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EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF STRUT AND TIE MODEL METHOD OF PILE CAP

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ABSTRACT : *Two usual methods used in the design of pile caps are bending theory and truss analogy. Bending theory is predominant when the shear span to depth ratio is greater than 2. Truss analogy is prominent when the shear span to depth ration is less than 2. While designing using Bending theory and Truss analogy the pile caps become over reinforced. In order to overcome this, new design procedure called the Strut and Tie Model (STM) method has been developed. A pile cap (1000mm×1500mm×3200mm) which supports a column carrying axial load of 4320kN is designed using Bending theory, Truss analogy and Strut and Tie Model method. The pile cap is supported on two 700mm diameter piles. A one-fifth scaled down model of the pile cap is analytically and experimentally investigated. The ultimate loads of the three analytical and experimental models were compared. The cost to strength ratio for the Strut and Tie model is found to be most economical.*

***Keywords* -** *Ansys, Bending theory, Truss analogy, Scaled down model, Strut and Tie Model Method,*

1. INTRODUCTION

The conventional methods evaluate the internal forces by assuming Bernoulli's hypothesis is valid. In reality Bernoulli's hypothesis is not valid in structures like deep beams, corbels, beam-column junction, etc is not linear. Strut-and-Tie model (STM) method is popular among research communities and engineers for the analysis and design of disturbed regions of structures. 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. In reality Bernoulli's hypothesis is not valid in structures like deep beams, corbels, beam-column junction, etc is not linear. 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. In the case of structures which are subjected to very intense loading, the behaviour 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 analysed and designed using STM with better accuracy when compared to other conventionally used methods

The main objectives of this study were to Design of pile cap using Bending theory, Truss analogy and STM method, Analytical modelling of pile caps (scaled down model) using Ansys 12.0.1,Determination of ultimate load capacity of the three pile caps experimentally. To compare the cost strength ratio and suggest the optimum design method.

Adebar, et al., (1996) [1] studied Design of Deep Pile Caps by Strut-and-Tie Models. A simple shear design procedure was proposed in which maximum bearing stress is considered the best indicator of "shear strength" for deep pile caps.

Leu, et al., (2006) [2] studied Strut-and-Tie Design Methodology for Three-Dimensional Reinforced Concrete Structures. A strut-and-tie design methodology was presented for three-dimensional reinforced concrete structures.

Tyler, et al., (2007) [3] studied Experimental Verification of Strut-and-Tie Model. Design Method and-tie models (STM) as a valuable tool for the design of irregular concrete members and presented the experimental results of tests conducted on small-scale, simply supported dapped beams with openings under the load.

Nori, et al.,(2007) [4] studied origin of Strut and Tie Models for detailing reinforced and prestressed concrete structures for the behaviour of reinforced concrete elements subjected the shear. Since then it had gained popularity in Europe for evolving practical reinforcing details in a variety of situations.

The general cross section of the pile cap was 1000mm×1500mm×3200mm. The pile cap was designed for a load of 4320kN using Bending theory, Truss analogy and Strut and Tie Model method. The materials used were M 30 concrete and Fe 415 steel. The analytical model of the one-fifth scaled down deep beam using strut and tie model, bending theory and truss analogy were developed in ANSYS 12.0.1. The ultimate loads obtained were compared to the actual design using all the three design principles. The one-fifth scaled down experimental models for the three pile caps were tested in UTM and their flexural behaviour is compared.

2. DESIGN SUMMARY

A pile cap of size 1000×1500×3200mm was designed using Bending theory, Truss analogy and Strut and Tie method. For the bending theory the pile cap was designed a simply supported beam. For Truss analogy a simple truss structure was analysed and the bottom reinforcements were provided for the tension in the bottom tie. The design of pile cap using Strut and Tie Model was based on the design of a single column two pile pile cap by ***Nori, et al.,(***2007)[4] . As the structure was large in size, a one-fifth scaled down model was used for analysis. As the three design methods show change in the flexural reinforcement only, only flexural reinforcements are provided in the scaled down model. Table 1 shows the design summary.

