

Civil and Architectural Engineering

**Analytical and Experimental Study of the Piles Cap Normal and Light Weight Aerated Concrete: Literature Review**

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**ABSTRACT**

The main objective of this study is to understand the work of the pile caps made of lightweight aerated foam concrete and study the many factors affecting the ability and the capacity of the shear. The study was done by analyzing previous practical and theoretical experiences on the reinforced concrete pile caps. The previous practical results indicated that all specimens failed by shear diagonal compression or tension modes except one specimen that failed flexural-shear mode. Based on test specimens' practical results and behavior, some theoretical methods for estimating the ultimate strength of reinforced concrete pile caps have been recommended, some of which evolved into the design documents available on the subject. A theoretical and practical study of compression concluded that the shear capacity is limited by the nodal zone bearing stresses. The flexural capacity can be described by the column load that would cause the yielding of the tie (i.e., steel reinforcement). Therefore, the design of pile caps should include a check on bearing strength to be added to the traditional section force approach for pile cap design.

**Keywords:** — Pile Cap, Light Weight Concrete, Aerated Foam Concrete, Shear

**الدراسات التحليلية والعملية لقبعات الركائز للخرسانة العادية و الهوائية خفيفة الوزن: مراجعة مقال**

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**الخلاصة**

الهدف الرئيسي من هذه الدراسة هو فهم عمل قبعات الركائز ودراسة العديد من العوامل التي تؤثر على قدرتها وقدرة القص ، خاصة أنها مصنوعة من الخرسانة الرغوية خفيفة الوزن ويتم ذلك من خلال التحليل السابق للخبرات العملية والنظرية على قبعات الركائز الخرسانية المسلحة . تشير النتائج العملية السابقة إلى أن جميع النماذج فشلت بسبب انضغاط القص المائل أو

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أنماط الشد باستثناء نموذج واحد فشل في انضغاط قص الانثناء. بناءً على النتائج العملية وسلوك نماذج الاختبار ، تمت التوصية بعدد من الطرق النظرية لتقدير القوة النهائية لقبعات الركائز الخرسانية المسلحة ، والتي تطور بعضها إلى وثائق تصميم متاحة حول هذا الموضوع. استنادًا إلى دراسة نظرية وعملية للانضغاط تم استنتاج أن سعة القص محدودة بسبب ضغوط تحمل المنطقة النقطية ويمكن وصف قدرة الانثناء من خلال حمل العمود الذي قد يتسبب في خضوع اطواق الحديد (أي. حديد التسليح). لذلك ، يجب أن يتضمن تصميم قبعات الركائز فحصًا لقوة التحمل لإضافتها إلى نهج قوة المقطع التقليدي لتصميم قبعة الركيزة. **الكلمات الرئيسية:** قبعة الركيزة ، خرسانة خفيفة الوزن ، الخرسانة الهوائية الرغوية ، قوة القص

## 1. INTRODUCTION

Pile caps transfer the load from column(s) to a piles group. Despite being a very important and common structural element, there is no generally unified procedure for the pile caps design. (**Abdul-Razzaq and Farhood, 2017**). Designers followed numerous empirical rules. Many building codes do not provide a protocol that defines how pile caps can behave and their characteristics, leading to differences in how well they perform. These disparities took place because most codes do not present a design procedure that provides a clear understanding of the behavior and strength of pile caps. Some codes and designers are assumed linear distribution of strain over the depth of a member (Fenella, 2016). The American Concrete Institute, 2005, 318 (ACI Committee 318, 2015) assumes the strain is distributed uniformly. Different assumptions exist in some of the concrete code and coding entities (**ACI-318 Committee, 2005**) which claim that the pressure is uniformly spread within a member's depth.

If one believes the principle of shear reinforcement, a pile cap is considered a beam bridging pile that requires longitudinal reinforcement based on the engineering beam theory. A selected depth to provide adequate shear strength is also required. The traditional design procedures for pile caps of ACI Building Codes (**ACI-318 Committee, 1999**) and the 2002 edition (ACI-318 Committee, 2002) use the same construction system as single-section footings soil-bolted foundations.

Strut-and-Tie model in which an internal load-resisting truss, is being used by other design provisions (**ACI-318 Committee, 1999**). It takes into account obligatory compression and shear capacities (Stout) and puts them into their calculations. According to ASTM, steel reinforcing bonds carry tensile forces, whereas concrete compressive struts carry compressive forces. The column's applied forces should be transferred to the piles through these struts and links.

(**ACI 318 Committee -2002**) developed a general design protocol for all D-regions dependent on Strut-and-Tie (discontinuity regions). Nonlinear as well as linear analyses, show that pile caps perform the role of three-dimensional components (**Abdul-Razzaq and Farhood, 2017**). There is a dynamic strain difference around the D-lengths, regions characterized by the formation of compressive struts between the applied forces of columns and supporting piles. As a result, pile cap construction procedures cannot be built on a sectional design process, as several experiments have shown the method's imprecision. Numerous researchers such as (**Adebar et al., 1990**) and (**Cavers and Fenton, 2004**) concluded that pile caps optimized for brittle shear failure often struggle in flexure. Numerous researchers especially (**Blévoit and Frémy, 1967**) had determined that using the Strut-and-Tie method is the most efficient and appropriate for determining how much reinforcement to apply to pile caps. They especially (**Blévoit and Frémy, 1967**) recommended their methodology for measurements and reinforcement over all other methods. Previous theoretical work on pile caps is outlined here, along with several significant findings proposed by multiple investigators (**Abdul-Razzaq, Farhood, 2017**).

