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Nonlinear Analysis of Four-Pile Caps

Análise Não-Linear de Blocos Rígidos Sobre Quatro Estacas

R. A. SOUZA[a]
rsouza@uem.br

T. N. BITTENCOURT[b]
tulio.bittencourt@poli.usp.br

Abstract

This paper deals with the classification of pile caps in rigid or flexible and proposes Strut-and-Tie Method and Beam Method as rational solutions to design this element. Results from nonlinear analysis, obtained for rigid four-pile caps subjected to different reinforcement layouts are presented, intending to show the potentialities of both Finite Element Method and smeared crack models in concrete three-dimensional fracture problems.

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

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.

[a] *Associate Professor, Universidade Estadual de Maringá, Civil Engineering Department, Av. Colombo, 5790, Bloco C67, CEP 87020-900, Maringá - PR, Brazil. E-mail: rsouza@uem.br*

[b] *Associate Professor, Escola Politécnica da Universidade de São Paulo, Structural Engineering and Foundations Department, Av. Prof. Almeida Prado, trav.2, n.271, Cidade Universitária, CEP 05508-900, São Paulo - SP, Brazil. E-mail: tulio.bittencourt@poli.usp.br*

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 to design pile caps do not provide structural engineers with a clear knowledge about the effective behavior of this structural element ([1]).
Visual inspections of pile caps under service load conditions are not possible and taking into account that the adequate behavior of this elements are extremely demanded to the security of constructions, an effective and safe knowledge about these elements is very necessary.
However, even at the present time, there are no rigorous solutions in literature about pile caps, and for this reason it is not surprising that many empirical rules still keep in evidence to design this element ([2]).
Basically, two procedures have been used with frequency to design pile caps, Strut-and-Tie Method and Beam Method ([1], [2], [3] e [4]), and principal researches have been conducted using linear elastic analysis and experimental investigation of pile caps, always applying the mentioned methods.
More attention should be given to the fact that either Beam Method or Strut-and-Tie Method can be used to design pile caps, depending on the dimensions of the pile cap under investigation. Unfortunately, there is no advice about this procedure in literature and even certain confusion may be realized.
Beam Method should be applied to flexible pile caps, while Strut-and-Tie Method should be applied to rigid pile caps. When a pile cap is rigid there is a very complex behavior, characterized by nonlinear deformations over the depth of the member.
Basically, this kind of nonlinear behavior in structural can be explained taking into account the great influence of shear forcer in delimited regions called "D Regions". In these special regions, typical of rigid pile caps, Bernoulli's Hypothesis cannot be applied and conventional methods may produce designs against security.
Inside a "D Region", the tensile force in the reinforcement tends to keep constant, the internal level arm changes and the element behaves like a tied arch, with shear forces being transmitted by compression through inclined struts ("strut actions"). In this type of problem, Strut-and-Tie Method can provide a rational and safe design, clearly indicating the necessity of anchorage of the longitudinal reinforcement.
Basically, design of rigid pile caps using Strut-And-Tie Method consists in idealizing a three-dimensional truss constituted by concrete struts and steel ties in the interior of the pile cap. Some experimental works using this procedure were conducted by Yan, Blévot and Fremy in the 60´s and has become classical in literature.
In an element that resists shear forces by beam mechanism, the tensile force acting in the longitudinal tie tends to change, in order to balance the applied external moment. Thus, the internal level arm keeps relatively constant and strains over the depth can be assumed as linear. In these cases, known as "B Regions", a Beam Theory can be applied with great security and with its validity is certified by years of professional practice.
Design of pile caps using Beam Method has been adopted by many structural codes, like American and Canadian concrete codes, for example. This codes assume that pile caps behaves as a beam spanning between piles, in a sense that a simplified theory can be used to quantify internal forces.
Beam Method divides the analysis of pile caps 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 realized that pile cap design adopting beam theory is perfectly acceptable, since the pile cap under investigation has a geometry that supports this hypothesis. Strut-And-Tie Method is generic and can be applied to any situation while Beam Method can be particularly useful in those cases of great number of piles situated faraway from column.

