EFFECT OF OPENINGS ON THE BEHAVIOR OF R.C FLAT PLATES
PART (I): PLATES WITHOUT EDGE BEAMS

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ABSTRACT

The most practical technique for constructing large open spaces is the beam-less flat plate system. Openings in flat plates are essential for large spaces in order to pass service ducts and house air conditioning cables ...... etc. This paper aims to provide an understanding of the parameters that affect the behavior of reinforced concrete flat plate roofs with openings. A high precision layered finite element computer program has been used to analyze reinforced concrete flat plates with openings under transverse uniformly distributed loads. A comparison is made between the finite element results and those obtained using the empirical method stated in the Egyptian Code of Practice, 1989.

1-INTRODUCTION

In residential buildings, plates represent a major part of the concrete skeleton. Building frames consisting of beamless flat plates supported directly on columns are widely used all over the world. Their popularity is due to the freedom that they provide for architectural and mechanical requirements.

Openings are essential for some of the large spaces in order to house air-conditioning cables. Service ducts are also passed through openings in the flat plates. Arranging the services in this way minimizes the dead space and thus leads to economy. However, introducing openings in a reinforced concrete plate reduces its stiffness and leads to more complicated behavior. Therefore, the effect of opening size and location on the strength and serviceability of such plates must be considered in the design process.

Keywords: Layered finite element; reinforced concrete flat plates; openings.

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The common methods of elastic analysis of this type of building frames are based on modeling the plate by a series of two dimensional crossing frames [1] and [2]. Several investigations had been carried out on the analysis and design of flat plates with and without edge beams [3], [4], [5] and [6]. However, little attention has been directed toward the behavior of plates with openings. Codes of practice (e.g, the CAN 3-A23.3-M77 [7] and the ACI Committee 318-89 [1]) provide recommendations concerning openings in flat plate structures. However, the Egyptian Code [2] does not have provisions for these types of plates.

This paper is the first part of a series of research work which deals with the effect of opening size and location on the behavior of reinforced concrete flat plates of different aspect ratios with and without edge beams. The objective of this part is to study the effect of openings on flat plates without edge beams subjected to uniformly distributed loads. The flexural moments and deflections of plates are used as the assessment tools.

2-MATHEMATICAL MODELING

The finite element analysis of a flat plate structure was carried out using the layered approach. The element used is a flat triangular shell element with 36 degrees of freedom consisting of different layers to represent the concrete and steel layers. A full description of the layered triangular finite element program used in the analysis is detailed elsewhere [8] (Figure 1.a). Through the layered approach, combined membrane-flexural behavior of reinforced concrete plate structures can be modeled easily.

In the layered model, the element is divided up through the thickness into a number of concrete layers while the steel reinforcement is smeared into equivalent steel layers [9] (Figure 1.b). Each concrete layer is assumed to be in a state of plane stress and the stress distribution of the concrete section is shown in Figure (1.c) [9]. On the other hand, the stress distribution of the steel layers having uniaxial properties is considered to be discrete in the section (see Figure 1.d) [9]. The proposed material models are then applied to each layer individually. Therefore, the main advantage of using the layered approach is the generality of allowing for material property variation through the thickness of the section with only two dimensional finite element analysis.

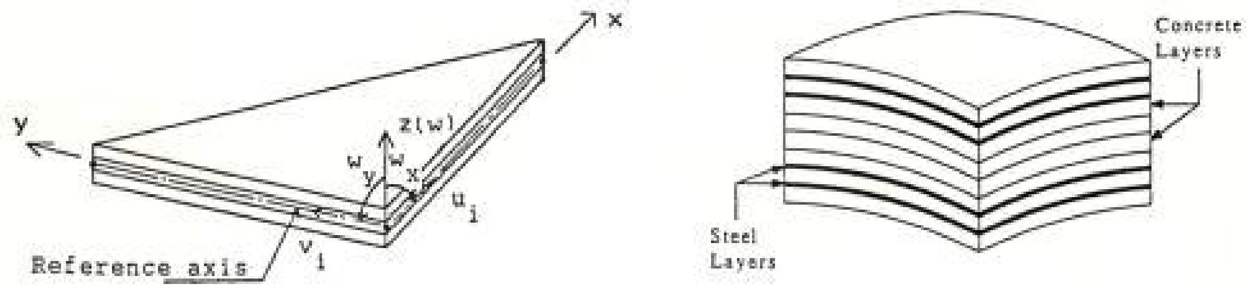
The general stress-strain relationship for the *j*th layer of a concrete section divided into K layers is as follows:

$$\{\sigma\}^T = [C]_j \, \{\varepsilon\}^T \qquad (1)$$

and the strain-curvature relationship at the mid-depth of a *j*th concrete layer is given by

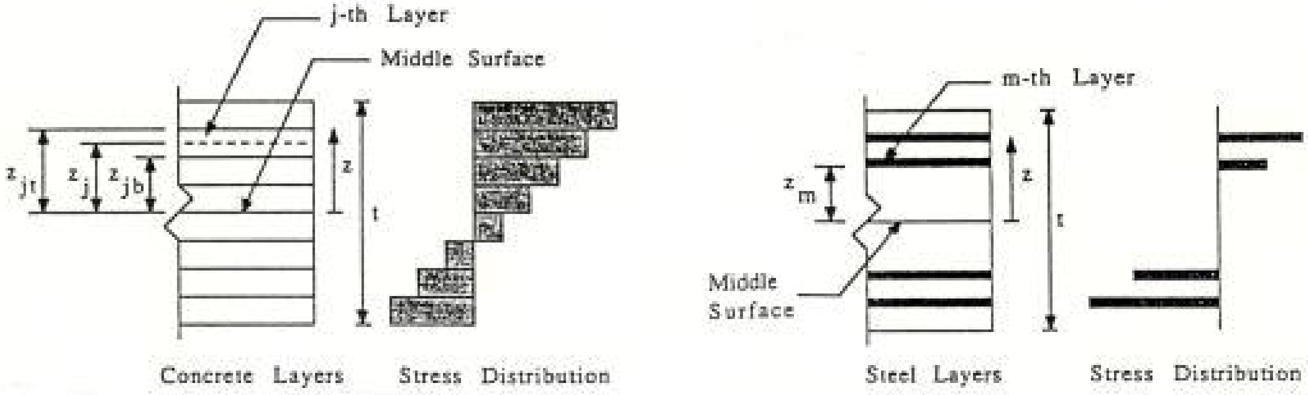
$$\{\varepsilon\}^T = \{\varepsilon_o\}^T + Z_j \, \{k\}^T \qquad (2)$$

