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Nonlinear Analysis of Four-Pile Caps

Análise Não-Linear de Blocos Rígidos Sobre Quatro Estacas


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Abstract

This paper aims to the classification of pile caps in thick or thin, proposing the Strut-and-Tie Method and the Beam Method as rational solutions for the design. The results of nonlinear analysis, obtained from investigation of thick four-pile caps with different layouts for the principal reinforcement are presented, intending to show the potentialities of the Finite Element Method and the smeared crack model applied to three-dimensional fracture problems.

Keywords: Pile Caps, Strut-And-Tie Model, Finite Element Method, Nonlinear Analysis and Smeared Crack Model.

Resumo

O presente trabalho tem por objetivo discutir a classificação dos blocos em rígidos ou flexíveis, propondo o Método das Bielas e o Modelo de Viga como soluções viáveis para o problema de dimensionamento. São apresentados os resultados de análises não-lineares, efetuadas para blocos rígidos sobre quatro estacas com diferentes disposições para as armaduras principais, com o objetivo de apresentar as potencialidades do Método dos Elementos Finitos e dos modelos de fissuração distribuída em problemas de fraturamento tridimensionais.

Palavras-chave: Blocos de Fundação, Método das Bielas, Método dos Elementos Finitos, Análise Não-Linear e Fissuração Distribuída.

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1 Introduction

Pile cap is a structural element whose function is to transfer load from a column to a group of piles. Unfortunately, the current procedures used for designing pile caps do not provide the structural engineer with a clear knowledge about the effective mechanisms of this structural element ([1]).
The visual inspection of pile caps under service load conditions is not possible and, moreover, as the adequate comportment of these elements is necessary for the security of the constructions, the true knowledge about these elements is very important.
However, even nowadays, there are not rigorous solutions in the literature about pile caps and, for that reason, it is easy to understand why many empirical rules still keep in evidence for designing of these elements ([2]).
Basically, engineers have been using two ways for designing pile caps: the Strut-and-Tie Method and the Beam Model ([1], [2], [3] e [4]). Moreover, the main research about pile caps usually focuses on linear elastic analysis and experimental investigation.
Careful attention should be given to the fact that the design of these elements using the Beam Method or the Strut-and-Tie Method depends on the dimensions of the pile cap under investigation. Unfortunately, it seems not to have this kind of alert in the literature and even certain confusion can be notice.
The Beam Method should be applied for the thin pile caps, while the Strut-and-Tie Method should be applied for the thick pile caps. When a pile cap is thick, the observed comportment is very complex, with nonlinear deformations over the member's depth.
Basically, this nonlinearity can be explained due the great influence of shear force acting in delimited regions, called as "D Regions". In these regions, usually found in thick pile caps on the whole, the Bernoulli's Hypothesis can not be applied and the frequent methods could produce designs against security.
Inside "D Regions", the tension force in the reinforcement tends to keep constant, the internal level arm changes and the element works as a tied arch, with the shear force being transmitted by compression through inclined struts ("strut actions"). In this kind of problem only the Strut-and-Tie Method can provide a rational and safe design, clearly indicating the necessity of anchorage for the longitudinal reinforcement.
Basically, the design of thick pile caps using the Strut-And-Tie Model consists in idealizing a three-dimensional truss formed by concrete struts and steel ties inside the pile cap. Some experimental works using this idea were conducted by Yan, Blévot and Fremy in the 60 and they became classical in the current literature.
By another way, for those elements which resist the shear force using the beam mechanism (a thin pile caps for example), the tension force acting in the tie reinforcement tends to change, in order to balance the applied external moment. Thus, the internal level arm is kept relatively constant and the so called "B Regions" arisen. For those cases the "General Flexure Theory" can be applied and the security has been proofed over the years by the professional experience.
The design using the Beam Method adopted by many structural codes, for example American and Canadian reinforced concrete codes, assumes that pile caps behaves as a beam above simple supports (piles), in the way that is possible to adopt a simplified theory for internal forces estimates.
The Beam Method divides the analysis in the following steps:

- Shear design, which involves the determination of a minimum depth to the pile cap, so that the concrete contribution to shear is bigger than existent shear in a critical section;
- Flexure design, which involves the usual assumptions of reinforced concrete beams for the determination of required longitudinal reinforcement;
  It should be observed that the pile cap design under considerations of beam theory is perfectly acceptable, since that pile cap has a geometry that supports this hypothesis. The Beam Method can be particularly useful in those cases with great number of piles. The Strut-And-Tie Method is more generic than Beam Method and can be applied to any situation.

