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Original Research Article

Analysis of Corner Column-Slab Connections in Concrete Flat Plates

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Abstract: A non-linear three-dimensional finite element analysis, using ANSYS computer program, has been done to study the load-deflection behavior and the load-carrying capacity of a reinforced concrete flat plate built on corner columns. Material non-linearity; such as cracking and crushing of concrete, yielding of steel and plastic deformation of concrete and steel; have been included. Comparison between the results obtained by the finite element analysis and available experimental results has been made. The analytical results compared satisfactorily with the experimental ones.
Keywords: corner column, finite element analysis, flat plate, nonlinear analysis, punching, reinforced concrete

INTRODUCTION

There are many methods used to analyze flat plate slabs, these methods include the direct design, equivalent frame, yield line, and strip design techniques, all of which approximate the results of classical plate theory. These methods have gained wide acceptance among engineers because of their simplicity.

However, these approximate techniques have significant limitations. Direct design and equivalent frame methods are both limited to structures with very regular geometry. The application of yield lines or strip design may lead to overly conservative designs as well as to poor serviceability.

As such, the finite element method has been an obvious choice for the modeling and analysis of reinforced concrete systems for many years. Finite elements have the unique capability to conform to virtually any geometry that could be physically implemented. Thus, the finite element method has gained acceptance as an appropriate tool for the analysis of flat plates, especially those with highly irregular or unusual geometries where the direct design and equivalent frame techniques are not valid.

One of the main objectives of the finite element analysis of structures is to determine the response of the structure when it is under loading. A typical load-deformation response for a monotonically loaded member is essentially linear up to a certain limit of load. Beyond this limit a non-linear load-deformation response occurs. Such a response is due to a combination of non-linear material behaviour (material non-linearities), large deformation in the structure (geometric non-linearities).

In the analysis of reinforced concrete structures, the effect of large deformations can be neglected for the majority of cases. This is due to the early onset of material non-linearity, with large deformations that occur only close to the structural collapse, such as in the flat plate concrete slabs. In the present study, the sources of material non-linearity are:

- Cracking of concrete;
- Crushing of concrete;
- Yielding of steel;
- Plastic deformation of concrete and steel.

At non-linear stage of behavior, it is not possible to solve the governing equilibrium equations directly. Therefore, resort has to be made to more sophisticated solution strategies. The combined incremental-iterative solution technique is used. The solution techniques adopted are operated under a load control increment scheme.

A large number of tests in reinforced concrete slabs have been conducted in the past, some of which

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on flat plate with different boundary conditions, such as (Sozen, M. A. 1963), (Zaghlool, E. R. F. *et al.*, 1970; Ingvarsson, H. 1974; Ingvarsson, H. 1977) & (Walker, P. R., & Regan, P. E. 1987 ; Tayel, M. A., *et al.*, 2004) and (Giduquio, M. B., *et al.,* 2017).

Some researchers deal primarily with the modeling and analysis of flat plate systems by the finite element method, one of the earliest published works concerning the application of the finite element method to reinforced concrete slabs was by (Zienkiewicz, O. C., & Cheung, Y. K. 1964; Davies, J. D.1970). applied the finite element method to evaluate deflections and moments in a corner supported rectangular slab. (French, S., *et al.*, 1975) derived the stiffness of a single element panel, and implemented a modeling technique based on using single elements for slab panels in the analysis of multistory flat plate structures subjected to lateral loading.

(Smith, E. T., & Faulkes, K. A. 1976) applied the finite element method to analyze a multistorey flat plate building, one of the first three-dimensional applications of the method in reinforced concrete, to analytically evaluate the flexural properties of flat plate systems.

(Mohr, G. A. 1979) demonstrated the successful application of elastic finite element analysis in the determination of approximate plastic design results for the flat plate.

(Anderheggen, E. *et al.,* 1994) presented a method of reinforcement design based on element nodal forces.

(Famiyesin, O. O., & Hossain, K. A. 1998) applied a three-dimensional degenerated layered shell reinforced concrete model to determine model parameter values to calibrate the non-linear analysis of fully restrained slabs, with the goal of extension to arbitrary configurations through parametric sensitivity studies.