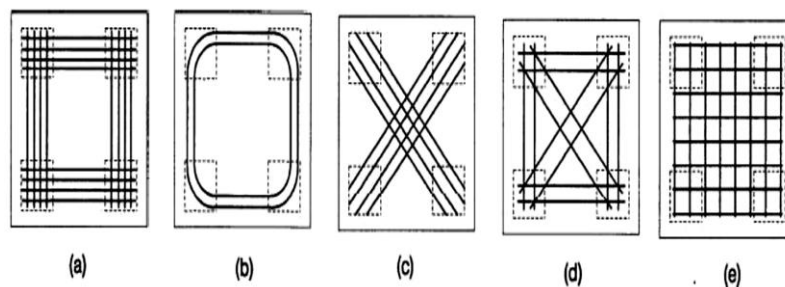
## 1.2 The Functions of a Pile Cap

- 1- To distribute a single load equally over the pile group and thus over a greater area of bearing potential.
- 2- To laterally stabilize individual piles, thus increasing the overall stability of the group.
- 3- To provide the necessary combined resistance to stresses set up by the superstructure and/or ground movement.
- 4- To transmit the building loads to the foundations and the ground soil layers, whether these load vertical or inclined.
- 5- To allow column or superstructure to reside on a stable and solid core foundation instead of residing directly on the ground (Varghse, 2009).

## 1.3 Review of the Literature on Pile Caps

### 1.3.1 Experiments

(Blévo and Frémy 1967) executed an overall series of tests. Researchers tested half-scale 51 four-pile caps and eight full-scale four-pile caps. The main objectives of the tests conducted were to compare the performance of pile covers when they contain different patterns of longitudinal reinforcement, as shown in Fig. 1, and check the efficiency of different Strut-and-Tie models. The results of the tests have shown that the use of bunched square layouts Fig. 1a led to a (20%) higher capacity than in specimens with the same reinforcement quantity distributed in a grid pattern Fig. 1e. The conclusion was found from these tests that the use of a square bunched of reinforcements only led to weak control of the crack. Therefore, the researchers recommended using complementary grid reinforcement. According to the authors, punching shear can take place at the failure, so results in interpretation concerning pile caps is complex. The authors have concluded that it is not possible in the pile caps to separate the shearing and bending behavior as is the case in the beams because increasing the longitudinal reinforcement leads to a significant increase in punching strength.



**Figure 1.** Various Layouts of Main Reinforcing Bars Used by (Blévo and Frémy, 1967).

In the study by (Sabnis and Gogate 1984), there were nine caps with a total height of 152 mm (5½ in), which were measured, and one of which was strengthened with four piles. Strength is regulated by the standardized depth of distribution of longitudinal reinforcement; they looked at the shear potential and how it is affected by deep pile caps. According to the manufacturer, both samples were found to have the same degree of delamination on the four different sides, showing a mixture of deep beam failures with the broad surface cracks and narrow slab-punching failures. Fig. 2 shows the details. Horizontal strengthening on the vertical faces just yielded little to no



advantage and did not increase the overall pile strength. The strengths of pile caps with shear span-to-depth ratios ranged from 0.49 to 1.8, and concrete strength was less than 41 MPa.

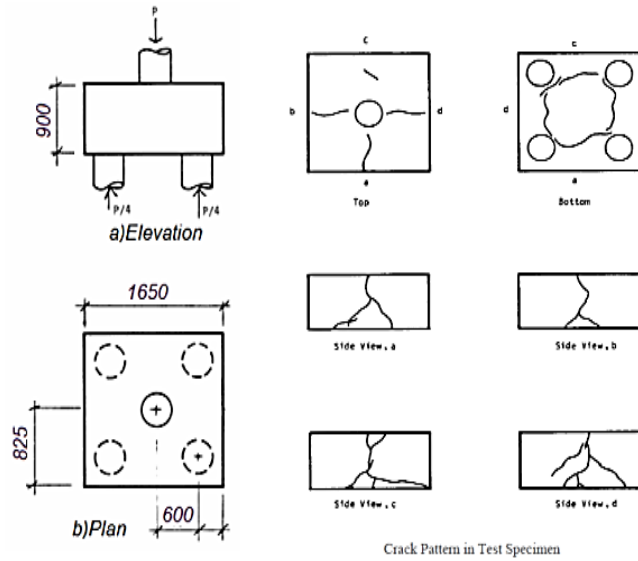


Figure 2. Pile Caps Details and Crack Pattern (Sabnis and Gogate, 1984). Dimensions in mm.

(Adebar et al. 1990) tested six full-scale pile caps with a different reinforcement arrangement to study the Strut-and-Tie model's performance for pile cap design. Four of their tests were on diamond-shaped caps, a cruciform-shaped cap, and a rectangular six-pile cap, as shown in Fig.3.