2 Classification of Pile Caps in Flexible and Rigid

In literature, researchers seem not to do a clear distinction between flexible and rigid pile caps, generating in this way some confusion about the validity of the proposed models.
It is observed that Beam Method seems to be the widely method to design pile caps. This fact characterizes a lack of investigation into this area, and might be spreading the introduction of a certain parcel of insecurity to the design of rigid pile caps.
Strut-and-Tie Method should be the widely method to design pile caps, mainly by its generic formulation, which is independent of the dimensions of this structural element.
Beam Method just considers forces in some critical sections and clearly overestimates the element capacity with regards to its effective depth.
In order to eliminate doubts about what model should be used to design pile caps, a simple classification in rigid or flexible should be done. Strut-and-Tie Method should be applied to rigid pile caps while Beam Method should be applied to design flexible pile caps.
According to Montoya et al. [5], a rigid 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 recommendations of the Spanish code EHE [7].
In the Spanish Code EHE[7], a pile cap is considered rigid when the maximum distance between the face of column to the center of the furthest pile is smaller than 2.H, being

H the pile cap depth. This means that struts will be inclined in relation to the horizontal direction with an angle not smaller than 26,56°.
The paper's authors, employing Saint Venant's Principle, believe that a pile cap should be considered rigid when the distance between the face of the column and the internal face of the furthest pile is smaller or equal two times the pile cap depth (H).
Moreover, the authors believe that if a rigid pile cap is designed using the hypothesis of flexible pile caps, i.e. taking into account a sectional approach, the obtained amount of reinforcement may be smaller than the demanded one, leading to an unsafely design.
Also, it must be registered that in a rigid pile cap, flow of forces between column through piles is made in a direct way, throughout inclined struts, and this fact are not verified in flexible pile caps. Finally, the rigid pile caps are not requested by punching shear, what is perfectly possible for flexible pile caps.

3 Description of the Referential Experimental Research

Some results of Sam & Iyer [3] have been taken as referential data once they have researched the behavior of rigid pile caps subjected to different layouts for the principal reinforcement, as depicted in Figure 1. The mentioned researchers have established the following conclusions, by applying nonlinear analysis:

- 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 Analysis Four-Pile Caps

Numerical analyses have been conducted using the package software DIANA and, taking into account symmetry conditions, only 1/4 of the pile caps geometry was investigated. Columns and piles were not described into the models, but they were substituted for equivalent supports and loading conditions. This procedure has been taken in order to avoid localized failures and to adjust the investigation as close as possible to the experimental work of Sam & Iyer [3].

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

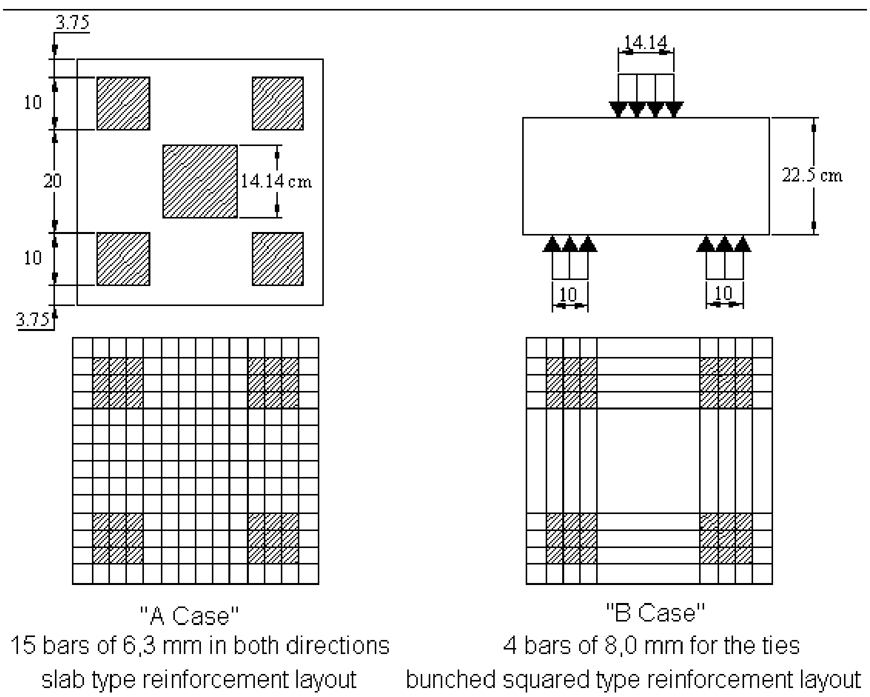


Table 1 – Material properties defined in the package software DIANA

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

Material properties have been prescribed based on the information given by Sam & Iyer [3] and some 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 detail the material properties used in the conducted nonlinear analysis.