(Phuvoravan, K., & Sotelino, E. D. 2005) derived a new finite element for non-linear finite element analysis of reinforced concrete slab systems, by combining the classic four-node Kirchoff shell element with two-node Euler beam elements to simulate the steel reinforcement.

(Husain, M. H. *et al.,* 2018), based on finite element analysis and using ANSYS computer program, analyzed double skin composite slabs under a uniformly distributed load.

(Russell, J. M., *et al.,* 2018) used finite element analysis to replicate column loss scenarios on a range of reinforced concrete flat slab floor models.

In the present work, the ANSYS computer program ("ANSYS Help"), is employed for analyzing all the samples.

Column-Slab Connection Modeling

The verification is done in order to check the validity and accuracy of the finite element procedure. Thus, three specimens with available experimental results have been analyzed here and the analytical results are compared.

A. Walker and Regan Flat Plate

In the present study, three slabs supported on four corner columns tested by (Walker, P. R., & Regan, P. E. 1987) are designated as SC.1, SC.2 and SC.3 (Walker, P. R., & Regan, P. E. 1987). They have spans of 3050 mm × 3050 mm and loaded with a twelve load points distributed on the slab. The dimensions and load arrangement details of these slabs are shown in Fig- 1.

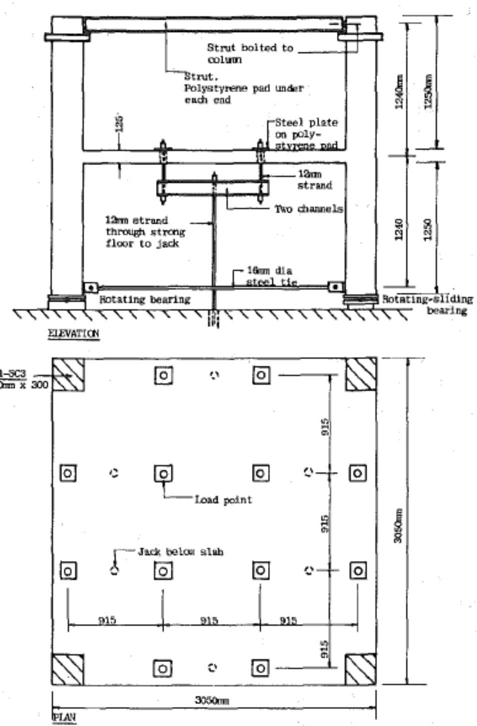


Fig-1Dimensions and load arrangement details for specimens (Walker, P. R., & Regan, P. E. 1987).

The slab reinforcement is 8 or 10 mm in diameter with a yield stress of 450 N/mm^2. Reinforcement details of the tested slabs are presented in Fig-2, and the material properties are given in Table - 1.

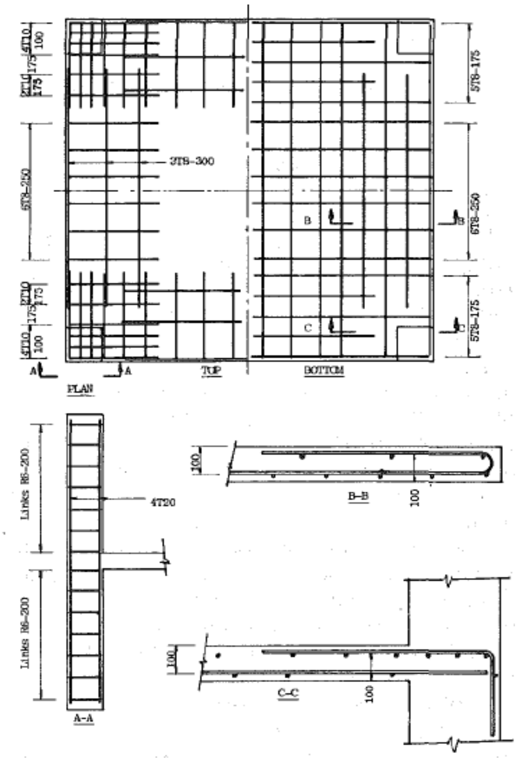


Fig-2Reinforcement details for specimens (Walker, P. R., & Regan, P. E. 1987)

