This paper reviews the results of some previous research studies on reinforced concrete pile caps. Majority of pile caps support only one column, besides only a few piles support the pile caps in turn. These are usually deep and short members with span/depth ratios of less than one and a half. Codes do not offer identical design for these types of pile caps. These pile caps have usually been designed as beams bridging piles with main longitudinal reinforcement for flexural capacity depending on the beam theory and a suitable depth for shear capacity. Lately, the Strut & Tie model (STM) has been used for the pile caps design (D-region or disturbed) in which the paths of load are proposed to be a 3D truss. The concrete compressive struts between the piles and column support the compressive forces while reinforcing steel placed between piles carry the tensile forces. The two models above have not presented uniform safety factors against failure or being able to expect whether failure will occur by fragile mode (shear) or ductile mode (flexure). Thus, in this paper, some remarkable experimental works on pile caps are summarized with conclusions.

**Keywords:** Reinforced concrete, Pile cap, Literature review, Strut-and-tie model, Design, Behavior

**INTRODUCTION**

Pile caps transfer the load from column(s) to a piles group. In spite of being a very important and common structural element, there is no a generally unified procedure for the pile caps design. In practice, designers followed numerous empirical rules. 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 (ACI-318 Committee, American Concrete Institute, 2005; British Standards Institution, 1990; British Standards Institution, 1997; Canadian Standards Association, 1994) assume a linear distribution of strain over the depth of a member. Therefore, a pile cap is
considered as a beam bridging piles that require 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, American Concrete Institute, 2005; ACI-318 Committee, American Concrete Institute, 1983; ACI-318 Committee, American Concrete Institute, 1999; and ACI-318 Committee, American Concrete Institute, 2002) uses the same sectional methodology used for two way slabs and for footings supported on soil. While Strut-and-Tie model in which an internal load-resisting truss is being used by other design provisions (ACI-318 Committee, Canadian Standards Association, 1994; Schlaich J, Schafer K and Jennewein M, 1987). STM states that tensile forces are carried by steel reinforcement ties and compressive forces are carried by concrete compressive struts. These struts and ties should transfer the applied forces from the column to the piles. Appendix A in [ACI 318-02] introduced a general design procedure based on strut-and-tie for all D-regions (discontinuity regions). Nonlinear in addition to linear analyses demonstrate that pile caps act as three-dimensional elements. Over the dimensions of the D-region, there is a complex strain variation in which compressive struts form between applied forces of columns and the supporting piles. That is why, pile caps design procedures should not be based on a sectional design method and many tests have showed the imprecision of this approach. Many researchers (Adebar P et al., Jan-Feb, 1990; Adebar P and Zhou Z, July-Aug, 1996; Bloodworth A G et al., Nov. 2003; Cavers W and Fenton G A, Feb, 2004; Park J et al., 2008) concluded that pile caps that were designed to fail in the brittle mode of shear have been reported to fail in flexure. While many researchers (Blévot J L and Frémy R, 1967; Clarke J L, 1973; Suzuki K and Otsuki K, 2002; Suzuki K, Otsuki K and Tsubata T, 1999; Suzuki K et al., 1998; Suzuki K et al., 2000) found that the strut-and-tie method presents a more appropriate procedure for dimensions proportioning and reinforcement selecting for the pile caps. Previous experimental works for pile caps and some important conclusions suggested by various investigators are summarized here.

**RESEARCH SIGNIFICANCE**

The present research provides useful guidance to researchers in order to contribute to the development of pile caps design recommendations under various types of loading. The experimental data collected from the literature are supporting here the appropriateness of using strut-and-tie model. As concluded from the literature, the use of the strut-and-tie model can provide rational models with safer and more economical solutions for the pile caps design than the sectional design method application.