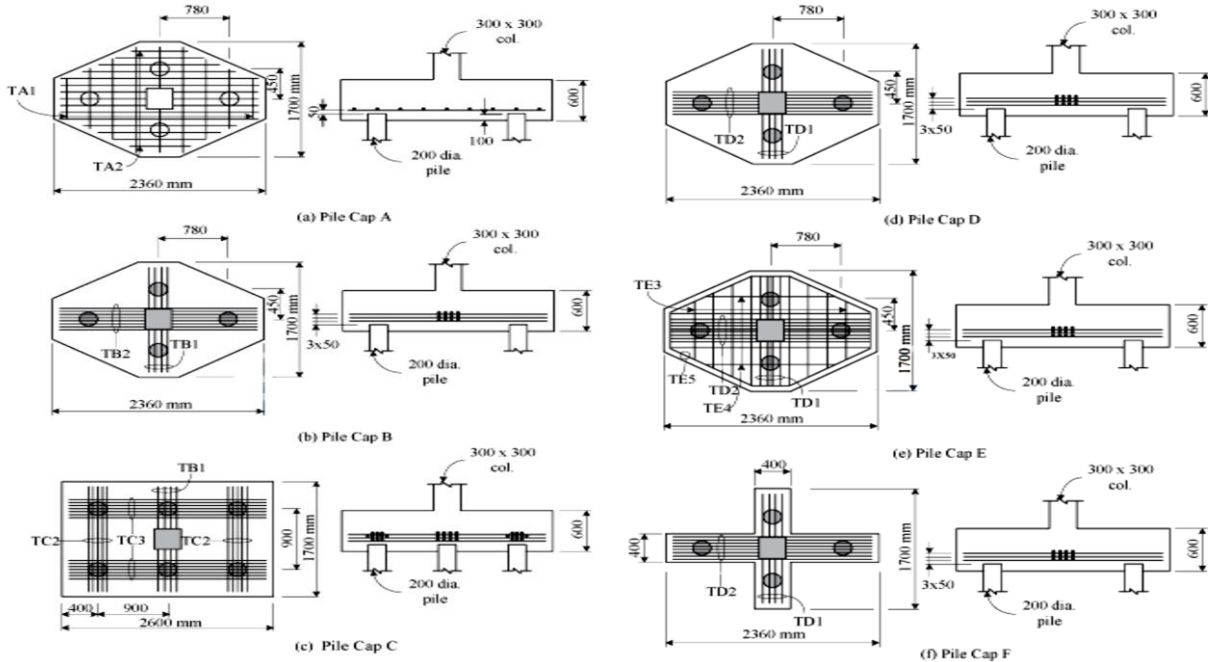
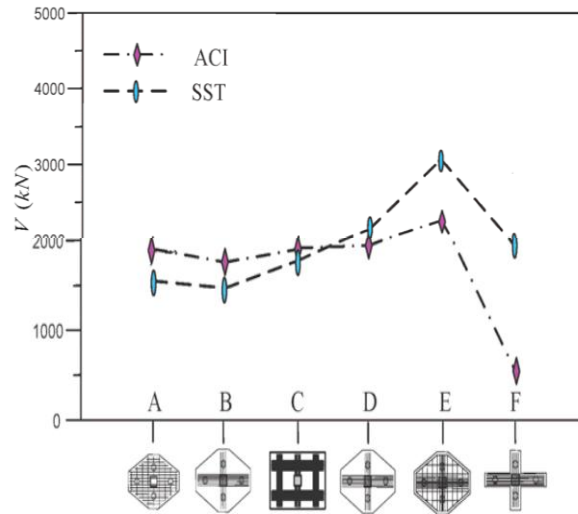


Figure 3. Pile Cap Type (Adebar et al., 1990). Dimensions in mm.

Test results revealed a considerable nonlinear distribution of strain prior to and after cracks. As a compression strut splits longitudinally, the loss occurred due to the off-axis tensile strain induced



by the distribution of the compressive stresses, with the overall bearing stress serving as a reasonable measure of the likelihood of strut splitting failure. The maximum bearing stress at failure was determined to be approximately  $1.1f_c$  for the checked pile caps. **Fig.4** illustrates the shear potential of the tested pile caps.



**Figure 4.** Shear Capacity of Pile Caps (Adebar et al., 1990).

Furthermore, Strut and Cross-Tie models successfully demonstrate the operation. They correctly illustrate how tightly strung piles fail in two-way shear mode depending on the quantity of longitudinal reinforcement.

(Adebar and Zhou 1993) found that the maximum bearing stress to cause transverse splitting depends on the amount of confinement in case compression struts are confined by plain concrete and the aspect ratio (height/width) of the compression strut. Two piles-cap were studied to illustrate their ideas of stress limits for the cap design using the Strut-and-Tie model, **Fig. 5**. The conclusion was found that the provisions of the design of the one-way shear present in (ACI-318M-2002) are exceedingly conservative for deep pile caps and that the traditional design of flexural procedures, and that the traditional design of flexural procedures for two-way slabs and beams are not conservative for pile caps. Flexural design can be accomplished using a simple strut-and-tie model. The test results showed that the longitudinal reinforcement must be concentrated on the piles.

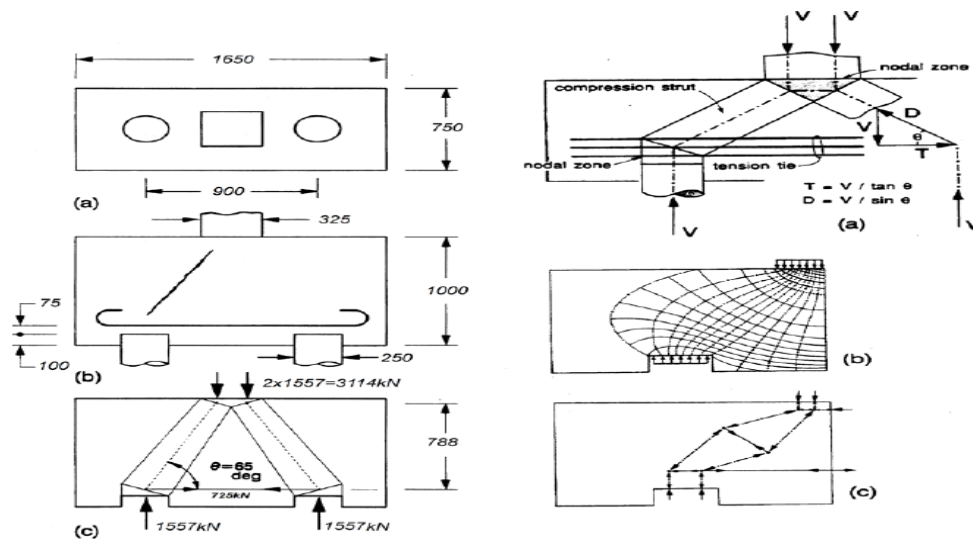


Figure 5. Two-Pile Cap (Adebar and Zhou, 1993). Dimensions in mm.

(Saaed et al., 2009) examined six simply supported pile caps of size 75 cm × 75 cm × 23cm staying on four piles. They were prepared based on certain theoretical ultimate loads applied to the center of pile caps using strut-and-tie model technique, two mix designs of concrete were used with three samples from each mix. Fig. 6, illustrates the shear and failure for the pile cap.