Table -1Material property parameters used for the tested slabs

Structural Component	Symbol	Definition	SC.1	SC.2	SC.3
Concrete	f_c'	Compressive Strength (MPa)	43.3	47.9	37.4
	E_c	Young's Modulus (MPa)	30927	32529	28743
	f_r	Tensile Strength (MPa)	4.08	4.29	3.79
	υ	Poisson's Ratio	0.15	0.15	0.15
Steel Reinforcement	f_y	Yield Stress (MPa)	450	450	450
	Tang Mod	Tangent Modulus (MPa)	4000	4000	4000
	υ_s	Poisson's Ratio	0.3	0.3	0.3
	E_s	Young's Modulus (MPa)	200000	200000	200000

Table -2 shows the areas of reinforcement and ultimate load for the three tested slabs.

Table-2 Details of tested slabs

Slab specimens	Top d (mm)	Bottom d (mm)	ω_1 (mm)	ω_2 (mm)	As_b (mm)	As_t (mm)	Column size (mm)	Ultimate load on slab (kN)
SC.1	100	100	730	730	804	471	300 sq	320
SC.2	100	100	730	730	1,087	302	300 sq	297
SC.3	100	100	730	730	503	609	300 sq	284

B. Finite Element Idealization

The three-dimensional finite element mesh for a quarter of the slab has been used by using ANSYS computer program, by taking the advantage of symmetry of the slab and loading. In order to analyze this slab numerically by using the finite element method, it is required to transform its geometric and material configuration into mathematical modeling, and insert as input to ANSYS computer program to simulate the actual behavior of the specimen, to determine an appropriate mesh density in the analysis (Hameed, A. M. 2011).

Fig-3 shows the picture of mesh of tested slabs SC.1, SC.2 and SC.3 represented by Solid65 elements. Figure (4) represents the mesh of Link8 elements. In addition, details about representation of structural component are presented in Table-3.

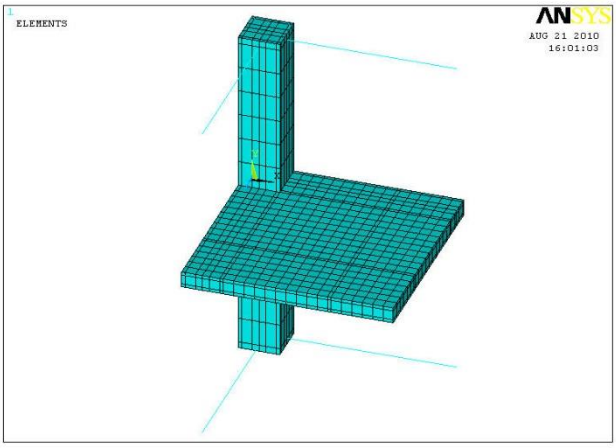


Fig-3 Mesh of SOLID65 elements for SC.1, SC.2 and SC.3

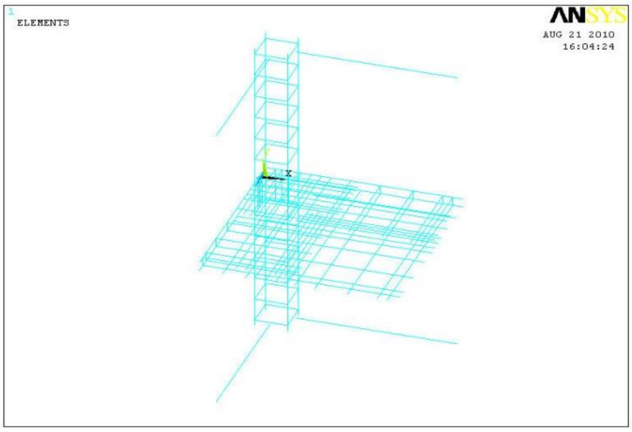


Fig-4 Mesh of LINK8 elements for specimen

Table-3 Finite element representation of structural components

Structural Component	Finite Element Representation	Element Designation in ANSYS	No. of Elements
Concrete	8-node Brick Element (3 Translation DOF per node)	SOLID65	2,091
Steel Reinforcement	2-node Discrete Element (3 Translation DOF per node)	3D-SPAR 8 (LINK8)	1,189

