Structural Consideration in Design of Reinforced Concrete Slabs with Openings

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ABSTRACT

Over 90% of framed structures in Uganda are built from reinforced concrete. Prior to the 1990's, most buildings had no openings in slabs, yet in city centers buildings butt against each other with widows at front and back only. This limited retail activities to front rooms of the ground floor and the buildings had to be narrow. A baseline survey of 50 shopping malls in Kampala Central Business District revealed that 40 of them have openings through all floors to the transparent roof section above. These openings allow improved air circulation and lighting, and facilitate full utilization of the structure for retail up to the last floor. However, the openings pose a break in the continuity of the slab; a potential weak point in the whole structure. Reinforced concrete slabs with openings are usually designed with help of traditional rules of thumb proposed by building codes. Such methods however, introduce limitations concerning size of openings and magnitude of applied loads. The research investigated the current methods of analysis and design of reinforced concrete slabs with openings. Approved plans were obtained and analyzed with emphasis on detailing. The problem is compounded when openings are made in existing slabs; strengthening methods for the slab are explored. The seismic performance, shortfalls in design and detailing methods of slabs with holes are explained.

Keywords: Design methods, holes in slabs, seismic performance.

1.0 INTRODUCTION

A slab is a thin planar member which transmits transverse loads by bending action to its supports. They can be made in-situ or prefabricated. In-situ can be classified according to; nature and type of the support i.e. simply supported; or continuous/fixed, direction/ method of spanning i.e. one way spanning; or two way spanning. Type of section such as solid and ribbed with permanent blocks; ribbed without blocks. A baseline study of 50 shopping arcades in Kampala CBD revealed that 40 of them have openings through all floor slabs. These openings have the advantages of; improved air circulation; aesthetics; and improved lighting. They also ensure full utilization of the building parts that would otherwise be cut off from natural light supply. However, these openings pose a break in the continuity of the slab causing weak points in the whole structure. They thus require special attention in analysis and design. They also limit the capacity of the slab to control the spread of fire.

In Uganda, design of concrete slabs with openings is a new development. The building codes propose instructions that are not supported by the underlying theories, (Rusinowski, 2005). The problem becomes more complex when openings are made in existing slabs. This paper presents a study of the design of slabs with openings and evaluates the detailing methods used by consultants in Uganda.


Figure 1: Large Openings in Reinforced Concrete Slabs
(Nabukera Plaza and Mabirizi Complex)

2.0 OVERVIEW OF ANALYSIS AND DESIGN METHODS FOR SLABS

2.1 Finite element plate based analysis

Finite elements have the unique capability to conform to virtually any geometry. Also by integrating the slab model with the three-dimensional frame, the combined effects of gravity and lateral loading conditions can be assessed together; the interaction of the slab and columns is accurately simulated. However, the results of finite element analysis are difficult to interpret and are usually unsuitable for direct use (Hillerborg, 1996). Interpretation of the results involves understanding several sign conventions and coordinate systems. Mistakes are easily made, leading to catastrophic results. Also the sheer volume of these results is too much for a normal design office. A structural model may contain several thousand finite elements and fifty or more loading cases, therefore difficult to reduce to a simple design. General lack of training in the finite element method complicates this further. The limitations of the finite element method demonstrate the need for a tool to simplify the design of flat plates using finite elements (Rusinowski, 2005).

2.2 Yield line method

The yield line method is an upper bound approach to limit analysis of reinforced concrete slab systems that should only be applied with sufficient knowledge and experience to assure an accurate design, or else the strength of the slab could be greatly overestimated. Thus it is a method to check the strength of an already reinforced slab system, (Hillerborg 1982). If used for design, the distribution of reinforcement is assumed initially and then checked. The yield line analysis assumes that failure due to shear or bond will not occur before the ultimate load. Unlike the Hillerborg method, it gives no direct indication of the resulting distribution of the load on the supports.