![Figure 1: Various Layouts of Main Reinforcing Bars Used by Blévot and Frémy, 1973](image)

**EXPERIMENTAL DATA FOR PILE CAPS**

There are some degree of limitations in the experimental test data on the pile caps performance. Unfortunately, as the patterns of reinforcement used in the test pile caps are not compatible with the design procedures, an important portion of these results are not so helpful for assessing these code provisions. A brief review of some notable test results is summarized here.
Blévot and Frémy (1967) carried out a comprehensive series of tests. Researchers tested half-scale 51 four-pile caps and eight full-scale four-pile caps. The main aims of these tests were to compare the pile caps performance when containing different longitudinal reinforcement patterns as shown in Figure 1 in addition to check the efficiency of different strut-and-tie models.

The tests results illustrated that the use of bunched square layouts (Figure 1-a) led to a (20%) higher capacity than in specimens with the same reinforcement quantity distributed in a grid pattern (Figure 1-e)). It was concluded in these tests that using only a bunched square layout of reinforcement led to poor control of crack, and therefore, the researchers recommended using complementary grid reinforcement. According to the authors, punching shear can take place at the failure, so results interpretation concerning pile caps is complex. The authors reached the conclusion that it is not possible in pile caps to separate shear and bending behavior such as in beams, because increasing the longitudinal reinforcement leads to an important increase in punching strength. This conclusion is also supported by other researchers such as (Blévot J L and Frémy R, 1967; Clarke J L, 1973; Suzuki K and Otsuki K, 2002; Suzuki K, Otsuki K and Tsubata T, 1999; Suzuki K et al., 1998; Suzuki K et al., 2000).

Clarke (1973) tested half-scale 15 four-pile caps. Figure 2 shows different longitudinal reinforcement patterns. The test specimens were designed to fail in flexure. The researcher concluded the unsafety of the sectional approach for shear capacity calculating. Flexural failure took place only in four caps, whereas shear failure took place in the remainder caps after longitudinal reinforcement yielding. The main conclusion of Clarke was that Comité Euro-International Du Béton (1970) and the British Standards Institution (1972) overstate the effective depth importance in shear strength calculating.

From his four-pile cap tests, the truss analogy was an adequate method of analyzing a four-pile caps in order to ascertain its flexural capacity and to calculate the required amount of tensile reinforcement. The experiments also showed that using a bunched square reinforcement pattern led to 25% higher failure loads than the failure loads determined when the same reinforcement amount was used in a grid pattern, which approved the Blévot and Frémy (1967) conclusions.

Sabnis and Gogate (1984) tested nine 1/5-scale four-pile caps. The grid reinforcement ratio was varying from 0.21% to 1.33%. The aim of these experiments was to find if the longitudinal reinforcement amount had an effect on shear strength. The researchers concluded that the reinforcement amount over 0.2% had no influence or little on capacity. A wide range of experiments (Blévot J L and Frémy R, 1967; Clarke J L, 1973; Suzuki K and Otsuki K, 2002; Suzuki K, Otsuki K and Tsubata T, 1999; Suzuki K et al., 1998; Suzuki K et al., 2000) did not support this conclusion.

Adebar et al. (1990) tested five four-pile caps with different geometries and reached the conclusions that the STM can well estimate the complex 3D element overall behavior as shown in Figure 3.
Failures generally took place after the longitudinal reinforcement yielding and with the diagonal compressive struts splitting that propagated from the column to the piles. This splitting also occurs in deep beams shear failures (Abdul-Razzaq et al., xxxx). These researchers recommended to limit the top of a pile cap maximum bearing stress to 1.0f'c in order to prevent compressive strut splitting failures. This recommendation was found to be not applicable for all member ranges despite its simplicity. This attributed to the fact that the mechanical reinforcement ratio and the shear span-depth ratio affects the maximum normal stress at failure acting on the tested caps columns (Blérot J L and Frémy R, 1967; Clarke J L, 1973; Suzuki K and Otsuki K, 2002; Suzuki K, Otsuki K and Tsubata T, 1999; Suzuki K et al., 1998; Suzuki K et al., 2000). The authors concluded that ACI 318-83 does not well identify the experimental test results trend. The authors suggested that the ACI 318-83 overestimates the effect of the effective depth and that the deep pile cap strength is better improved by increasing the concentrated loads bearing area than by increasing the pile cap depth.