RESULTS AND DISCUSSIONS

The experimental results by Walker and Regan and numerical results obtained in the present study, for slabs SC.1, SC.2, and SC.3, are shown in Figures (5) to (10). The external applied load is plotted against the mid-span deflection. For these slabs, the failure load obtained by the experimental work and that predicted by the finite element solutions are listed in Table (4). It can be noted from the figures and Table (4) that the finite element solutions are in good agreement with the experimental results throughout the entire range of behavior.

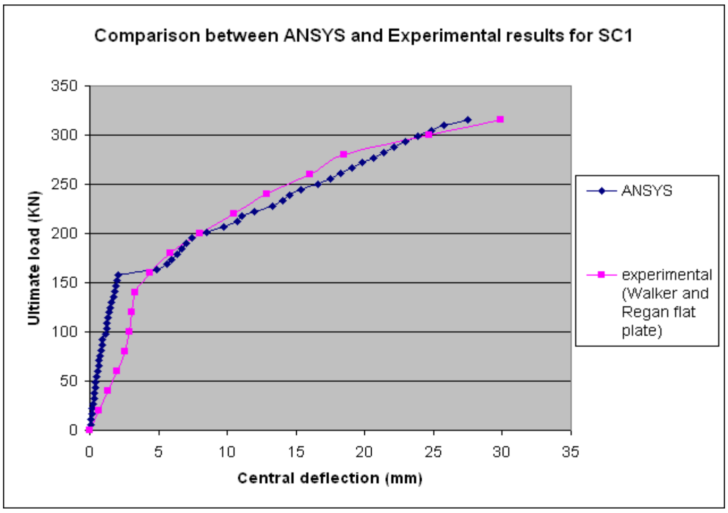


Fig-5 Load-Deflection response at mid-span of SC.