2 Classification of Piles in Thin and Thick Cases

In the literature, most of researchers do not seem to do a clear distinction between thin and thick pile caps, what becomes incoherent some hypothesis of design actually considered. It is observed that the Beam Method seems to be the most spread method for designing pile caps. This fact characterizes the lack of investigation into this area, favoring the introduction of insecurity in pile caps design, mainly for the tick ones.
It is believed that Strut-and-Tie Method should be the most used method for pile caps design, mainly by its generic formulation, which is independent of the element dimensions. The Beam Method just considers the forces in some critical sections and clearly overestimates the element capacity with regards to its effective depth.
In order to eliminate remaining doubts about how method must be applied, pile caps should be adequately classified into thick or thin cases. The Strut-and-Tie Method should be applied to thick pile caps while the Beam Method should be applied to the thin pile caps.
In accordance with Montoya et al. [5], a thick pile cap is a structural element which maximum distance between the column face and the center of the furthest pile (a) is smaller than 1,5.d, being d the effective depth of the pile cap. In recent versions, Montoya et al. [6] has shown the same recommendation of the Spanish code EHE [7].
For the EHE[7], a pile cap is considered thick when the maximum distance between the face of column and the center of the furthest pile is smaller than twice the pile cap

depth (H). This means that struts will be inclined in relation to the horizontal direction with an angle not inferior than 26,56°.
The present paper's authors, employing the Saint Venant's Principle, believe that a pile cap should be considered thick when the distance between the face of the column and the internal face of the furthest pile is smaller or equal twice the pile cap depth.
Moreover, the authors believe that if a thick pile cap is designed using the hypothesis of thin pile caps (taking in consideration the moments and shear forces acting in a critical section) the amount of reinforcement obtained will be inferior to that effectively necessary, leading to an unsafely design.
Also, it must be registered that in a tick pile cap, the flow of forces between column and piles is made in a direct way, throughout inclined struts, and this fact are not verified in thin pile caps. Finally, the tick pile caps normally are not requested by punching shear, what is possible for the thin pile caps.

3 Description of the Referential Experimental Research

Some results of Sam & Iyer [3] were taken as referential data once they have researched the behavior of thick pile caps with different dispositions for the principal reinforcement as depicts Figure 1.

The pile caps were loaded until failure by means of a concentrated load applied in the column position and by means of further numerical investigation the researchers established the following conclusions for their work:

- The pile cap with bunched square-type reinforcement layout resists the least load when compared with the other alternative (slab-type reinforcement layout), which opposes the classical results;
- At low load levels the beam action is predominant (very different deformations between the center and the extremities of the reinforcements) while at higher loads the arch effect (constant deformations trough the reinforcement) starts to be predominant, independent of the type of distribution chosen for the longitudinal reinforcement;
- A portion of concrete, below the column, extends from the column to the pile with form similar to a frustum of pyramid, leading the pile cap to failure by punching shear, irrespective of the reinforcement layout;
- The nonlinear analysis using the package software ADINA was able to predict the ultimate load fairly accurately.

4 Nonlinear Analyses of the Four-Pile Caps

The numerical analyses were conducted using the package software DIANA and due the conditions of symmetry, only 1/4 of the pile cap geometry was investigated. The columns and piles were not described in the model, but they were

Figure 1 – Characteristics of the pile caps tested by Sam & Iyer (3)