According to an experimental and analytical study of compression struts under concrete confinement, Adebar and Zhou (1993) suggested a direct approach for shear strength verifying. In this proposed approach, the maximum bearing stress has a more important effect on any prescribed critical section than shear stress. The authors found that when compression struts are confined by plain concrete, the maximum bearing stress to cause transverse splitting depends on the aspect ratio (height/width) in addition to the amount of confinement of the compression strut. A simple example of two piles-cap was studied to illustrate their suggestions of stress limits for the design of the cap using strut-and-tie model. After that, Adebar and Zhou (1996) compared their previously suggested model with testing 48 pile caps. They concluded that the ACI 318-83 provisions for one-way shear design are extremely conservative and that the conventional procedures of flexure design for two-way slabs and beams are unconservative for pile caps. To solve these issues, the authors proposed that the design of pile caps when using STM should also through using an indirect and additional shear verification. This suggestion is according to the evidence presented by Schlach et al.,(1987)[25] in which the design of an entire D-region when using STM can be valid if the maximum bearing stress is kept lower a certain limit.

Suzuki et al. (1998) tested 28 four-pile caps in which the layouts of the longitudinal bars and edge distances were varied (the edge distance is the shortest distance from the pile center to the footing slab peripheral). The majority of pile caps failed by shear after longitudinal reinforcement yielding and only four specimens failed by shear without longitudinal reinforcement yielding. It was found that bunched square layouts (shown in Figure 4) resulted in higher strengths.
and that the distance of the edge affected the load of failure. To increase deformation and strength capacity even after yielding of reinforcement, the edge distance was suggested to be about 1.5 times the diameter of the pile. After that, Suzuki et al. (1999) tested 18 four-pile caps tapered footings (with top inclined slabs) and proved that cracking load has a tendency to decrease as the ratio of reinforcement increases. In these experiments, most specimens failed in shear after longitudinal reinforcement yielding, and only two specimens failed by shear before yielding of reinforcement.

Suzuki et al. (2000) tested thirty four pile caps that reinforced with a grid layout as shown in Figure 5. A significant aim of the research was to evaluate the edge distance effect between the cap and the piles on behavior and strength. The results have shown that the load of the 1st crack and the flexural capacity decreases even if the slab reinforcement is the same when shortening the edge distance.

Suzuki and Otsuki (2002) tested eighteen four-pile caps with grid reinforcement. The parameters of test involved type of anchorage and concrete strength. The edge distance was maintained equal to the pile diameter and it was easy to prove that f’c has no effect on ultimate strength and failure mode. In the majority of pile caps, the mode of failure was because of the shear that took place before yielding of the reinforcement. Whereas all specimens were expected to fail by flexure, ten of them did not fail by flexure. The researchers reached the conclusion that it was because of the effect of shortened edge distances on the failure by shear. Even though the researchers did not make a certain anchorage length conditions reference, it looks obvious that short edge distances have a direct effect on the longitudinal reinforcement development. The same problem of anchorage looks like to happen in the test data of Suzuki et al. (2000).

Souza et al. (2007) proposed an adaptable 3D STM that can be used in the analysis or design of four-pile caps supporting rectangular columns that apply compressive forces and biaxial flexure onto the pile cap top. Most codes did not treat this very common situation, and that is why, designers have been applying a simplified strut-and-tie model or the bending theory (Blévit J L and Frémy R, 1967) developed for the situation of subjecting axial load to square columns. The authors also proved that using the sectional design approaches can be an invalid approach for stocky pile caps. In addition to conclusions that the shear approaches can be unconservative, pile caps show brittle failures when subjected to overload. STM better characterizes the forces flow in pile caps nonetheless enhanced models are required that can take into considerations the nonlinear behavior of concrete.