Figure 6. Four-Pile Cap Load Position and Shear Failure (Ahmed et al., 2009)

The Strut-and-Tie model was found to be a reliable solution for estimating the shear intensity of pile caps.

(Fadhil, 2017) studied the STM (Strut and Tie Method) technique and was conducted for three similar deep beams on a small scale. The beams are simply supported and statically loaded with a concentrated load in the mid-beam span. These deep beams had two symmetrical openings near the point of application of the load. Both the deep beam, where linear stress distribution cannot be assumed, and the presence of openings, which causes interruption stress, make the use of the Euler-Bernoulli thin beam theory not applicable. STM has established an idealized beam first; an experimental test was then conducted to study the ability of the STM to deal with stress distortion caused by the presence of near-load apertures in addition to the nonlinear distribution of stress occurring in the deep beam. Test results showed that the beam designed using STM was able to withstand a higher load than the final designed load. Service loading, in contrast, was within the range of one estimated. The result of this study can then be added to the relatively few available experimental studies related to STM technology to enhance STM validation to efficiently address various structural configurations where the linear stress assumption cannot be applied.

### 1.3.2 Analytical Work

(Whittle and Beattie, 1972) used (Code of Practice, CP 110) to propose a system for designing pile caps that required caps to be constructed as beams according to basic bending theory. When measuring the region of tensile strengthening, they make allowance for the size of the column or pile. This leads the steel region to be greater than that calculated using the Strut-and-Tie formula.

(Gogate and Sabnis, 1980) performed research on the pile cap design. It was analyzed the one-way and two-way shear behavior of deep participants and the ACI Building Code's current requirements (ACI Committee -318, 1977). They divided the pile cap into two types: dense and small. According to them, dense pile caps are those with a thickness equivalent to or greater than the gap between the pile's centerline and the face of the supported pole. They concluded that although the provisions of (ACI Committee -318, 1977) can be used for thin pile caps, they cannot be used for thick pile caps as described above without certain modifications.

(Bride and Duan, 1995) investigated 36 piles in a group using a three-dimensional (FE) discretization to determine the pile cap's resistance to combined filling (vertical and flexural moments). It was proposed that when the cantilever's length to thickness ratio ( $L_c/H$ ) is less than or equal to 2.2, the pile cap may be assumed rigid. This study aimed to analyze pile cap rigidity, as shown in Fig.7, to propose new controls for cap stiffness in assessing pile reactions. A standard pile base was selected to analyze the stiffness of reinforced concrete pile caps using a three-dimensional finite element computer model. Based on the numerical study performed following conclusions were drawn:

1-the pile cap may be assumed to be rigid when the length-to-thickness ratio of the cantilever is less than or equal to 2.2

2- the assumption that the rigidity of pile cap is not valid when the ratio of length to thickness is greater than 2.2

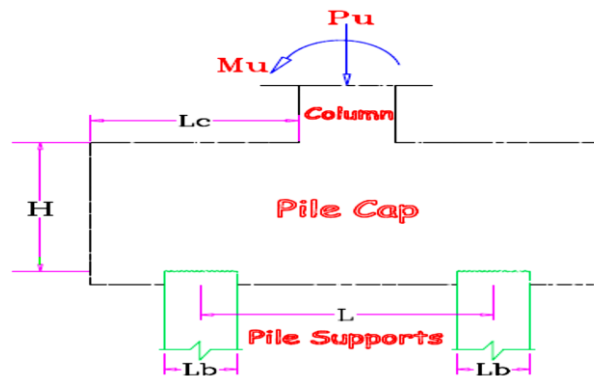


Figure 7. Pile Foundation Under Axial and Moment, (Duan and Bride, 1995).

(Shirato et al., 2002) suggested a design methodology for ultimate shear strength of pile caps that undergo different stresses, based on numerical analyses and experiments. Firstly, it was determined an evaluation equation for shear strength of pile caps with compressive piles. Secondly, the clarified was found the shear resistance mechanism of pile caps with pull-out piles and confirmed to be able to apply the determined evaluation equation to those with pull-out piles



by modifying the setting of shear span. The suggested methodology was inserted into the current version of the Japanese specifications for Highway Bridges (**Japan Road Association,1996**).

(**Saeed et al., 2009**) used the Strut and Tie Model to determine the shear intensity of four pile caps (ASTM). The Strut and Tie model has been extensively used in the construction of reinforced concrete buildings with split regions and non-flexural components. Since a pile cap is typically a separated area with a limited duration to depth ratio, it cannot be subjected to conventional flexural theory for beams.

(**Teguh, 2009**) calculated the displacement ductility factor to the local curvature ductility of a fixed-head pile-to-pile cap connection embedded in cohesive and cohesion less soil based on the kinematic model described. It is worth noting that the first plastic hinges for both soil styles appeared at the fixed-head pile attachment interface.

(**Jensen and Hoang, 2012**) identified a Strut-and-Tie method for predicting the strength of reinforced concrete pile caps using an upper bound plasticity approach. They defined and tested a variety of collapse failure mechanisms in order to determine the load-carrying ability and the crucial collapse mechanism. They have contrasted their load-carrying capacity performance to those of 200 tests. A satisfactory agreement was discovered, and it was proposed that the upper bound solution could be a valuable alternative to the commonly established strut-and-tie procedure for determining the lower bound, especially when assessing the intensity of current systems.

(**Buttignol and Almeida, 2013**) investigated the effect of concrete compressive characteristic power on the resistance potential of three-pile caps via a numerical study. The computational research was carried out using the (FE) program ATENA 3D, as shown in the **Fig. 8**. The findings showed that an improvement in characteristic compressive strength did not translate into a noticeable increase in pile cap strength, owing to concrete cracking (i.e., open cracks parallel to principal compressive stresses caused by perpendicular tensile stresses inside the structure) and connect steel bars yielded.