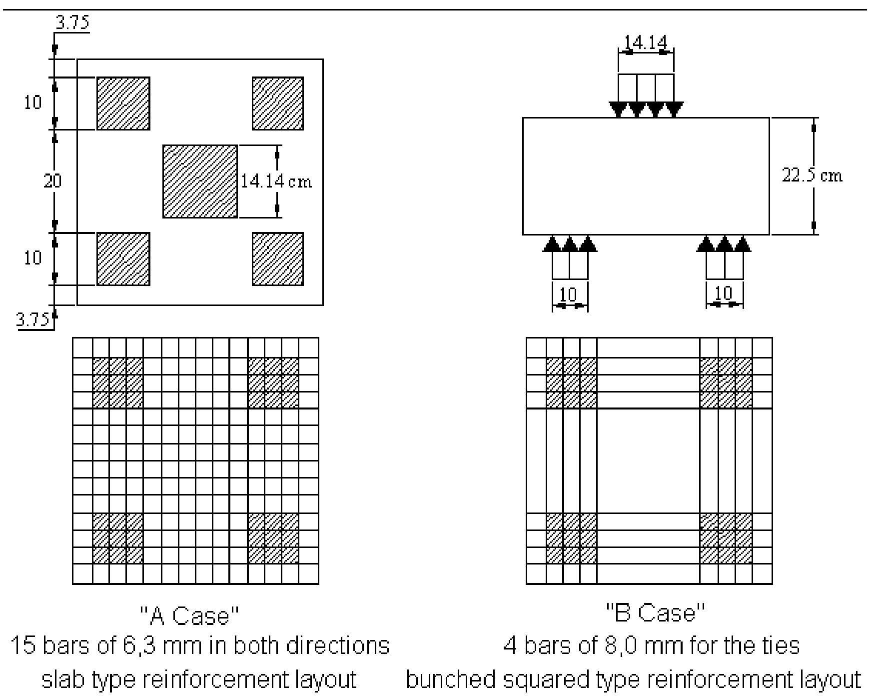


Table 1 – Material properties defined in the package software DIANA

Concrete					Steel	
E_c (MPa)	f_t (MPa)	f_c (MPa)	G_f (N.mm/mm^2)	G_c (N.mm/mm^2)	E_s (MPa)	f_y (MPa)
22.077,00	1,90	19,00	0,0431	4,30	200.000,00	300,00

substituted for equivalent support and loading conditions. This way was taken in order to not give attention for a possible localized failure, as well as, for adjusting the investigation with the experimental work of Sam & Iyer [3].
The material properties were obtained from Sam & Iyer [3] and the parameters not described in their paper, but necessary for the conduction of the nonlinear analysis, were estimated using the recommendations of Feenstra & Borst [8]. Table 1 presents in details the material properties used for numerical investigations using DIANA.
For the "A Case", shown in the Figure 1, have been tested various smeared crack models and the failure load acts in the limit defined by 615,44 kN < F_u < 622 kN. The results indicated a difference between 10 and 12% in relation of the experimental failure load (690 kN) obtained by Sam & Iyer [3]. The model which conducted to the best results was the "Rotating Crack Model", using a linear method of solution and shear retention factor equals 0,99.
For the "B Case", have also been tested various smeared crack models, and the failure load acts in the limit defined by 524 kN < F_u < 664 kN. The results indicated a difference between 5 and 20% in relation of the experimental failure load (630 kN) obtained by Sam & Iyer [3]. The model which conducted to the best results was the "Fixed Crack Model", using a secant method of solution and shear retention factor equals 0,001.
Both in "A Case" and "B Case", cracks have propagated in an inclined way from the pile through the column, forming a series of cracks in the region of contact between the column and the pile cap at the ultimate stage. Cracks have propagated in a significant manner in the lateral faces of the pile caps, in the region between piles, with great intensity in the center of the related spam. Figures 2 and 3 present the crack pattern developed in top and bottom surface for the "B Case". The crack pattern is very closer to the crack pattern obtained for the "A Case".
In both cases have been observed at failure a very small tension in the reinforcement, approximately 168 MPa for the "A Case" and approximately 136 MPa for the "B Case", indicating that do not have occurred yielding for the principal reinforcement and that the pile cap failure was due the concrete compression.

Figure 2 – Developed cracks in the top surface of the four-pile cap ("B Case")