For the "A Case", shown in Figure 1, various smeared crack models have been investigated and failure load has reached a limit defined by 615,44 kN < F_u < 622 kN. The obtained numerical results indicated a difference between 10 and 12%, when compared to the experimental failure load of 690 kN obtained by Sam & Iyer [3]. "Rotating Crack Model", defined with linear method of solution and shear retention factor of 0,99, was the smeared crack model which conducted to the best results.

For the "B Case", also shown in Figure 1, various smeared crack models have been investigated too, and failure load reached a limit defined by 524 kN < F_u < 664 kN. The obtained numerical results indicated a difference between 5 and 20%, when compared to the experimental failure load 630 kN obtained by Sam & Iyer [3]. "Fixed Crack Model", defined with secant method of solution and shear retention factor of 0,001, was the smeared crack model which conducted to the best results.

Both in "A Case" and "B Case", cracks have propagated in an inclined way from the piles 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 on the center of the related spam. Figures 2 and 3 present the crack pattern developed in top and bottom surface for the "B Case". This crack pattern is very close to the crack pattern obtained for the "A Case".

In both cases, a very small tensile stress has been realized for the reinforcement. The tensile stress was approximately 168 MPa for the "A Case" and 136 MPa for the "B Case", indicating that yielding did not occurred for the main reinforcement. As result, the supposed failure of the investigated pile caps was due to concrete compression.

Differently from the observations made by Sam & Iyer [3],

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

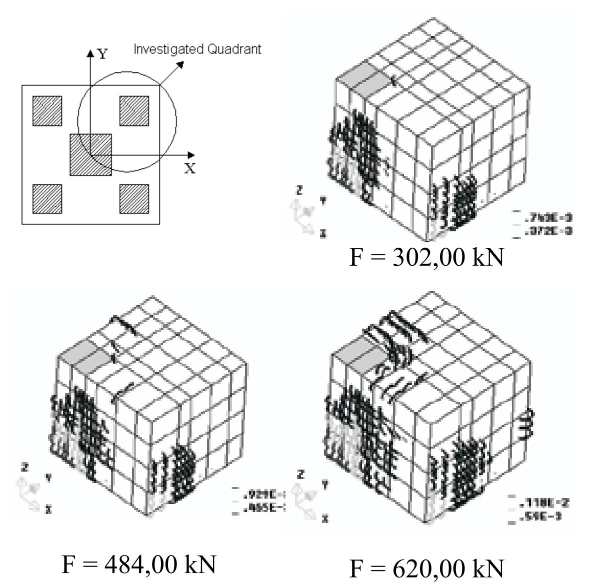
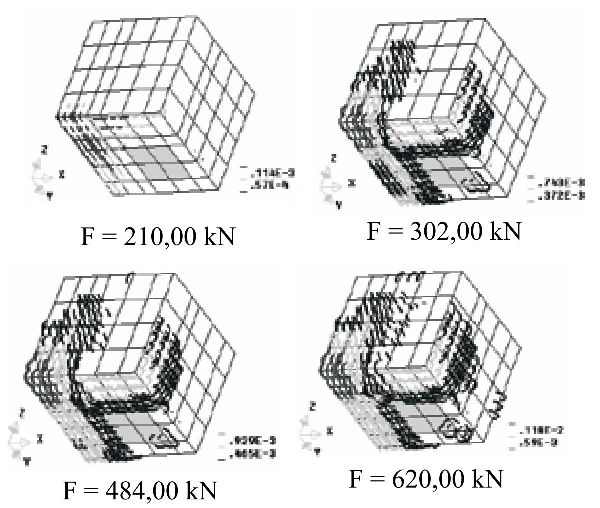


Figure 3 – Developed cracks in the bottom surface of the four-pile cap ("B Case")



the measure deformations in the reinforcements remained constant and deformations on concrete were nonlinear along the depth, since the beginning of the loading.