where $\{\sigma\} = \{\sigma_x, \sigma_y, \sigma_{xy}\}$ is the stress vector in global coordinates, $[C]_j$ is the inplane constitutive matrix for individual concrete layer, $\{\varepsilon\} = \{\varepsilon_x, \varepsilon_y, \varepsilon_{xy}\}$ is the strain vector in global coordinates, $\{\varepsilon_o\} = \{\varepsilon_{xo}, \varepsilon_{yo}, \gamma_{xyo}\}$ are the strains at the middle surface of the section, $\{k\} = \{k_x, k_y, k_{xy}\}$ are the curvatures; and Z_j is the distance between the



(a) A 36 DOF Triangular Layered Element [8]

(b) The Layered Model [9]



(c) Stress Profile for Concrete Section [9]

(d) Stress Profile for Steel Reinforcement [9]

Figure 1 A layered finite element modelling of reinforced concrete sections center of the *j*th layer and the middle surface of the section. The full derivation and the determination of stresses and moments for a layered model is given elsewhere [8].

The structure modeled in this study is a single story consisting of three panels in both the (x) and the (y) directions. Figure 2 shows the dimensions and the finite element mesh of the studied floor system. The infinite stiffness of the columns has been taken into consideration. In each case investigated, the entire floor system was uniformly loaded with a total load of 1400 kg/m^2 (500 dead loads, 500 live loads, 150 flooring and 250 equivalent load for walls). The concrete characteristic strength was taken as 350 kg/cm^2 and the steel reinforcement rank was 40/60. The flat plate thickness was maintained at 0.2 meters, which satisfies the serviceability requirements of the Egyptian Code 1989[2].

3-DESCRIPTION OF STUDIED FLOOR SYSTEMS

A typical floor plan with variable aspect ratio (L1/L2) was considered in the analysis (see Figure 2). The chosen plate aspect ratios were 1.0, 1.167 and 1.333. The short span L2 was maintained at 6.0 meters. The openings were located at the mid length of the panel, as shown in Figure 2. The opening size (a x b) was varied to study the effect of opening aspect ratio. The chosen opening aspect ratios were 0.67, 1.0, 1.5 and 2.0. A total number of thirty four combination cases between the different studied parameters (see Table 1) have been considered in the analysis. Figure 3 shows a key plan for all the studied plate cases. The results of these studied combinations will be discussed herein.

4-DISCUSSION OF THE RESULTS

The results of the parametric study reported in this investigation include the effect of plate aspect ratio, opening location, opening aspect ratio and opening size upon the flexural moments and mid-span deflection of the plate systems. The results are shown in Figures 4 through 8.

4-1 Effect of Plate Aspect Ratio

The effect of plate aspect ratio upon flexural negative and positive moments is shown in Figure 4 for both of the column and field strips of the studied plates respectively. It can be seen from Figures 4 (a) and 4 (b) that the negative and positive moments obtained by the finite element program are almost the same for all square panels (L1/L2 = 1) whether or not openings were introduced. However, this is not the case for higher aspect ratios.

Figures 4 (a-1) and 4 (a-2) show that the effect of plate aspect ratio is more significant for the negative column strip moment in the long direction, M2 than for the moment in the short direction, M1. The increase of the plate aspect ratio by 0.33 leads to an increase of moment M2 by 82% and 74% for plates with openings in column strips and solid plates, respectively. For plates with openings in field strips, this value did not change than that for solid plate roofs (74%), which indicates that the introduction of an opening did not affect the value of M2 for plates with openings in the field strip. It was