2.3 The Hillerborg strip method

The strip method assumes twisting moment in a slab to be zero. The method provides lower bound solutions and so a safer design. Also in contrast to the yield line technique, the strip technique is a pure method of design, not a method for checking a previously designed system.
According to Hillerborg, 1996 the stated objective of the strip design technique is to "seek a solution to the equilibrium equation [and] reinforce the slab for these moments" The load is assumed to be carried by strips of the slab that are oriented in the directions of reinforcement. This method is only applicable in scenarios where the strips can be suitably be approximated as beams with pin or fixed supports. Once a field of strips has been determined, each strip is then analyzed independently for the loading assigned to that strip. According to Hall *et al* 1990, holes and free edges can be accommodated by use of strong bands which act as beams formed within the thickness of the slab by use of heavy reinforcement. The major drawback is that the load on strips varies from one strip to the next leading to continuous variations of longitudinal reinforcement- which complicates the construction. There is a possibility of poor performance with respect to serviceability (Gamble & Park, 2000).

3.0 PROVISION OF HOLES IN SLABS

In design, two-way slab systems are divided into column and middle strips in two perpendicular directions. The middle strip is bounded by two column strips. The column strip width on each side of the column centerline is equal to 1/4 of the length of the shorter span in the two perpendicular directions. Section 13.4.1 of ACI 318-05 permits openings of any size in any new slab system, provided an analysis that demonstrates both strength and serviceability requirements are satisfied is performed. Alternatively, ACI 318-05 gives the following guidelines for opening size in different locations for flat plates and flat slabs. These guidelines are illustrated in Figure 2 for $l_2 \geq l_1$;

- In the area common to intersecting middle strips, openings of any size are permitted. This is the most favorable from a structural point of view and the most unfavorable from an architectural point of view because it's the most disruptive to the function of the space,
- In the area common to intersecting column strips, the maximum permitted opening size is 1/8 the width of the column strip in either span, and
- In the area common to one column strip and one middle strip, the maximum permitted opening size is limited such that only a maximum of quarter of the slab reinforcement in either strip may be interrupted.

To apply this simplified approach, the total amount of reinforcement calculated for the panel without openings, in both directions, must be maintained; thus, half of the reinforcement interrupted must be replaced on each side of the opening.

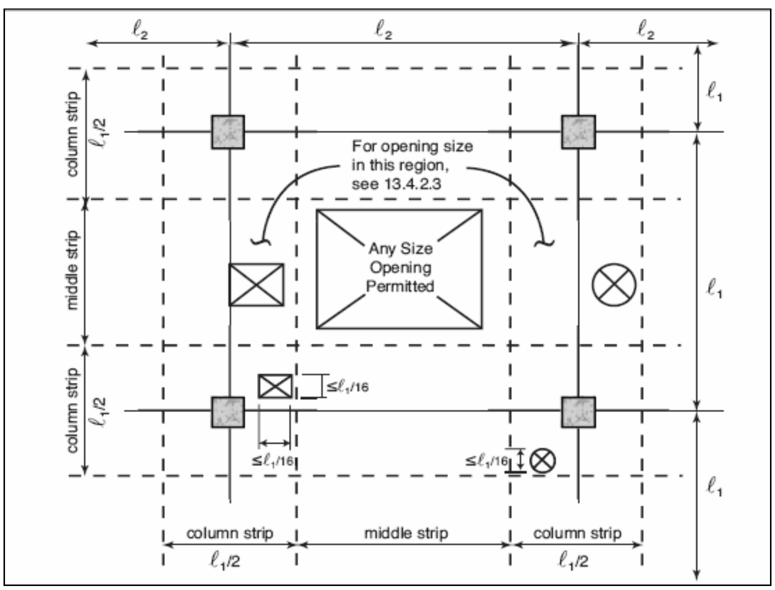


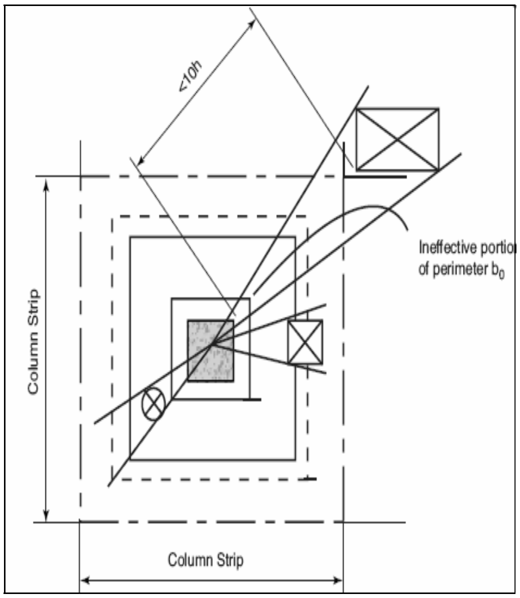
Figure2: Suggested opening sizes and locations in flat plates with $l_2 \geq l_1$