TABLE 1 Design Summary

Sl no	Theory	Size of Original Pile (mm)	Reinforcement	Size of Scaled down Pile (mm)	Reinforcement
1	Bending Theory	1000×1500×3200	21#20□	200×300×600	2#10□ ,1#12□
2	Truss Analogy	1000×1500×3200	15#20□	200×300×600	2#12□
3	Strut and Tie Method	1000×1500×3200	10#20□ ,11#12□	200×300×600	2#8□ ,1#10□

3. FINITE ELEMENT MODELLING USING ANSYS 12.0.1

To create the finite element model in ANSYS, there were multiple tasks that had to be completed accurately for the model to run properly. Models can be created using command prompt line input or the Graphical User Interface (GUI). For this model, the GUI was utilized to create the model

3.1 Element Types And Material Properties

The Solid65 element was used to model the concrete. This element has eight nodes with three degrees of freedom at each node – translations in the nodal x, y, and z directions. This element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. A Link8 element was used to model steel reinforcement. This element is a 3D spar element and it has two nodes with three degrees of freedom – translations in the nodal x, y, and z directions. This element is also capable of plastic deformation. The real constants for this model are shown in Table 2.

Table 2 Real Constants

Real constant set	Element Type	Constants			
		Parameters	Real constants for rebar 1	Real constants for rebar 2	Real constants for rebar 3
1	Solid 65	Material Number	0	0	0
		Volume Ratio	0	0	0
		Orientation Angle(θ)	0	0	0
		Orientation Angle(□)	0	0	0
2	Link8	Cross-sectional Area (mm^2)		5.0265E-5	
		Initial Strain		0	
3	Link8	Cross-sectional Area (mm^2)		7.85E-5	
		Initial Strain		0	
4	Link8	Cross-sectional Area (mm^2)		1.13E-4	
		Initial Strain		0	

The Solid65 element was used to model concrete which is a non-linear material. Linear isotropic and multi linear isotropic properties had to be given while defining Solid 65. The multi linear isotropic material uses the von Mises failure criterion along with the Willam and Warnke (1974) model to define the failure of the concrete. Typical shear transfer coefficients range from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer). The shear transfer coefficients for open and closed cracks were determined using the work of Kachlakev, et al. (2001)[5] as a basis. No deviation of the response occurs with the change of the coefficient. Therefore, the coefficient for the open crack was set to 0.1. The uniaxial cracking stress was based upon the modulus of rupture. The uniaxial crushing stress in this model was based on the uniaxial unconfined compressive strength and is denoted as f_r. It was entered as -1 to turn off the crushing capability of the concrete element as suggested by past researchers (Kachlakev, et al. 2001)[5]. Convergence problems have been repeated when the crushing capability was turned on.

3.2 Modelling

The pile cap and supports were modelled as volumes. The model has length of pile cap in X direction , Width in Z direction and depth in Y direction. Displacement boundary conditions are needed to constrain the model to get a unique solution. To ensure that the model acts the same way as the experimental beam, simply supported boundary conditions are applied along the nodes along the mesh line at the location of the nodes. The load acting on the analytical structure is divided among the nodes in the area of the load acting in the region. The loads and. To obtain good results from the Solid65 element, the use of a rectangular mesh is recommended. Therefore, the mesh was set up such that square or rectangular elements were created. The volume sweep command was used to mesh the solid 65 element. This properly sets the width and length of elements in the plates to be consistent with the elements and nodes in the concrete portions of the model. The necessary element divisions are noted. The meshing of the reinforcement is a special case compared to the volumes. The necessary mesh attributes as described above need to be set before each section of the reinforcement is created. The reinforcements were divided into the same number of divisions as the concrete to enable coupling. Fig.1 shows the 3D model of the pile cap.