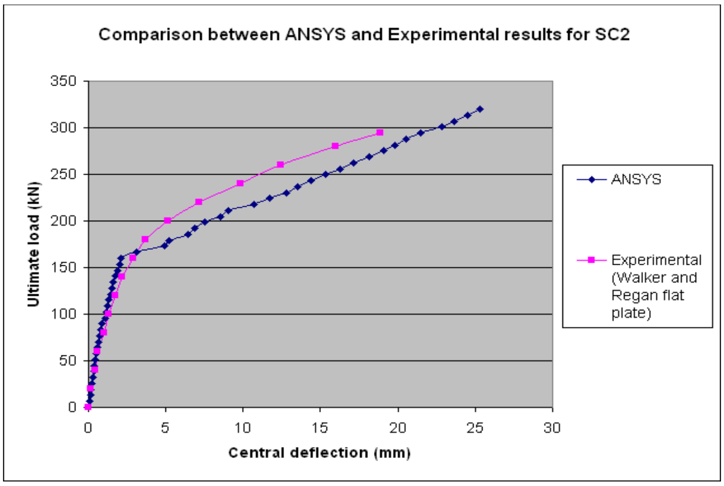


Fig-6 Load-Deflection response at mid-span of SC.2

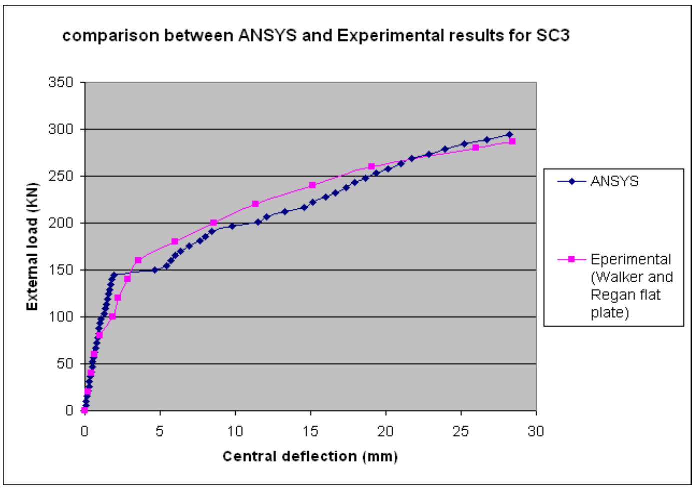


Fig-7 Load-Deflection response at mid-span of SC.3

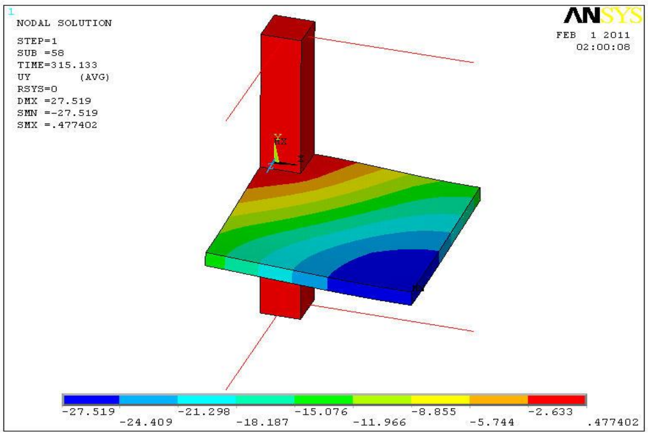


Fig-8 Variation of UY (vertical displacement) along quarter of SC.1 at load equal to 96.6% of ultimate load

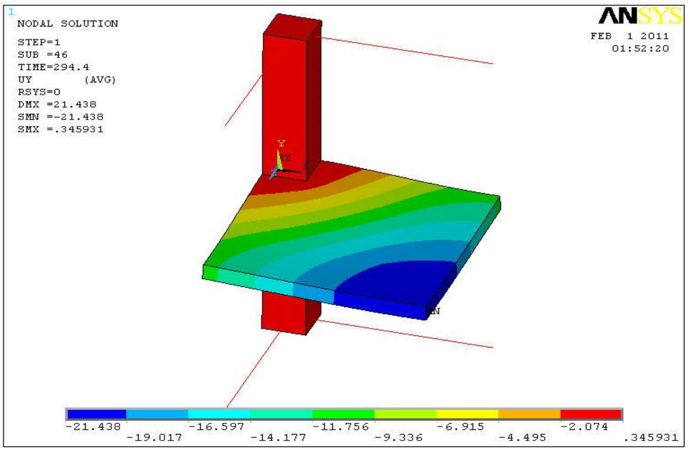


Fig-9 Variation of UY (vertical displacement) along quarter of SC.2 at load equal to 98.5% of ultimate load

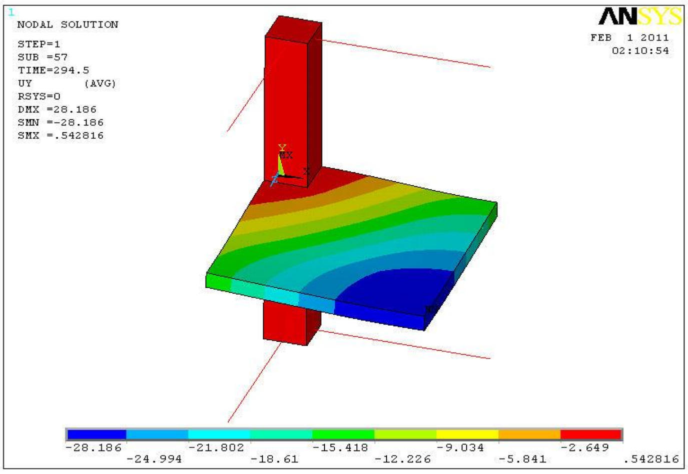


Fig-10 Variation of UY (vertical displacement) along quarter of SC.3 at load equal to 99% of ultimate load

Table-4 Experimental and predicated failure loads for slabs

Specimens	Ultimate Load (kN)		$\frac{P_u\ (\text{Analytical})}{P_u\ (\text{Experimental})}$	Error (%)
	Experimental	Analytical		
SC.1	320	319.1	0.997	-0.3
SC.2	297	322.4	1.086	8.6
SC.3	284	294.5	1.037	3.7

Comparison by Figures between theoretical analysis and experimental results in cracking and punching failure for slab SC1 is shown in Figures (11) to (16).