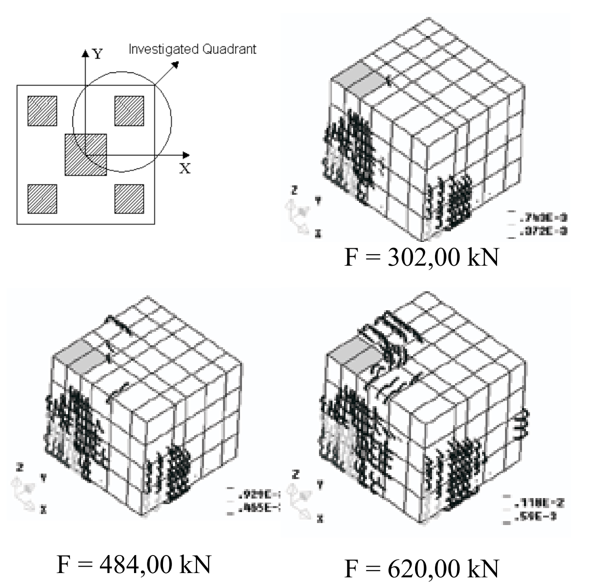
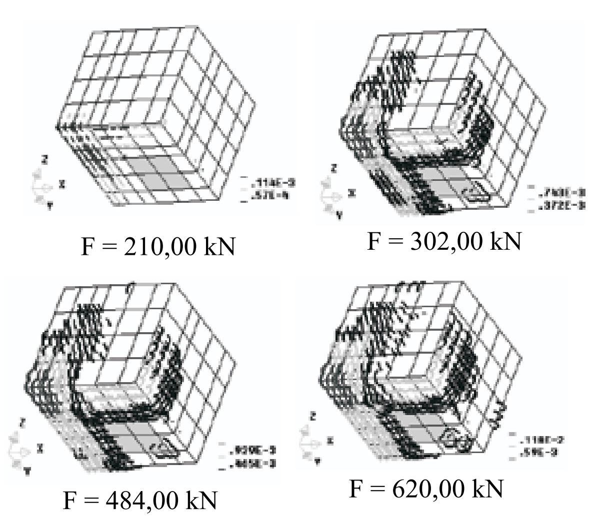


Figure 3 – Developed cracks in the bottom surface of the four-pile cap ("B Case")



Differently from the observations made by Sam & Iyer [3], the measure deformations in the reinforcements remained constant and deformations in concrete were nonlinear along the pile caps depth, since the start of loading.

5 Conclusions

It has been observed for the problem in question a great difficulty for estimate a limit load, which suggests that for diagonal cracks (typical for shear) is more interesting to adopt a range of variation for the failure load and not only a single limit value.
The variation range found, as well as the aspect of the failures, is very closer with the experimental results, confirming the great potentiality of nonlinear analysis in complex structural problems.
A classic strut-and-tie model applied to the problem has indicated a failure load very below from that found experimentally. It is believed that it is probably due the fact that the pile caps under investigation have a relation a/d (depth-to-span) smaller then 0,5. This fact suggests a behavior for the pile caps very closer to that found in partially loaded surfaces, which asks for a refined strut-and-tie model.
As related, Sam & Iyer [3] believed the mechanism that provoked the failure was a punching of the piles or the column. The authors of the present paper do not agree with this affirmation and believe that the mechanism that provokes the failure was the transversal tension in the inclined struts, whose function is to transfer the load from the column directly to the piles.
Should be borned in mind that the punching shear problem normally appears in cases where a slab is directly supported by a column. Due the high shear tension in a critical perimeter around the column, failure planes of approximately 35° within the horizontal direction normally appears. This failure planes tends to separate the connection between slab-column in a fragile way, forming a failure surface that looks like a frustum of pyramid, with cracks around the column position.
In the geometry of the pile caps tested by Sam & Iyer [3], the critical perimeter for punching of the columns captures the presence of the piles, and for this reason the load is supposed to goes directly from column to the piles throughout inclined struts. Moreover, the crack patterns do not present radial cracks around the column but skirting them, remembering a crack pattern of spalling.
It is believed that this fact confirms that the pile caps failed by a strut fail and not in punching shear. Just the form of the collapse looks like punching failure, but not the mechanism, that is closer to that verified for partially loaded surfaces. In accordance with CEB-FIP Model Code 1990 [9], item 3.3, the failure of partially loaded surfaces can occur by spalling near the end face of the column, by splitting in deeper zones and by surface crushing.
The anterior information leads to the necessity of using horizontal stirrups along the pile caps with relation a/d under 0,5, in order to contain the transversal tensions that may develop along the pile caps depth. If do not exists the intention of using this horizontal stirrups it is necessary to limit the maximum tension under the column in $0{,}8.f_{ck}$, such an way that the concrete can absorb the transversal tension stress.
Finally, it is recommended to put reinforcements in form of an orthogonal mesh (slab type reinforcement) in the bottom of pile caps having relation a/d under 0,5, intending to contain the development of cracks that can lead this structures prematurely to failure.

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