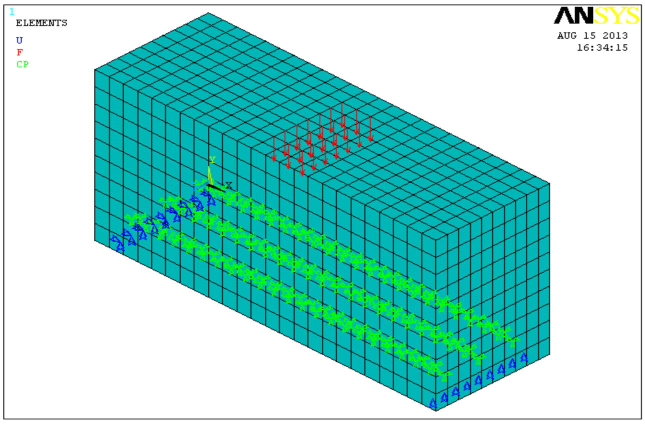

Fig.1 3D model of the pile cap

3.3 Analysis

The finite element model for this analysis is a simple beam under transverse loading. For the purpose of this model, the static analysis type is utilized. The Restart command is utilized to restart an analysis after the initial run or load step has been completed. The use of the restart option will be detailed in the analysis portion of the discussion. The Sol'n Controls command dictates the use of a linear or non-linear solution for the finite element model. The large displacement option is set as analysis option. All solution items are to be written to the file. In the particular case considered in this thesis the analysis is large displacement and static. The time at the end of the load step refers to the ending load per load step.

All values for the nonlinear algorithm are set to defaults. The values for the convergence criteria are set to defaults except for the tolerances. The tolerances for force and displacement are set as 0.99 to obtain a convergent solution. The program behaviour upon non convergence for this analysis was set such that the program will terminate but not exit. The rest of the commands were set to defaults. The FE analysis of the model was set up to examine three different behaviours: initial cracking of the beam, yielding of the steel reinforcement, and the strength limit state of the deep beam. The Newton-Raphson method of analysis was used to compute the nonlinear response. The application of the loads up to failure was done incrementally as required by the Newton-Raphson procedure. Failure of the beam occurs when convergence fails, with this very small load increment. The load deformation trace produced by the analysis confirmed the failure load.

4. EXPERIMENTAL ANALYSIS

The method of mix design consists of determining the water content and percentage of fine aggregate corresponding to the maximum nominal size of aggregate for the reference values of workability, water–cement ratio and grading of fine aggregate. The basic data required for the design of concrete mix are: characteristic compressive strength at 28 days (f_{ck}), degree of workability, limitations on water-cement ratio and minimum cement content to ensure adequate durability for the type of exposure; type and maximum nominal size of aggregate; and standard deviation (s) for compressive strength of concrete. The mix proportioning as per I.S:10262 -2009[6]. Table 3 shows proportioning of concrete. Table 4 shows the 28 days compressive strength of the cubes casted as per the mix design. Fig.2 shows the experimental test set up.

TABLE 3. Proportioning of concrete.

Material	Cement	Fine Aggregate	Coarse Aggregate
Weight (kg)	437.779	643.68	1104.36
Proportioning	1	1.47	2.52

TABLE 4. Test result for 28 days strength of concrete cubes

Specimen no	Load value, (kN)	Cross sectional area,(mm^2)	Compressive strength,(N/mm^2)
1	870	22500	38.66
2	850	22500	37.77
3	890	22500	39.56
Average compressive strength,(N/mm^2)		38.66	

Fig.2 Specimen loaded on the UTM

5. RESULTS

5.1 Load Deflection Curves

B1, B2, B3 are the pile caps designed by Bending theory, Truss analogy and Strut and Tie Model. Fig.3a shows the comparison of the analytical models of pile caps B1, B2 and B3. B1 has an ultimate load of 120kN and B2 and B3 have an ultimate load of 115kN. So B1 which has more reinforcement compared to the other has more load carrying capacity when compared to B2 and B3.