Based on these analysis results, it can be concluded that the failure mechanism obtained shows the slabs fail near the columns. The possible failure of the slabs seems to be due to flexural punching mechanism due to local flexural yielding around the column.

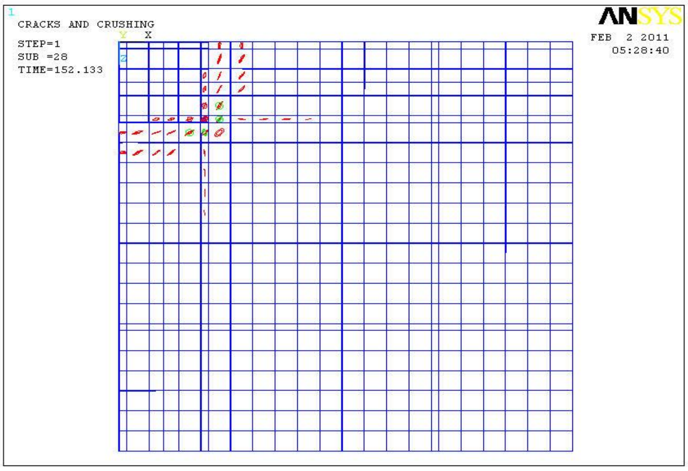


Fig-11 Cracking in top surface near the column for slab SC1 by using ANSYS program