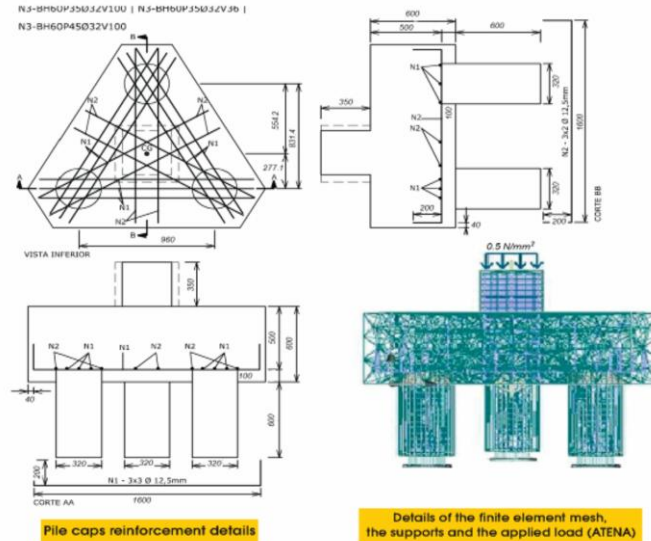


Figure 8. Three-Pile Cap dimensions in mm.

Fig. 9 showed that there is no discernible difference in the pattern of the cracks. However, there is a greater decline of the pile caps opening cracks in terms of percentage from model 1 to model 3. There was an increase of 21,32% (from 2,58 MPa to 3,12 MPa) in the concrete tensile stress and a reduction around 30% in the crack opening intensity.

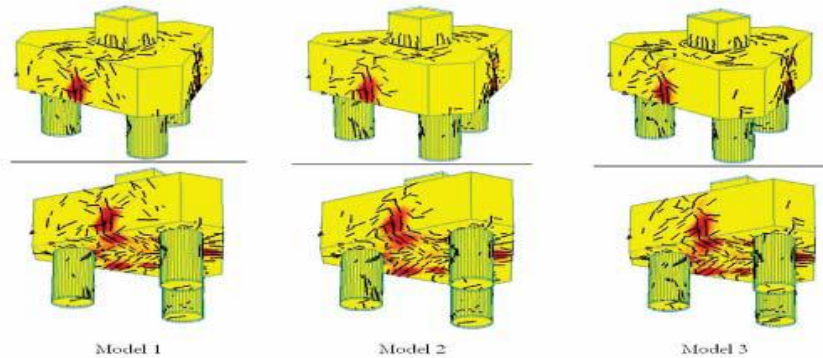


Figure 9. Crack Pattern at Failure Load (Buttignol and Almeida, 2013).

## 2. AERATED CONCRETE

### 2.1 Introduction

Light weight concrete can simply be defined as concrete, which has been made lighter than conventional concrete by one means or another. This is the least dense kind of concrete, thermal conductivity, and reliability of any type of concrete. For works in situ, the usual aeration methods are by mixing in stabilized foam or by whipping air in with the aid of an air-entraining agent. The addition usually makes the precast products of about 0.2 percent aluminum powder to the mix, which reacts with alkaline substances in the binder, forming hydrogen bubbles. Aerated concrete that has been air-cured is used in low-strength applications such as roof screeds and drain lagging. The maximum strength is measured by the interaction between lime and siliceous aggregates. For equal densities, the strength of high pressure steam cured concrete is approximately double that of



air-cured concrete, with shrinkage of about one-third or less. Aerated concrete is a porous, lightweight material made of cement, lime, sand, or another siliceous material. It is generated either physically or chemically by injecting air or gas into a slurry. It is usually free of coarse particles. Aerated concrete used in construction is usually steam-cured under high pressure. In 1929, Sweden patented autoclaved aerated concrete, which is still produced worldwide. One of the primary characteristics of light weight is its low density. Reduced density equates to less weight, which equates to less dead load. From a design standpoint, structures constructed with lightweight materials can minimize the average size of the foundations and structural components, which is critical when constructing high-rise buildings, thereby reducing the overall construction expense. Due to the properties of light weight concrete, it would also aid in higher construction times due to reduced haulage and handling. Additionally, lightweight concrete has a poor thermal conductivity, which increases with decreasing density. Additionally, aerated concrete has a better fire tolerance and excellent sound absorption properties. **(Raj and John, 2019)**. Aerated lightweight concrete is considered to be economical in terms of material use and the use of by-products and surplus resources such as fly ash **(Hamad, 2014)**.

## 2.2 The Applications of Aerated LWC

- 1) Aerated LWC is commonly used in the fabrication of single skin tilt-up lightweight concrete wall panels.
- 2) Aerated LWC may be used to insulate between thick weight concrete.
- 3) Sandwich panels with a variety of surface materials and columns and filler made of lightweight concrete are gaining expanded popularity as partition walls, middle walls, and interior walls in residential houses and apartments.
- 4) Lightweight Concrete is sometimes defined as a filler material.
- 5) Additionally, lightweight concrete is known as a cost-effective method of rehabilitating existing floors **(Mulgund and Kulkarni, 2018)**.

## 2.3 Review of Literature on Aerated Concrete

### 2.3.1 Experimental Researches

**(Kersley and Wainwright, 2001)** investigated cement (up to 75% by weight) with both classified and unclassified fly ash on the property of foamed concrete. This study reports only on the results of permeability and porosity measured up to an age of 1 year on well-cured concretes. Porosity was found to be dependent mainly on the dry density of the concrete (foamed concrete mixture of different casting densities (1000, 1250, and 1500 kg/m<sup>3</sup>) and not on ash type (with different percentages of ash replacement (50%, 66.7%, and 75%) or content. Permeability was measured in terms of water absorption and water vapor permeability. The volume of water (in kg/m<sup>3</sup>) absorbed by foamed concrete was approximately twice that of an equivalent cement paste but was independent of the volume of air-entrained, ash type, or ash content. They concluded the Water vapor permeability improved as porosity and ash content increased.