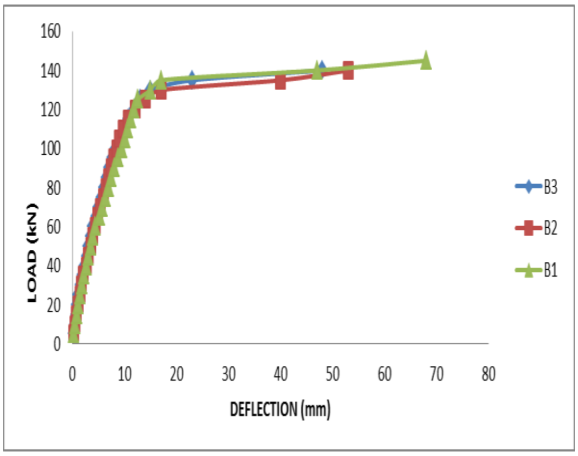

Fig.3a Load deflection curves Experimental models

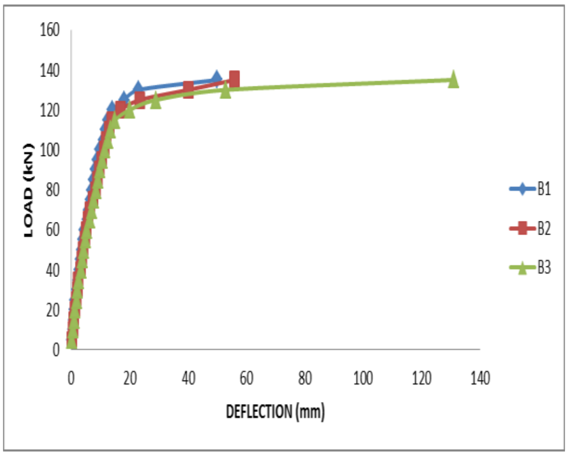

Fig.3b Load deflection curves Analytical models.

Fig.3b shows the comparison of the experimental models of pile caps B1, B2 and B3. B1 has an ultimate load of 135kN and B2 has an ultimate load of 130kN and B3 has an ultimate load of 130kN.

5.2 Cost To Strength Ratio For The Pile Caps

The costs for the three beams are compared using the results obtained using Analytical study as well as experimental study. Table 5 shown below indicate the Cost-Strength ratio for the Analytical pile caps and experimental pile caps.

TABLE 5 Cost-Strength Ratio for analytical models and Experimental models

				Analytical Models		Experimental Models	
Sl. No	Method	Concrete(m^3)	Steel(kg)	Load(kN)	Cost- Strength Ratio	Load(kN)	Cost- Strength Ratio
1	Bending Theory	0.036	1.19	120	2.28	135	2.02
2	Truss Analogy	0.036	0.84	115	2.22	130	1.97
3	Strut and Tie	0.036	0.78	115	2.20	130	1.94

6. CONCLUSIONS

A pile cap (1000mm×1500mm×3200mm) which supports a column carrying axial load of 4320kN is designed using Bending theory, Truss analogy and Strut and Tie Model method. It was found that only flexural reinforcements have changed. Casting of full scale pile cap was difficult and as a result one fifth scaled down models were analysed. Analytical modeling for the pile caps designed using the three methods was done in Ansys 12.0.1. The ultimate loads for the analytical models for Bending theory was obtained as 120kN. The ultimate load for the analytical models for Truss Analogy was obtained as 115kN. The ultimate load for the analytical models for Strut and Tie Method was obtained as 115kN. The ultimate loads for the experimental models for Bending theory was obtained as 135kN. The ultimate load for the experimental models for Truss Analogy was obtained as 130kN. The ultimate load for the experimental models for Strut and Tie Method was obtained as 130kN. Using the results cost to strength ratios for the analytical models and experimental models were obtained. The cost to strength ratio for the analytical model using Strut and Tie model was found to be

2.112, which was found to be the least when compared to Bending Theory and Truss Method. The cost to strength ratio for the experimental model using Strut and Tie model was found to be 1.94, which was found to be the least when compared to Bending Theory and Truss Method The analysis of cost to strength ratio of analytical models show that Strut and Tie Method is the most economical method for the design of a single column double pile pile caps.

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