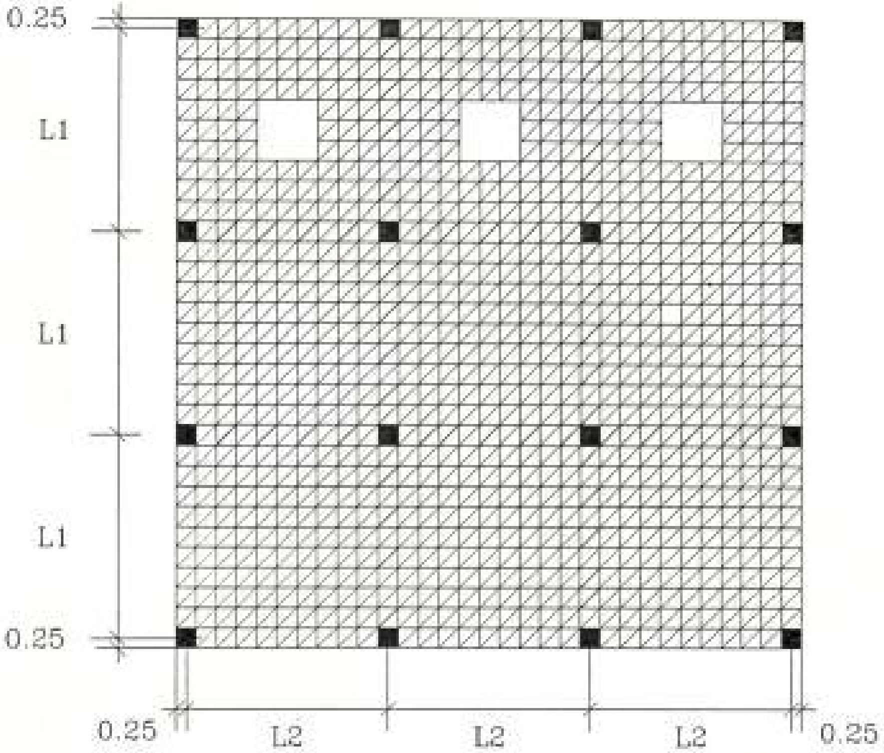


Figure 2 A typical finite element mesh for the studied floor

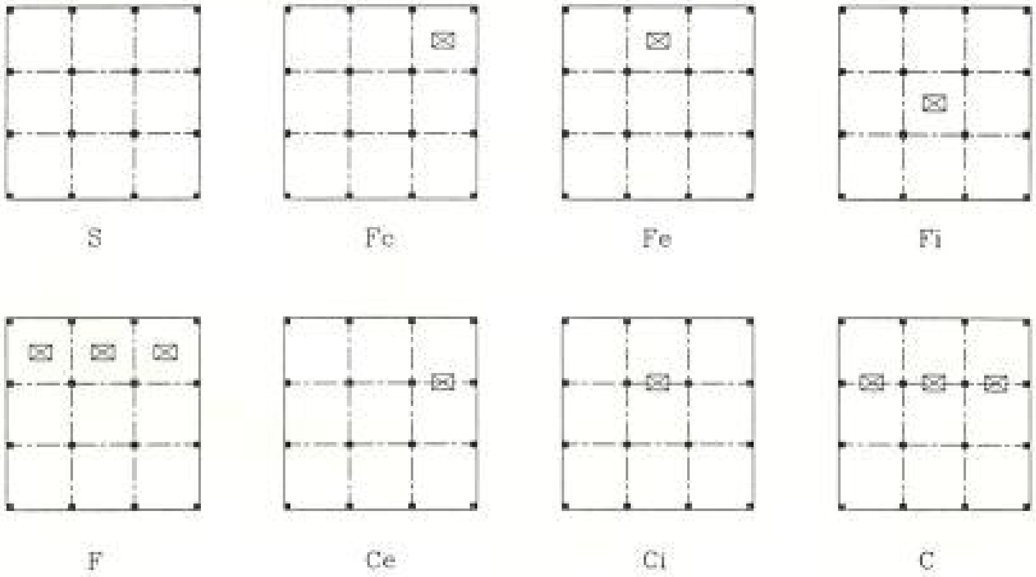


Figure 3 A key plan of the different slab cases

Table 1 Description of the Studied Flat Plate Cases

Group Key	Case No.	Studied Parameters		
		L1/L2	Opening Size (a x b)	Opening Location
S	1	1.000	-----------	-----------
	2	1.167	-----------	-----------
	3	1.333	-----------	-----------
C	1	1.000	50 x 50	Column Strip (see Figure ~~2~~3)
	2	1.000	75 x 50	
	3	1.000	100 x 50	
	4	1.000	50 x 75	
	5	1.000	75 x 75	
	6	1.000	100 x 100	
	7	1.167	100 x 100	
	8	1.333	100 x 100	
Ce	9	1.000	100 x 100	Column Strip (edge panel)
	10	1.167	100 x 100	
	11	1.333	100 x 100	
Ci	12	1.000	100 x 100	Column Strip (interior panel)
	13	1.167	100 x 100	
	14	1.333	100 x 100	
F	1	1.000	50 x 50	Field Strip (see Figure ~~2~~3)
	2	1.000	75 x 50	
	3	1.000	100 x 50	
	4	1.000	50 x 75	
	5	1.000	75 x 75	
	6	1.000	100 x 100	
	7	1.167	100 x 100	
	8	1.333	100 x 100	
Fc	9	1.000	100 x 100	Field Strip (corner panel)
	10	1.167	100 x 100	
	11	1.333	100 x 100	
Fe	12	1.000	100 x 100	Field Strip (edge panel)
	13	1.167	100 x 100	
	14	1.333	100 x 100	
Fi	15	1.000	100 x 100	Field Strip (interior panel)
	16	1.167	100 x 100	
	17	1.333	100 x 100	

noticed that the values of the moments, M1, were almost identical regardless of the opening location. Figure 4 (a-3, a-4) shows that the effect of aspect ratio upon the positive column strip moments is less than that for the negative moments shown in Figure 4(a-1, a-2). For example, the increase of aspect ratio by 0.33 leads to an increase of 64%, 64% and 60% in positive moment M2, for plates with openings in column strip, with openings in field strip and solid plates, respectively.

It is clear from Figure 4(a) that the results obtained by the empirical method [2] are lower than those obtained by the finite element program, especially for negative moments in column strips. In addition, the difference between the results obtained by the empirical method [2] and the finite element results increases with the increase of aspect ratio.

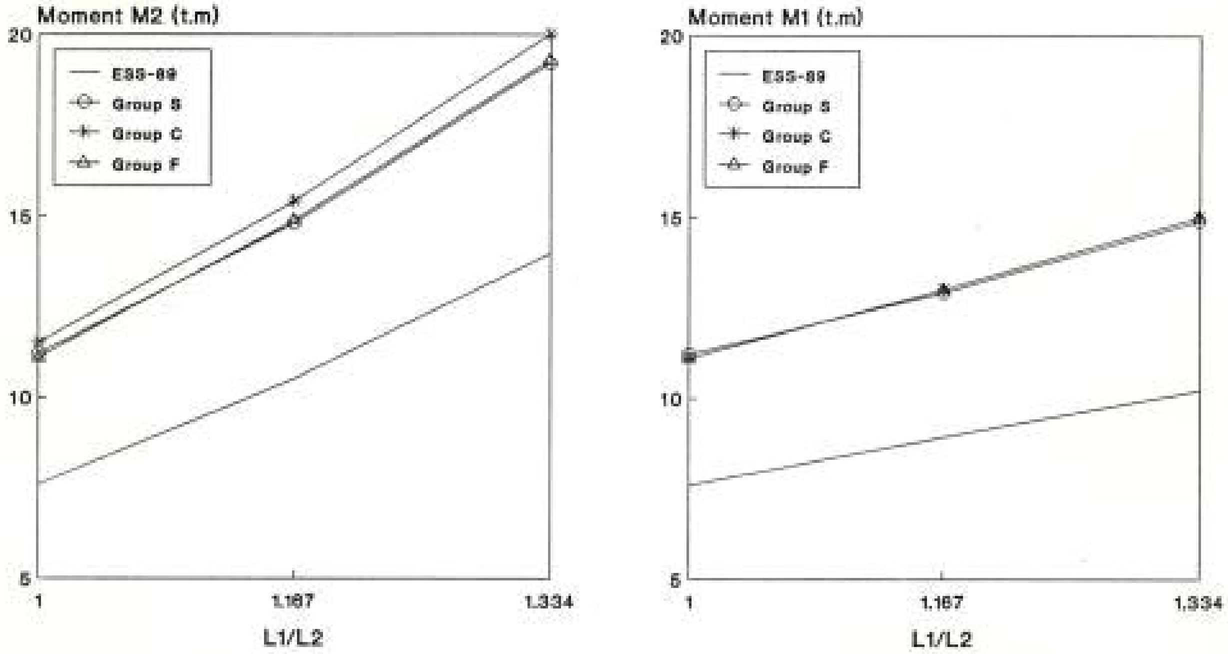
Figure 4 (b) shows the effect of plate aspect ratio on the field strip moments. It can be seen from the figure that the effect of aspect ratio is more significant for the moment in the long direction, M2 than that for the short direction moment, M1 regardless of the presence of openings (see Figure 4 (b-1)). Figure 4(b-4) shows that the introduction of openings was more effective on the positive moment, M1, especially when the openings are located in the column strip and the effect decreased when the openings are located in the field strip regardless the plate aspect ratio .