**(Namibiar and Ramamurthy, 2009)** investigated shrinkage behavior of preformed concrete and the factors that influence it, such as density, moisture content, and structure, which includes the filler – cement ratio, foam volume, and so on. Due to the absence of coarse aggregates in aerated concrete, foam concrete shrinks less than standard concrete. They concluded The shrinkage of foam concrete with a 50% foam volume was observed to be decreased to 36% as opposed to standard concrete. Shrinkage is significantly increased in the low moisture content range. Although



water elimination from larger Although artificial air pores do not cause shrinkage, they may indirectly influence volume stability by allowing for some shrinkage; this effect was more pronounced at a higher foam volume. Shrinkage reduces as the foam content increases.

**(Kumar and Ramamurthy, 2015)** studied the influence of fineness of aluminum powder through an evaluation of variation in the workability of the mix, rate of aeration and fresh density with time, dry density, compressive strength, and water absorption of aerated cement paste and mortar. They concluded The amount of aluminum powder used to reach the perfect density decreases as the fineness of the powder increases. Water absorption improves as the fineness of aluminum powder in aerated cement paste or mortar with a specified dry density, or compressive intensity is increased. For aluminum powder with a defined fineness, the optimal dose and water-cement ratio must be determined in relation to the ideal density and weight, or strength to density ratio.

## 2.4 Analysis and Design Recommendations

Pile caps are important structures because they are essential to the integrity of the structure, as the reinforced concrete pile caps are used in highway bridges and other constructions extensively to transfer structural loads to piles. Although there is no generally accepted procedure in designing pile caps, many experimental details rules are practically followed, but these rules differ greatly. The main reason for these discrepancies is that most codes do not provide a design methodology that provides a clear understanding of the strength and behavior of this important structural element. There are two common ways; in the first way, the cap is considered a deep beam and is designed for shear at assumed critical sections. The second way is based on the Strut-and-Tie method recommended by **(ACI 318M-2011)** in which the pile cap forces are calculated using an idealized equilibrium model.

Attempting to predict the relationships between the many factors that may affect the carrying capacity of a concrete pile foundation can help add a clearer view of pile use (design or analysis) than economic factors such as effective depth of pile cap ( $d$ ) and pile surface were roughness were found to be a good contribution to influencing shear strength **(Esmat and Fadhil, 2016)**.

An important concept to consider is the ratio of the cohesive forces distributed between piles in this model and the tensile stress on reinforcing struts. This model determines the loads transferred to a moment by piles **(Demeyere, 2018)**.

### 2.5.1 Analysis of the Pile Group in General

Three approaches are available for analyzing pile group-supported pile caps.

#### 2.5.1.1 Rigid Plate Theory

The pile group is symmetrical, the cap is very thick, piles are all vertical, and the load is applied to the center of the pile group. It is usual practice to assume that each pile carries an equal amount of load **(Bowles, 1988)** as Eq. (1):

$$R_i = P/n \tag{1}$$



For a pile cap eccentrically loaded, the combined stress equation is used when calculating the load per pile, as Eq. (2):

$$R_i = \frac{P}{n} \pm \frac{M_x \cdot Z}{\Sigma Z^2} \pm \frac{M_z \cdot X}{\Sigma X^2} \quad (2)$$

#### 2.5.1.2 Equivalent-Bent Method

The concept of this method considers a coplanar pile group under vertical, horizontal forces and moment, consisting of a pile cap and free standing piles that are rigidly connected to the rigid cap. This system can be transformed into an equivalent-bent composed of a pile cap supporting columns. The rotation and translation of pile head under normal load or moment are being equated to the rotation and translation of a cantilever under the same load and have the same moment of inertia (**Polous and Davis, 1980**).

#### 2.5.1.3 Method of Stiffness (stiffness matrix)

The stiffness method was suggested by (**CRSI Handbook, 2008**) and has been extended into a general third-dimensional problem, which was further elaborated into a third-dimensional system (**Saul, 1968**). Considering that this setup is dealing with the pile and the boundary conditions, this method has to be applied nonlinearly to each pile and the action of each particular pile, as No additively to the soil accumulation. This method accepts only one pile volume and one pile property as an input. It gives a number result rather than several pile-related variables in the form of a multidimensional composite of a number of parameters. Suppose there are distributed pile rigidity effects (and in which they occur, there are beams, supports, and/soil or other non-elliptical elements within the pile). In that case, a model using (FE) is appropriate to be used to simulate the parameters required for the pile load. Suppose there are distributed pile rigidity effects (which occur where there are beams, supports, and/soils, or other non-elliptical elements inside the pile). In that case, a model using finite elements is appropriate to use to simulate the piled load is required.

#### 2.5.2 Requirements for Structural Design

(**Bowles, 1988**) presented the requirements for the reinforced concrete pile cap as follows:

- 1-Bending moment is taken at the same section as for reinforced concrete footing.
- 2-Pile cap shear is computed at critical sections, as shown in **Fig. 11**.
- 3-Pile cap should end at least (150mm) beyond the outside face of exterior piles (i.e., clear edge distance  $E'$ ).
- 4-Piles should be embedded at least (150mm) into the cap. Some building authorities may allow as much as (75mm) of the pile embedded into the cap. If the embedment length is not at least (150mm), the pile should be assumed hinged to the cap.
- 5-The minimum thickness of the pile cap above the bottom reinforcing bars is (300mm).
- 6-Tension connectors should be attached to the pile to ensure that the pile and the cap retain continuity if any of the piles are subjected to tensile forces.