5 Conclusions

It has been realized a great difficulty for estimating a limit load, which suggests that for diagonal cracks (typical for shear) it is more interesting to adopt a range of variation than adopt just a single limit value.
The variation range found, as well as, the aspect of the failures, is very close to the experimental results obtained by Sam & Iyer [3], confirming the great potentiality of nonlinear analysis for researching complex structural problems.
A classical strut-and-tie model has been used for analytical verification and has indicated a failure load much smaller than that one found experimentally. It is believed that it is probably due to the fact that the pile caps investigated have a relation a/d < 0,5. This fact suggests that pile caps with low relations span-to-depth behaves like partially loaded surfaces, demanding a more refined strut-and-tie model to analyze the problem.
As mentioned before, Sam & Iyer [3] have concluded that the mechanism which has provoked failures was a punching of the piles or the column. The authors of the present paper do not agree with this hypothesis and believe that the mechanism that provokes failures was the transversal tensile stress acting in the inclined struts, used to transfer loads from the column to the piles.
It is interesting to remember that punching shear usually appear in those cases where a slab is directly supported by a column. Due to the high shear tension in a critical perimeter around the column, a failure plane of approximately 35° usually appears in relation to the horizontal direction. This failure plane tends to separate the union slab-column in a fragile way, developing a failure surface that seems a frustum of pyramid, with many cracks surrounding 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 load is supposed to flow directly from column to piles. Moreover, the realized crack patterns do not present radial cracks around the column but skirting them, remembering a crack pattern of spalling.
It is believed this fact confirms the hypothesis that the investigated pile caps have been failed by a strut failure (transversal tensile stress) and not by punching shear. Only the appearance of the collapse is similar to a punching failure, but not the mechanism, that is close to that one verified in partially loaded surfaces. According to CEB-FIP Model Code 1990 [9], item 3.3, failure of partially loaded surfaces can occur by spalling near the end face of the column, by splitting in deeper zones or by surface crushing.
The previous information leads to the necessity of using horizontal stirrups along the pile caps with relation a/d (span-to-depth) under 0,5, in order to contain the transversal tensile stress that may occur along the pile caps depth. If there is no intention of using this horizontal stirrups then is necessary to limit the maximum tension under the column to $0{,}8.f_{ck}$, in order to avoid failure by transversal tensile stress in the struts.
Finally, it is recommended to introduce an orthogonal mesh (slab type reinforcement) in the bottom face of pile caps with span-to-depth relation (a/d) under 0,5 , intending to contain the development of cracks that can lead this elements to a premature failure.

6 References

[01] ADEBAR et al.. "Strut-and-Tie Models for the Design of Pile Caps: An Experimental Study". ACI Structural Journal, v.87, n.1, pp.81-92, 1990.
[02] IYER, P. K.; SAM, C.. "Three-Dimensional Analysis of Pile Caps". Computers & Structures, v.42, n.3, pp. 395-411, 1992.
[03] SAM, C.; IYER, P. K.. "Nonlinear Finite Element Analysis of Reinforced Concrete Four-Pile Caps". Computers & Structures, v.57, n.4, pp.605-622, 1995.
[04] CHAN, T. K.; POH, C. K.. "Behaviour of Precast Reinforced Concrete Pile Caps". Construction and Building Materials, n.14, pp. 73-78, 2000.
[05] MONTOYA, P.J; MESEGUER, A. G.; CABRE, F. M.. "Hormigón Armado". Gustavo Gili, Barcelona, 1973.
[06] MONTOYA, P.J; MESEGUER, A. G.; CABRE, F. M.. "Hormigón Armado". Gustavo Gili, Barcelona, 2002.
[07] EHE. "Instrucción de Hormigón Estructural". Spanish Code, Second Edition, Madrid, 1999.
[08] FEENSTRA, P. H.; BORST, R.. "Aspects of Robust Computational Modeling for Plain and Reinforced Concrete". Heron, v.38, n.04, Delft, Netherlands, 1993.
[09] CEB-FIP Model Code 1990. Thomas Telford Services Ltd., Comité Euro-International du Béton, Laussane, 1993.