It can be seen from Figure 4 (b) that the difference between the results of the empirical method and the finite element program is lower for the field strip moment than that for the column strip one (see Figure 4 (a)). In addition, a comparison between Figures 4 (a) and 4 (b) shows that the trend of increase or decrease of the empirical results compared to finite element ones depends on the location of the moment under consideration (i.e. column strip or field strip moment). For example, the results obtained by the empirical method are lower than the finite element ones for negative column strip moment, M1 while the opposite is true for the field strip moment (see Figures 4 (a-2) and 4 (b-2).

It was found from the finite element results that the deflection increases with the increase of plate aspect ratio. However, the magnitude of this increase is not affected by the presence and/or the location of the opening. For example, an increase of aspect ratio by 0.33 leads to an increase of 119%, 120% and 115% in the deflection for plates with openings in column strip, plates with openings in field strip and solid plates, respectively.

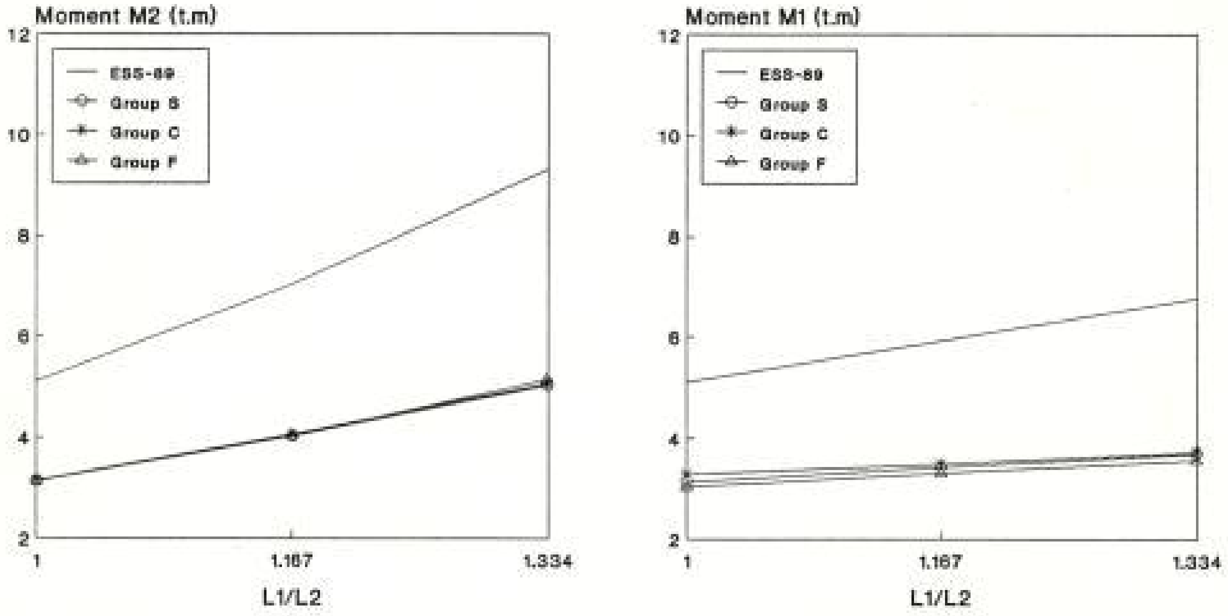
4-2 Effect of Opening Location

The effect of opening location upon flexural moments was studied for plates of aspect ratio (L1/L2 = 1). The results are shown in Figure 5 as a function of the moments (ESS-89) obtained by the empirical method [2]. It can be seen that the opening location has a negligible effect on the flexural moments compared with the plate aspect ratio (see Figure 4). The variation of moments with the change of aspect ratio was more noticeable for the field strip moments compared with the column strip ones regardless of the opening location. For example, the decrease of aspect ratio from 1.33 to 1 leads to a decrease of negative and positive field strip moments from 0.93 and 1.37 to 0.63 and 0.93 times the moment (ESS-89), respectively. On the other hand, the same change of