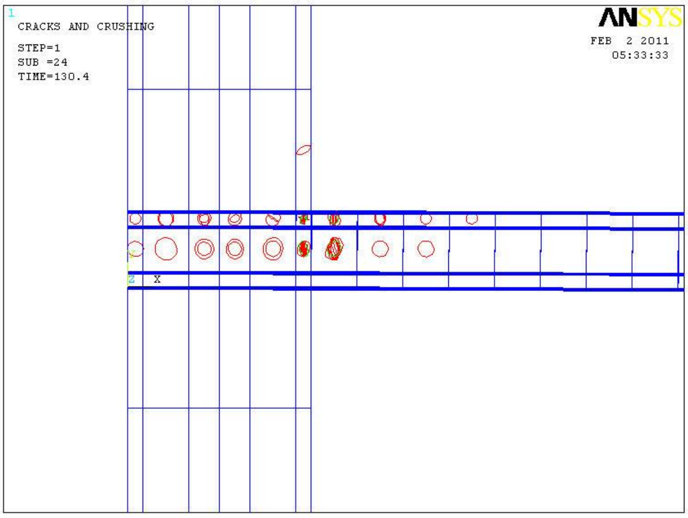


Fig-12 Cracking in edges near the column for slab SC1 by using ANSYS program

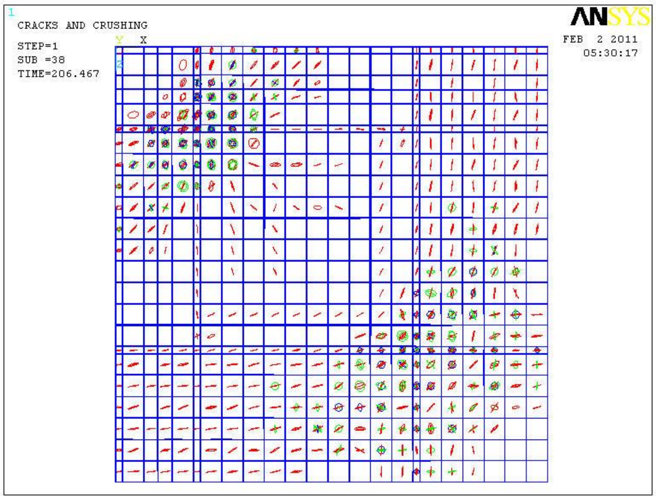


Fig-13 Cracking in top surface for slab SC1 by using ANSYS program

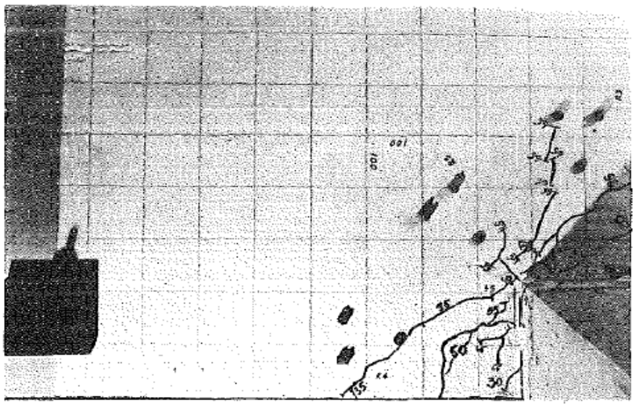


Fig-14 Cracking in top surface near the column for slab SC1 (Walker, P. R., & Regan, P. E. 1987).

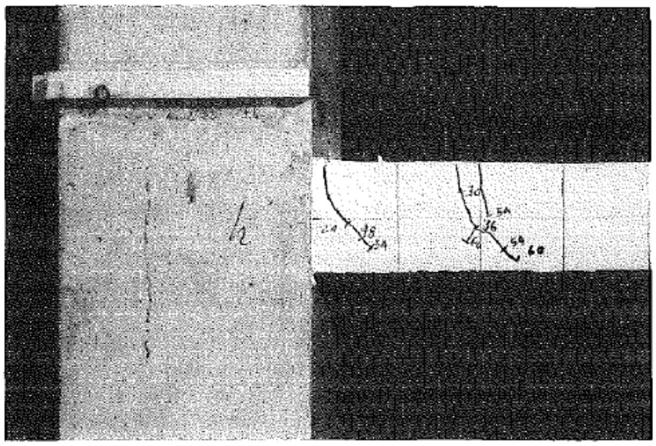
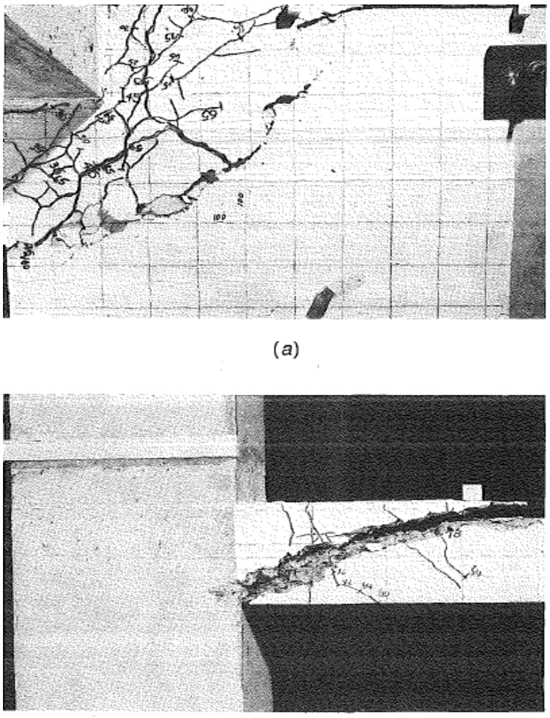


Fig-15 Cracking in edges near the column for slab SC1 (Walker, P. R., & Regan, P. E. 1987).



(a)

(b)

Fig-16 Punching failure for slab SC1 (Walker, P. R., & Regan, P. E. 1987).

CONCLUSIONS

Depending on the numerical results obtained in this study, the following conclusions can be drawn:

- A three-dimensional non-linear finite element analysis has been conducted to investigate the general behavior of the reinforced concrete flat plate slab built on four corner columns.
- The smeared cracking model, used to describe the cracking of the reinforced concrete slab built on corner columns, gives good prediction for crack pattern.
- The failure mechanism observed, in all slabs analyzed, shows the slabs fail near the columns. The possible failure of the slabs seems to be due to flexural punching mechanism due to local flexural yielding around the column.

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