To avoid vertical edge breaking (**CRSI Handbook, 2008**) recommended the following minimum edge distance  $E$  from the middle of piles:



- a. 375mm minimum for pile capacity of 600kN.
- b. 525mm minimum for 600kN pile capacity of 1200kN.
- c. 675mm minimum for pile capacity of 600kN. Minimum pile size of 1200kN is 2000kN.
- d. 750mm Minimum for piles with a capacity greater than 2000kN.

For hooked or headed end anchorage, a minimum clear edge distance ( $E'=E-75\ 225\text{mm}$ ) is needed.

### 2.5.3 The Traditionally Accepted ACI Code Design Method

The, (ACI Committee -318 ,1999). makes no mention of deep pile caps. Thus, the construction process for pile caps is identical to those used for soil-supported footings and two-way slabs. The technique is broken down into five distinct parts.

#### 2.5.3.1 Shear Design

Shear design involves pile calculation design criterion that assigns minimal shear resistance in relation to the headpin stiffness requirement; thus, the pile will always shear unless the headpin stiffness is below its designated tolerance or attributed by the code. Due to the variety of conditions generated by the pile group patterns and the various configurations of applied loads, a variable number of shear-critical parts must be examined. A standard pile cap and its essential parts are depicted in Fig. 11 (ACI Committee -318, 1999). Special regulations governing the shear construction of slabs and footings mandate that designers take into account both one-way shear (as a result of beam action) and 2-way shear (as a result of punching) according to (ACI Committee -318, 1999) Code as Eq. (3):

$$V_u \leq \phi V_c \tag{3}$$

(ACI 318M-99 Section 11.3.1.1) suggests the following relationship for members subjected to one-way shear (i.e., beam shear) and flexural only as Eq. (4):

$$V_u = \frac{V_u}{\phi}$$

$$\frac{V_u}{\phi} \leq \frac{\sqrt{f'_c}}{6} \times b_w \times d \tag{4}$$

$$\phi = 0.85$$

(ACI 318M-99 Section 11.12.2.1), (Tanacan, 2009) suggested using the smallest value of concrete shear strength for non-pre-stressed slabs and footings as follows:

$$V_c = \left(1 + \frac{2}{\beta}\right) \times \frac{\sqrt{f'_c}}{6} \times b_o \times d \tag{5}$$

$$V_c = \left(2 + \frac{a_s \times d}{b}\right) \times \frac{\sqrt{f'_c}}{12} \times b_o \times d \tag{6}$$



$$V_c = \frac{\sqrt{f'_c}}{3} \times b_o d \tag{7}$$

2.5.3.2 Flexural Design

According to the (ACI - 318 1999) Code, the crucial on the face of concrete columns, a section for moment in footings is found. The amount of longitudinal strengthening required at this crucial segment is measured using industry-standard procedures for reinforced concrete members, assuming that plane sections remain plane after bending and that flexural compression tension is uniform around the member's width. The longitudinal reinforcement that is required would be uniformly distributed across the footing (except that the short-direction reinforcement of rectangular footings would be somewhat more localized near the corners). Fig. 10 illustrates the standard pile cap critical segment for a moment (ACI 318M-99 section No.5).

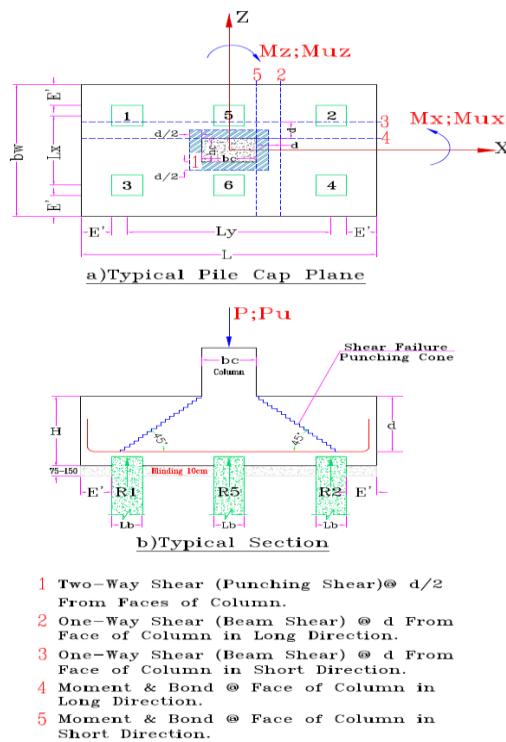


Figure 10. Typical Pile Cap with Critical Section.

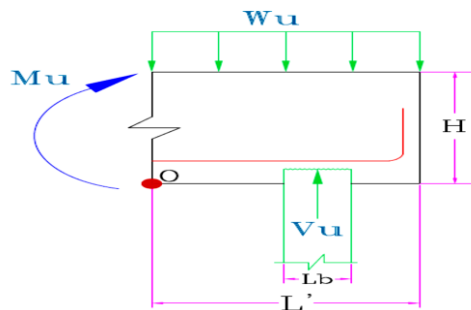


Figure 11. Critical Pile Cap Location for Moment.



Now Mu can be calculated by taking a moment about corner base point O depended on (ACI - 318M,1999) as the following equations:

$$M_u = V_u \times \left( L - E - \frac{L_b}{2} \right) - W_u \times L' \times b_w$$

$$L' = \frac{L-b_c}{2} \tag{8}$$

$$R = \frac{M_u}{\phi \times f'_c \times b_w \times d^2} \tag{9}$$

$$\omega = \frac{1 - \sqrt{1 - 2.36 \times R}}{1.18} \tag{10}$$

$$\rho_s = \omega \times \frac{f'_c}{f_y} \tag{11}$$

$$A_s = \rho \times b_w \times d \tag{12}$$

Since the required depth of the pile cap is usually controlled by shear, the flexural reinforcement ratio is usually near or controlled by the minimum ratios required by (ACI- 318M, 1999).