Ahmed et al. (2009) tested six simply supported pile caps of size 75 cm × 75 cm × 23 cm resting on four piles were designed with STM for assumed external loads applied to the center of pile caps. Two mix designs of concrete were...
used with three samples from each mix. These experimental loads were compared with the theoretical shear capacity of the pile caps designed by STM, Plate (1).

They observed that strut-and-tie model provides a reliable solution for predicting the shear strength of pile caps and the experimental results fell very close to the theoretical values based on strut-and-tie model.

**CONCLUDED REMARKS**

Many engineers use approximate empirical procedures to design the reinforced concrete pile caps because worldwide practice codes do not state unified guidance to design the reinforced concrete pile caps. That is why, the majority of practice codes of induce using sectional method to design the reinforced concrete pile caps. This is inadequate for most pile caps that compression struts flow directly from the loading point application to the pile (very stocky). Therefore, the Strut and Tie model could be used instead of sectional force methods. From other side, Strut and Tie method was found conservative in predicting shear strength, hence it is a desirable method for design of stocky pile cap.

From the previous brief review of some experimental studies concerning RC pile cap, the followed summary can be drawn:

1-The conventional methods evaluate the internal forces by assuming Bernoulli’s hypothesis is valid (shear span to depth ratio is greater than 2). In reality Bernoulli’s hypothesis is not valid in structures like deep beams, corbels, beam-column junction, etc. the strain in these type of structures are not linear. Strut-and-Tie method (STM) is popular among research communities and engineers for the analysis and design of disturbed regions of structures (shear span to depth ration is less than 2). This method produces much accurate results when compared to the conventional empirical methods. The conventional methods evaluate the internal forces by assuming Bernoulli’s hypothesis is valid (beam theory assumption that plane sections remain plane). The inelastic regions where Bernoulli’s hypothesis is not valid are known as Disturbed or D-region and the regions which obey Bernoulli’s hypothesis is known as Bernoulli’s or B-region. The Strut and Tie Model method was developed in order to account for such nonlinearities and to overcome this over reinforced problem. In the case of structures which are subjected to very intense loading, the behavior of the whole structure will be inelastic. In such case, even the B-regions get converted to D-regions. These types of structures can also be analyzed and designed using STM with better accuracy when compared to other conventionally used methods. Not like conventional design approaches, STM do not separate shear and flexural design; though, it may be said that the “design for shear” using STM for deep members includes limiting the stresses of concrete to insure that the reinforcement of the tensile tie yields prior to the shear failure of concrete.

2-Experimental tests on pile caps that designed to fail by flexure led to fail by shear. The
conventional shear approaches can be -to a certain extent- unconservative when used for pile caps. The exaggeration in the importance of the effective depth in case of using the sectional design methods caused this early failure in shear.

3-Some codes of practice such as American Concrete Institute (ACI) code, Canadian Standards Association (CSA), Australian Standard, New Zealand Standard are now supporting the strut-and-tie method as an appropriate and alternative design procedure for pile caps. Shear verification is highly recommended by many researchers when designing pile caps although it is not recommended in these practice codes when designing by the strut-and-tie method. The researchers gathered that shear failure in pile caps is attributed to the longitudinal splitting of the compression struts. Therefore, a relation shear span/depth ratio under 1.0 and a compressive stress under 1.0f'c normally can result in ductile failures. Based on this, designers may believe that the longitudinal reinforcement yielding prior to the splitting or crushing of compression struts.

Some researchers illustrate that less 10 to 20% of longitudinal reinforcement amount to carry the same loading will be used in case of designing by a strut-and-tie method although the opposite situation was concluded by other researchers.

Therefore, although strut-and-tie method can offer a more safe and rational method for proportioning the pile caps depth for shear, it is economical than the sectional approach or not.

ACKNOWLEDGMENT

The completing of this present work was in the Department of Civil Engineering, College of Engineering, University of Diyala. Therefore, the moral support that was provided is gratefully acknowledged.

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