	4131 (eq)	4275	11442
2	Thin plate (STAAD)	4986 (eq)	5160	13810
3	STM			
	ACI 318-2005	4625	4786 (eq)	12810
	IRC 21	4132	4277 (eq)	11445
4	Deep beam action	2587 (eq)	2812	7165

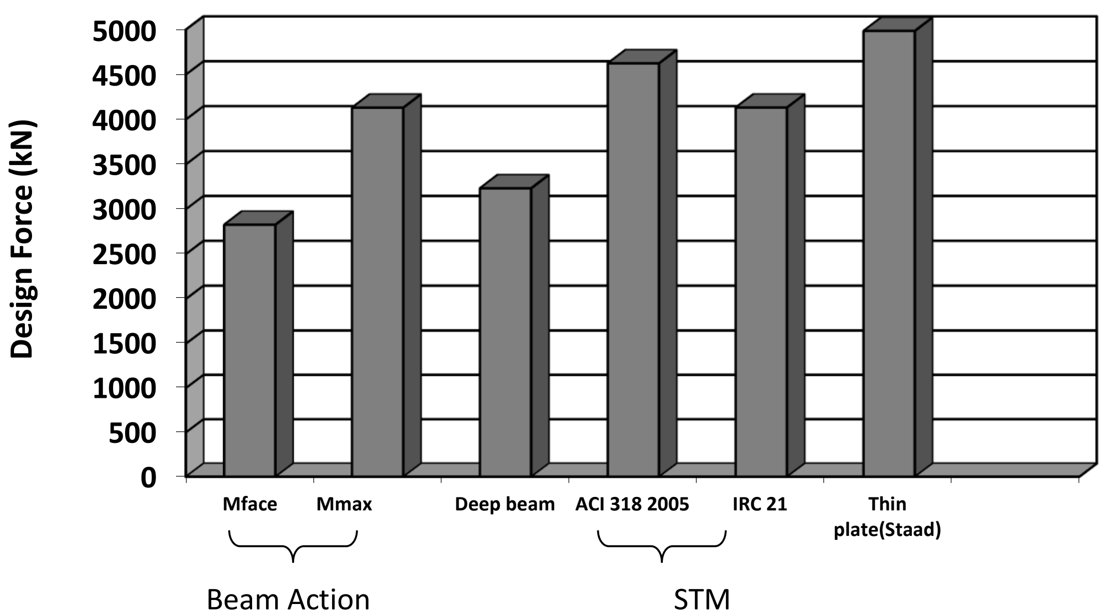


Figure-6 Comparison chart of Design Tensile force (longitudinal reinforcement) for pile cap in four pile group by various methods.

RESULTS AND DISCUSSION

Based on the analysis of Figures 2, 4, and 6, the following key points have been observed regarding the design of pile caps using different methodologies:

1. **Comparison of Strut-and-Tie Models (ACI 318-2005) and IRC 21**

- The Strut-and-Tie Models (STM) specified in **ACI 318-2005** consistently result in higher design forces and consequently higher requirements for longitudinal reinforcement in all pile cap configurations (two-pile, three-pile, and four-pile groups) compared to the provisions outlined in **IRC 21**.
- This difference arises because STM explicitly considers the thickness behavior of the pile cap and the complex force flow within D-regions. In contrast, IRC 21 relies on simplified design assumptions that may underestimate the required reinforcement, potentially compromising structural safety.

2. **Comparison of IS 456-2000 and ACI 318-2005 for D-Regions**
   - The design provisions in **IS 456-2000**, which are based on **deep beam action** for D-regions, yield lower longitudinal reinforcement requirements compared to the STM approach in **ACI 318-2005**.
   - The STM provides a more rigorous and detailed analysis of force transfer through compression struts, tension ties, and nodal zones. This leads to a conservative design that ensures safety in D-regions, where stress concentrations and complex force distributions are prevalent. In contrast, the deep beam action approach in IS 456-2000 does not fully capture these intricacies, resulting in lower reinforcement estimates.
3. **Effect of Pile Group Configuration on Design Results**
   - For a **two-pile group**, the STM (used for D-regions) yields higher design forces and reinforcement requirements compared to the **Beam Action Method** (used for B-regions). This is because the two-pile configuration creates significant discontinuities, making it critical to consider D-region behavior.
   - For a **three-pile group**, the STM results in lower reinforcement requirements compared to the Beam Action Method. This is likely due to the force distribution and redundancy provided by the additional pile, which reduces the complexity of the force flow within the pile cap.
   - For a **four-pile group**, the STM again provides higher design forces and reinforcement requirements compared to the Beam Action Method. This is attributed to the increased thickness and complexity of the pile cap in a four-pile configuration, where D-region behavior becomes more pronounced.
4. **Comparison of Thin Plate Theory with Strut-and-Tie Models (ACI 318-2005)**
   - Among the conventional design methods, the **Thin Plate Theory** shows the least variation in results compared to the STM specified in ACI 318-2005.

- This similarity indicates that the Thin Plate Theory accounts for some of the thickness effects in pile caps, making it more compatible with the STM approach. However, it is important to note that while Thin Plate Theory approximates the behavior of pile caps more closely than other conventional methods, it may not fully address the complexity of force flow in D-regions, as STM does.

CONCLUSIONS

The analysis underscores the superiority of the Strut-and-Tie Method (ACI 318-2005) in accurately capturing the behavior of pile caps in D-regions. While the conventional methods, including those specified in IS 456-2000 and IRC 21, may offer simpler design approaches, they often underestimate the reinforcement requirements, potentially compromising the safety and performance of the structure. Among the conventional methods, the Thin Plate Theory aligns more closely with STM results, indicating its relative effectiveness in accounting for thickness behavior.

The findings also highlight the importance of considering the pile group configuration when selecting a design methodology, as the force distribution and complexity of the pile cap vary significantly based on the number of piles. Adopting the STM approach, particularly for D-regions, ensures a safer and more reliable design, justifying its recommendation as a standard design method in modern codes.

From the forgoing design chart in each pile group case, it is seen that the STM method (ACI-318-2005) for pile caps will result in more flexural reinforcement than what one would have obtain by other conventional methods permitted by IS:456-2000 and hence it is more conservative.

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