1) Negative Moment in Long Direction

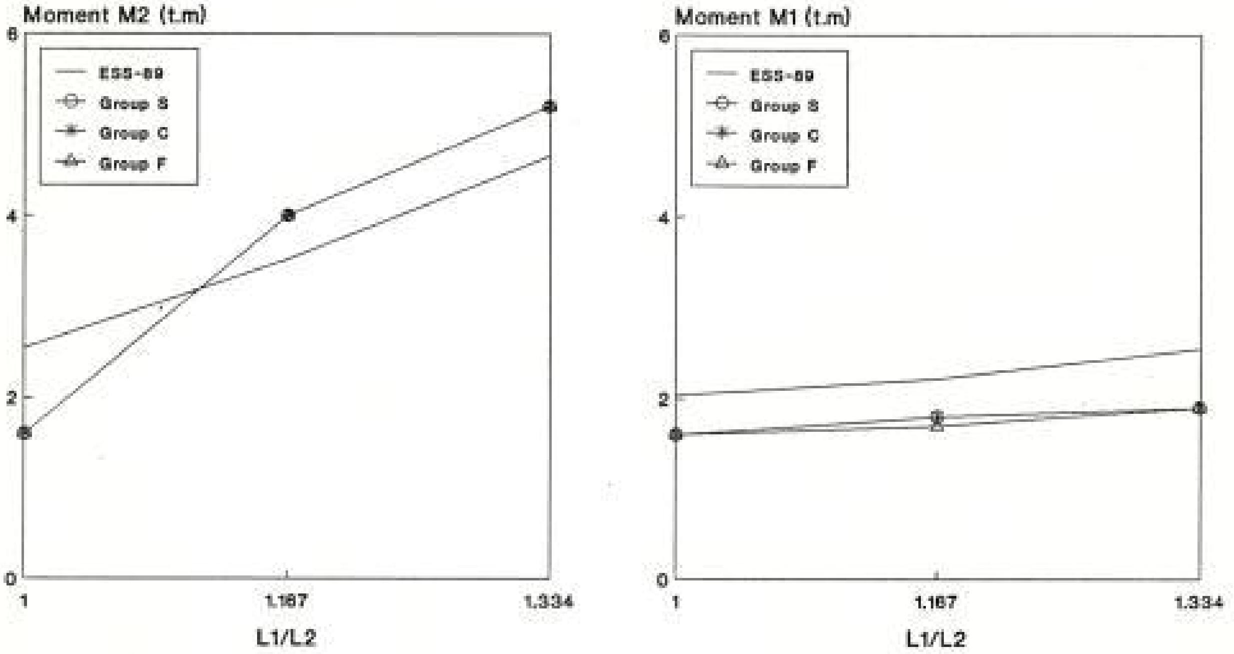
2) Negative Moment in Short Direction



3) Positive Moment in Long Direction

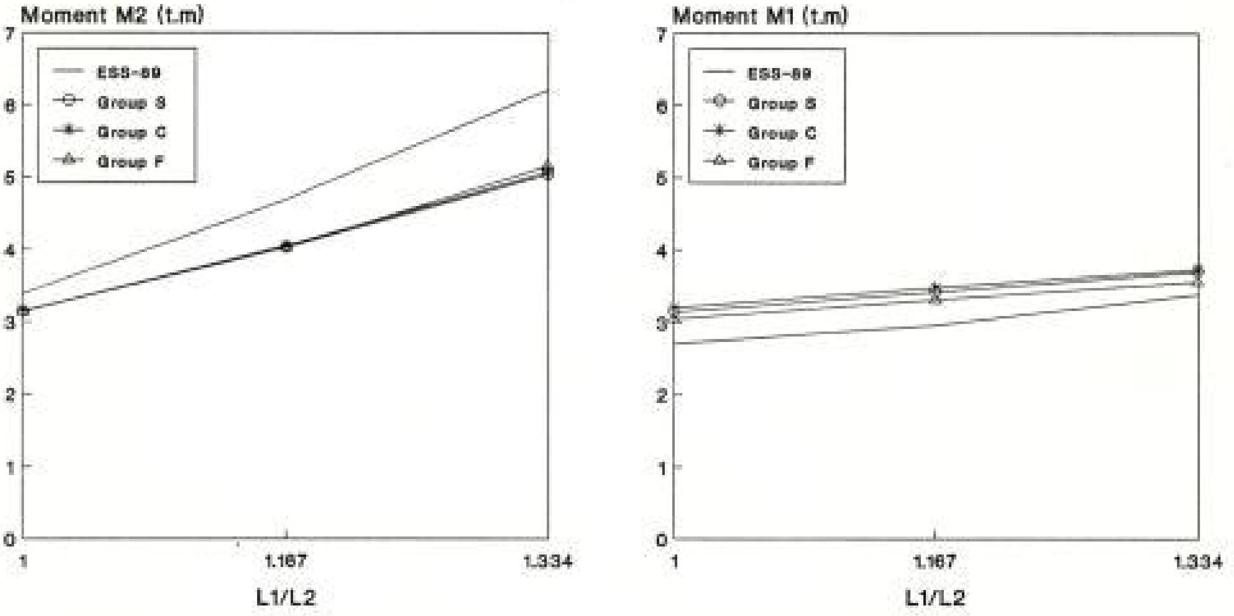
4) Positive Moment in Short Direction

Figure 4(a) Effect of Plate Aspect Ratio on Column Strip Moment
(Opening size 100x100)



1) Negative Moment in Long Direction

2) Negative Moment in Short Direction



3) Positive Moment in Long Direction

4) Positive Moment in Short Direction

Figure 4(b) Effect of Plate Aspect Ratio on Field Strip Moment
(Opening size 100x100)

aspect ratio leads to a reduction of the negative and positive moments of the column strip from 1.47 and 0.61 to 1.45 and 0.51 times the moment (ESS-89) respectively. It is clear from the figure that the empirical method [2] underestimates the negative moments and overestimates the positive ones in the column strip. The opposite is true for the field strip except for square plates (L1/L2=1.0).

It was found that the opening location has an insignificant effect on the plate deflection. The maximum deflection was about 1.0 cm for all the studied cases.

4-3 Effect of Opening Aspect Ratio

The effect of opening aspect ratio upon flexural moments was studied for plate aspect ratio (L1/L2 = 1). The results are shown in Figure 6 for the different studied opening aspect ratios. It was found that the opening aspect ratio has only a significant effect on the column strip positive moment, M1, for plates with openings in the column strip. For example, the increase of opening aspect ratio from 0.67 to 2.0 leads to a decrease of column strip positive moment by 21.7% (see Figure 6-b) while the same increase of opening aspect ratio leads to a maximum decrease of about 1% in the other flexural moments (see Figure 6-a,c,d). It can be seen that the negative and positive moments are gradually decreased except that the column strip positive moment which decreased dramatically for small aspect ratios (0.67 up to 1) and started to decrease gradually for higher aspect ratios.