### 2.5.3.3 Reinforcement Development

For pile, all reinforcing bars must be provided with standard end hooks even when straight bars are fully developed at the face of the column in accordance with common practice. (ACI- Committee 318, 2011) Sections (12.2 and 12.5) recommends the following expressions for checking the adequacy of available development length or standard hooks as Eq. (13,14):

$$l_d = \frac{f_y \times d_{bar}}{1.7 \sqrt{f'_c}} \tag{13}$$

$$l_{dh} = \frac{0.24 \times f_y \times d_{bar}}{\sqrt{f'_c}} \tag{14}$$

Where  $d_{bar}$  is the nominal diameter of flexural steel reinforcement bar use

### 2.5.4 Strut-and-Tie Models Method

There are some methods of construction. Using struts that take into account the movement of the entire force, instead of just focusing on one stage forces, actual structural movement is measured on a large scale accurately and fairly. Concrete Fig.11 models where the straining and expansion internal strain paths are almost the same would have stress and strain expansion and compression resistance. In contrast, load paths that face more in one direction (truss models that face just one way) are simplified to a few regions. Stress elements reinforcements (bonds) are at the nodal areas, and struts connect to one another at the concrete points are the main reinforcing points (pier-sails). These regions are known as truss members (ACI -Committee 318, 1999).

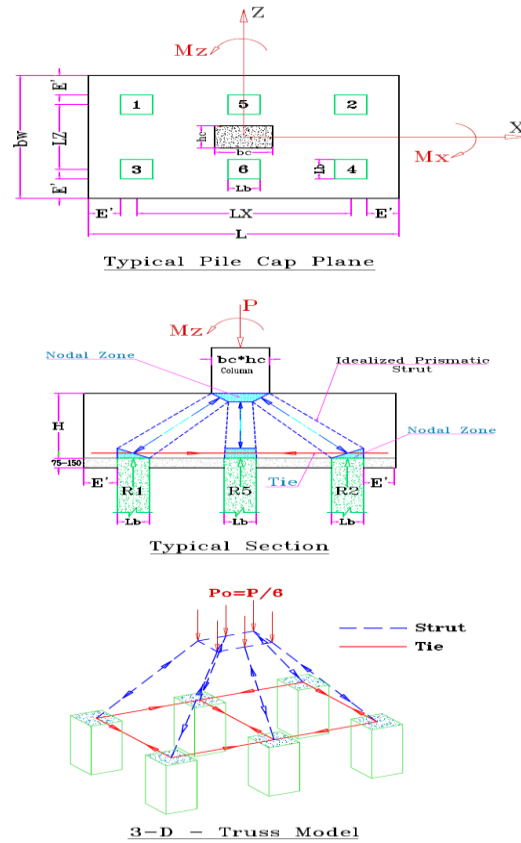


Figure 13. Typical Pile Cap Representation by STM- Simple Truss.

### 2.6. Conclusions

As a result of the previous analysis of experiments on reinforced concrete pile caps, the following remarks about the influence of these parameters can be listed from the literature:

1-Shear period to depth ratio ( $av/d$ ) has a considerable effect on the diagonal cracking capability and ultimate shear intensity of pile caps that fail in shear or flexural mode. It was found that by decreasing the shear span to effective depth ratio from 1 to 0.6, the diagonal cracking and ultimate shear strengths are increased by average ratios of 16.75 % and 35.6 %, respectively.

2-Shear strengthening in the transverse direction has a major impact on the shear potential of pile caps.

3-The value of the concrete compressive strength  $f'c$  has a significant influence on the shear capacity of pile caps, whereas the behavior of such elements does not differ when using high strength concrete from that observed using normal strength concrete.

4-When the ( $av/d$ ) ratio is kept, the value of effective depth  $d$  influences the shear capacity of pile caps. The ultimate shear strength  $V_u$  is more affected by increasing the effective depth  $d$  as compared with the cracking shear strength  $V_{cr}$  (i.e., insignificant effect).

5-The increase in longitudinal flexural reinforcement improves the shear capacity, especially when the value of ( $av/d$ ) is small, whereas the increase in longitudinal reinforcement becomes useless when the value of ( $av/d$ ) is large.

6-When increasing the horizontal shear reinforcement ratio from 0% to 0.393 % and decreasing the vertical shear reinforcement ratio simultaneously (i.e. keeping total amount of shear reinforcement constant), an increase in the diagonal cracking shear strength by an average ratio of





23.5% is obtained. This will give a view on the effect of increasing the strength in this type of concrete member. In this work, a comparison will be provided based on these findings. The behavior of pile caps from aerated reinforcing concrete will also be studied in this work and the effect of the shear.

There is no research on the use of lightweight concrete as a pile cap and maybe the first consideration for research in this discipline. There is a suggestion of the need for further research, as there is a need to study the mechanical properties and behavior of the special foundation in pile cap.

**NOMENCLATURE**

$R_i$	is the load per pile
$P$	is the total applied vertical loads
$n$	is the number of piles in the group
$M_x$ and $M_z$	moments about X and Z axes, respectively.
X and Z	distance from X and Z axes to any pile.
$\Sigma X^2$ and $\Sigma Z^2$	section moduli of the group.
$V_u$	the section's shear force factored.
$V_c$	nominal shear strength provided by concrete
$b_w$	the transverse dimension of pile cap
$d$	the effective depth of pile cap measured from centroid of longitudinal flexural reinforcement for two-way shear (i.e. punching shear)
$\beta$	the ratio of long side to short side of column.
$b_o$	the perimeter of column section
$\alpha_s$	40 columns for interior columns, 30 columns for edge columns, and 20 columns for corner columns.
$W_u$	the total vertical loads above pile cap including its own weight.
R and $\omega$	dummy notation (unit less).
$\rho_s$	is the ratio of steel reinforcement in the concrete section.



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