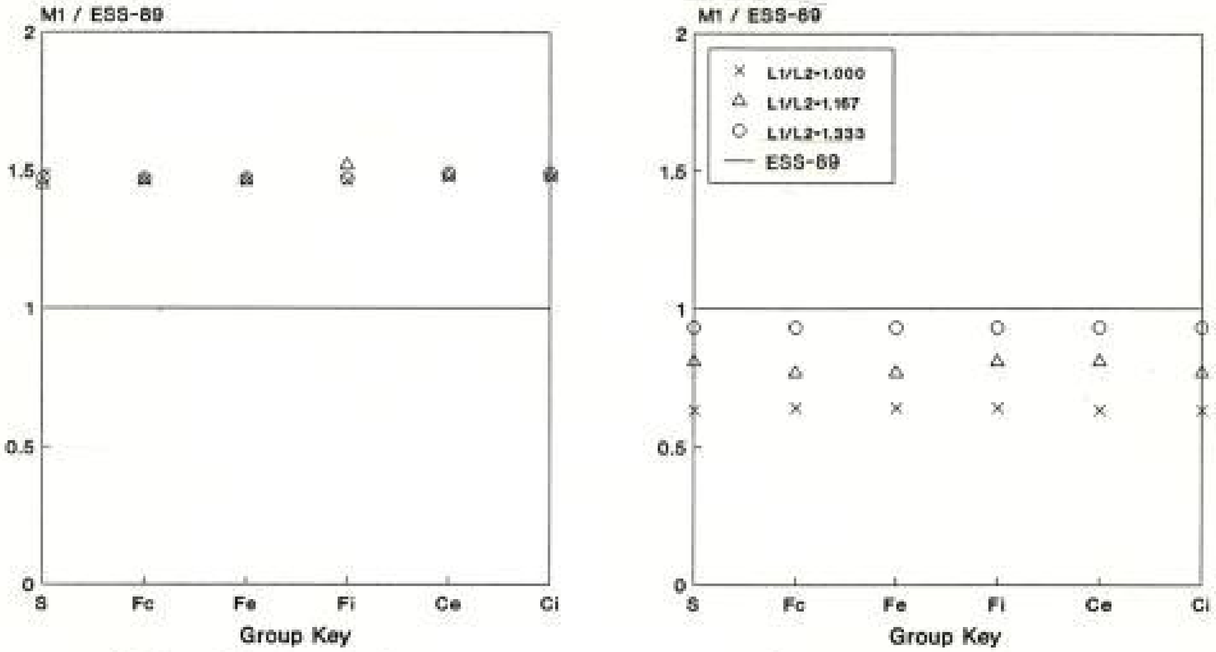
Figure 6 shows also that the results obtained by the empirical method [2] are overestimating the column strip positive moment, field strip negative and positive moments by 38%, 37% and 7% respectively. The opposite is true for the column strip negative moment where the empirical method underestimates the results by about 32%.

4-4 Effect of Opening Size

The effect of opening size upon the flexural moment M1 is shown in Figure 7. The results were compared with those of solid plate systems. It can be seen from the figure that the effect of opening size was more significant for the positive moment in column strip case (see Figure 7-b) than that in the other cases (see Figure 7-a,c,d). For example, the increase of opening size from 0.5 x 0.5 to 0.75 x 0.75 leads to an increase of column strip positive moment by 13.8% while the same increase of opening size leads to an increase of the column strip negative moment and field strip positive and negative moments by not more than 1.9%.

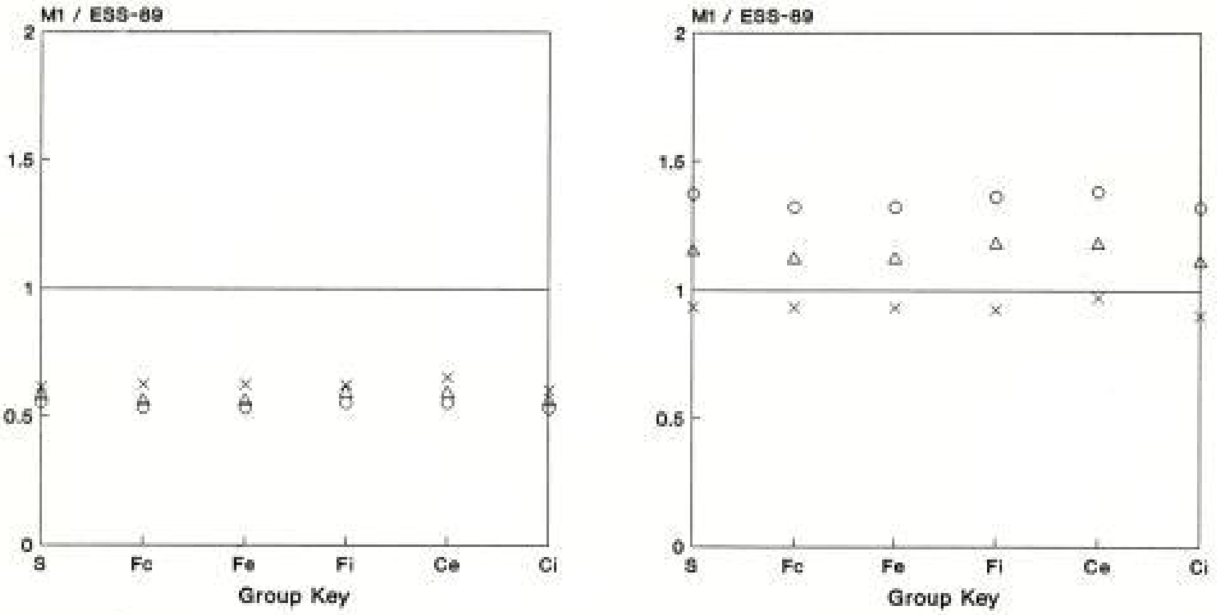
It can be seen from Figure 7, as was mentioned previously for opening aspect ratio, that the results obtained from the empirical method [2] were conservative for the column strip negative moment.

It was found from the results of the studied cases that the opening aspect ratio and opening size have almost no effect on the plate deflection. The maximum deflection was about 1.0 cm for all the studied flat plate roofs.



a) Column Strip Negative Moment

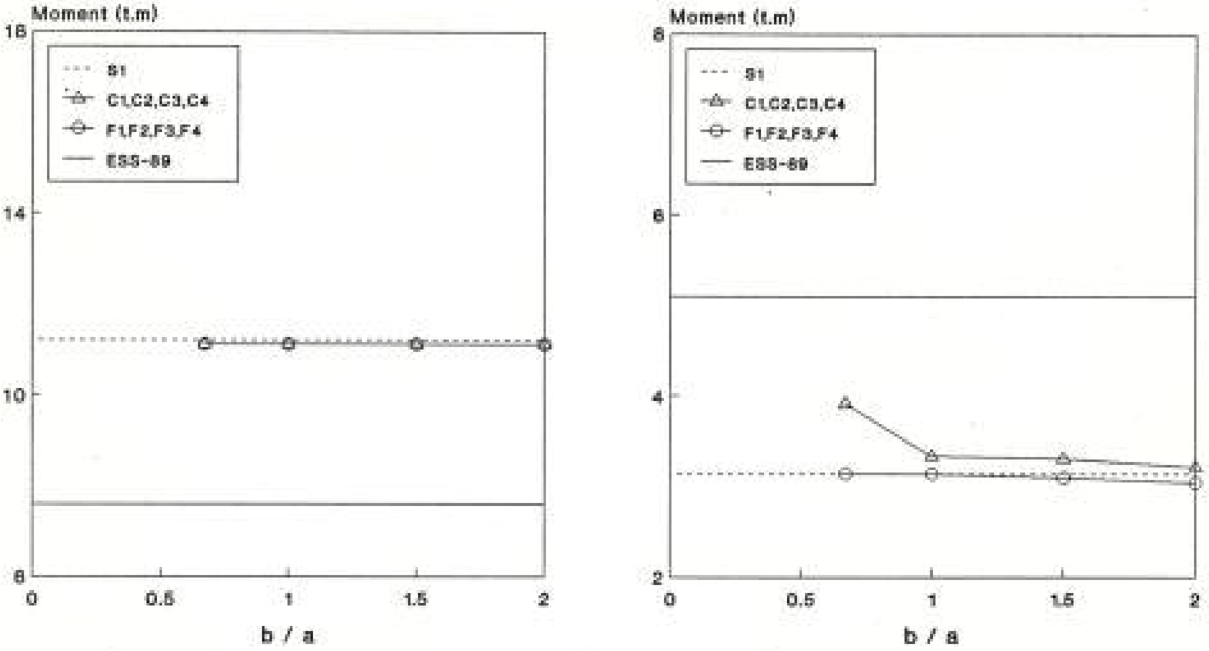
b) Field Strip Negative Moment



c) Column Strip Positive Moment

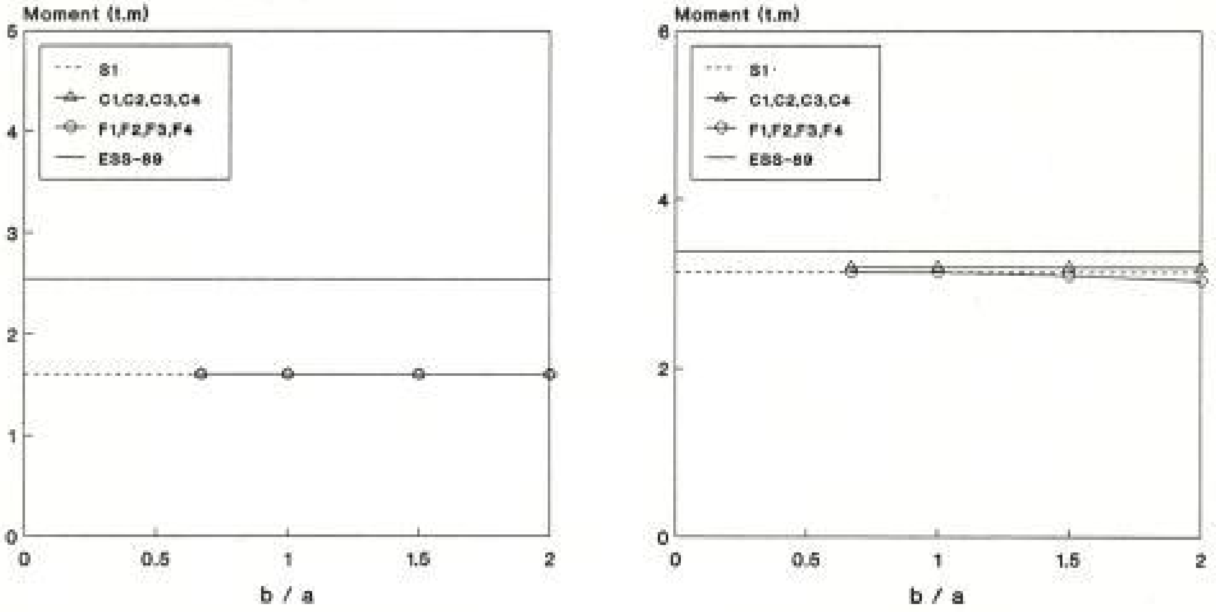
d) Field Strip Positive Moment

Figure 5 Effect of Opening Location on Plate Moment (M1)
(Opening size 100x100)



a) Column Strip Negative Moment

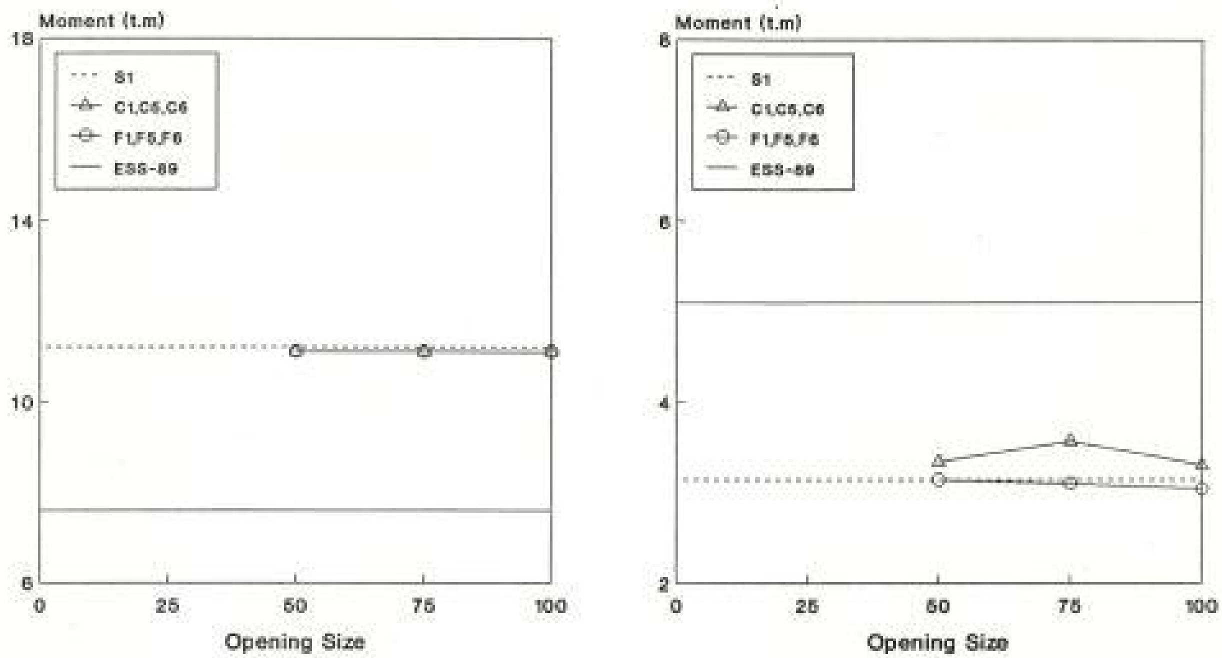
b) Column Strip Positive Moment



c) Field Strip Negative Moment

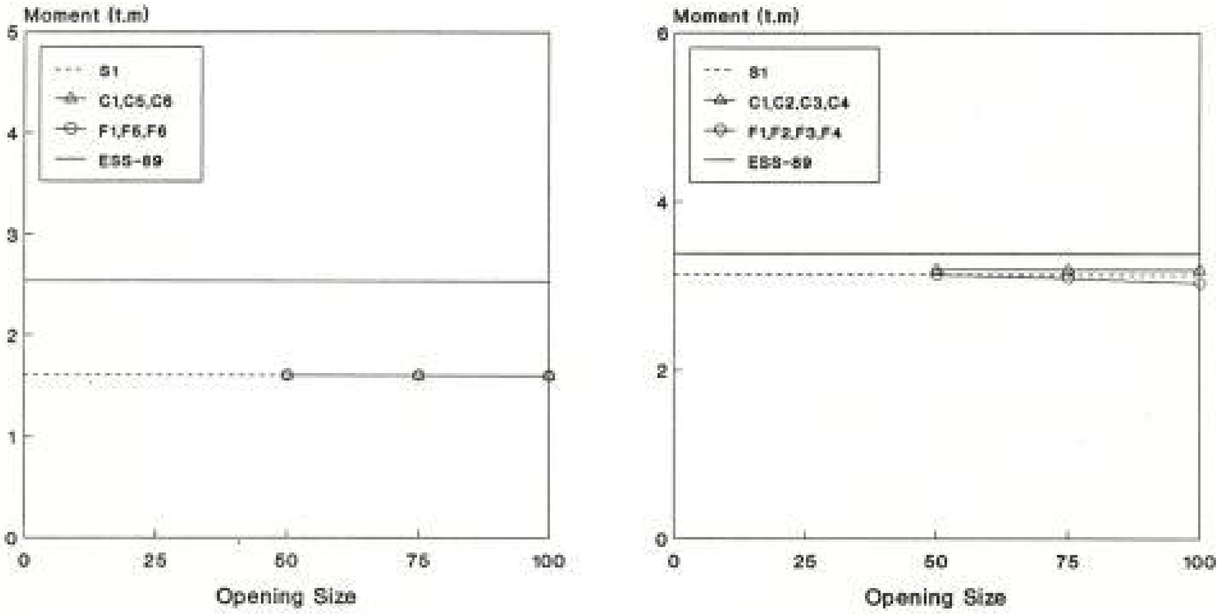
d) Field Strip Positive Moment

Figure 6 Effect of Opening Aspect Ratio on Plate Moment (M1)



a) Column Strip Negative Moment

b) Column Strip Positive Moment



c) Field Strip Negative Moment

d) Field Strip Positive Moment

Figure 7 Effect of Opening Size on Plate Moment (M1)

5-CONCLUSION

This study has illustrated the degree of sensitivity of beamless flat plates with openings to plate aspect ratio, opening location, opening aspect ratio and opening size. From the obtained results and within the limits considered, the following observations can be concluded:

1. The plate aspect ratio has a significant effect on the negative and positive moments in the short direction especially for plates with openings in the column strip.
2. The opening location and plate aspect ratio have a more significant effect on the field strip moments compared to the column strip ones. This may be attributed to the fact that the openings in this study were always placed at the middle of the column or field strips. It is expected that positioning the openings near the columns would have a more profound effect on the moments in the column strip.
3. The opening size and aspect ratio have a noticeable effect on the column strip positive moments and have a minor effect on all other moments.
4. The most important factor affecting the mid-span deflection is the plate aspect ratio regardless of the presence and/or the location of openings in the flat plates.
5. It was found that the empirical method given by the Egyptian code underestimates the negative moments in column strips and, in some cases, positive moments in field strips. It is recommended that designers use the formulae of the code in the above mentioned cases with caution.

6-REFERENCES

1. ACI Committee 318-89, "Building Code Requirements for Reinforced Concrete and Commentary", ACI 318-89, 1989.
2. "Egyptian Code for the Design of Reinforced Concrete Structures", Cairo, 1989.
3. Fraser D., "Elastic Analysis of Laterally Loaded Frames", Journal of the Structural Division, ASCE, Vol. 109, No. 6, June 1983.
4. Elkafrawy M.F., "Analysis of Building Frames", Ph.D Thesis, Carleton University, Ottawa, Canada, 1983.
5. Coull A. and Chee W., "Coupling Action of Slabs in Hull-Core Structures", Journal of Structural Engineering, ASCE, Vol. 110, No. 2., Feb. 1984.
6. Hartley G. and Abdel-Akher A., "Analysis of Building Frames", Journal of Structural Eng., ASCE, Vol. 119, No. 2, Feb. 1993.
7. Canadian Standards Association, "Code for Design of Concrete Structures for Buildings", CAN 3-A23.3-M77, Rexdale, Ontario, 1977.
8. Aly H.N and Shaaban I.G., "Analysis of Skew Composite Plates", Civil Engineering Research Magazine, Al-Azhar University, Vol. 16, No. 7, July, 1994, pp. 616-631.
9. Hu H.T. and Schnobrich W.C., "Nonlinear Finite Element Analysis of Reinforced Concrete Plates and Shells Under Monotonic Loading", Computers & Structures Vol. 38, No. 5/6, 1991, pp. 637-651.