Also the reduction in slab shear strength must also be considered when the opening is located anywhere within a column strip of a flat slab or within 10 times the slab thickness from a concentrated load or reaction area. The effect of the slab opening is evaluated by reducing the perimeter of the critical section b_o by a length equal to the projection of the opening enclosed by two lines extending from the centroid of the column and tangent to the opening, as shown in Figure 3(a). For slabs with drop panels to assist in transferring slab shear to the column, the effect of the opening is reduced, and bo is reduced by only half the length enclosed by the tangential lines, as shown in Figure 3(b).

3.1 Openings in two-way beam-supported slabs

For openings in two-way beam-supported slabs, the situation is reversed because much of the shear is transferred to the column through the beams;

- An opening at the intersection of middle strip is least desirable. Maximum dimension of $1/8$ of the span is permitted, and
- Openings of up to 1/4 of the span are allowed in the intersection of column strips as long as the beams are left intact.



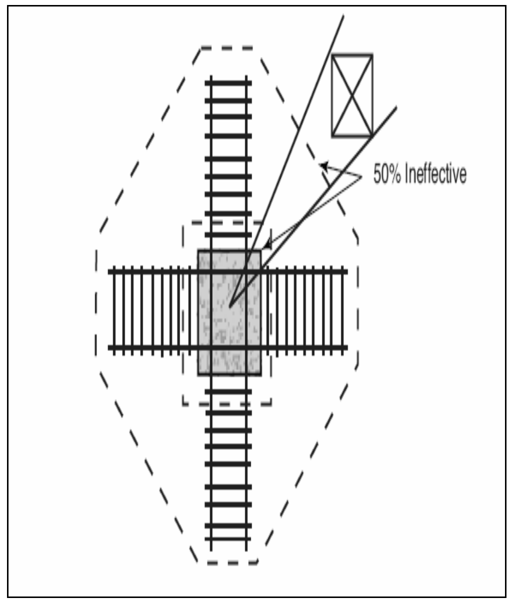


Figure 3a: Reduced perimeter **Figure 3b:** Effect of column heads

- Openings in the intersection of middle and column strips are more problematic because they may intersect the portion of the slab used as a T-beam.
- When removing an entire panel of slab between beams, it's advantageous to leave an overhang to allow anchorage of reinforcing bars from adjacent spans and the beams should be checked for torsion because the balancing moments from the portion of the slab that was removed will no longer be present.
- Re-entrant corners are points of weakness and require supplementary reinforcement in the way of overlapped side and end bars. And diagonal bars to divert the stress around the opening.
- For large openings, it is necessary to stiffen the slab with beams around the opening.
- The reinforcement that is interrupted by the opening is added to the sides of the opening.

Swedish code, BBK 04 (2004) allows applying openings of dimensions not longer than $1/3$ of the shortest slab span. The moments and the shear forces from area of the openings should be divided and added to bands around the opening together with the existing moments and shear forces.

The Polish code for concrete structures (PN-B-03264) the reinforcement is designed for a homogeneous slab and then the amount of the reinforcement from the opening is distributed around the opening, if the limits is exceeded the opening dimension or the magnitude of the load, the code demands a kind of trimmer members to be designed in form of hidden beams. The width of such beams cannot exceed four slab heights.

4.0 METHODS OF STRENGTHENING SLABS

In most cases new shopping malls are constructed, however in a few instances holes are made in existing slabs in which case strengthening methods must be employed. The selection of the most appropriate strengthening method depends on the amount, location of strengthening and architectural requirements. Some of the strengthening methods include:

(a) Steel plates installed on the bottom of the slab using post-installed anchors to avoid interference with flooring surfaces. Also, since overlapping of the plates is difficult, this method works best for strengthening is required in only one direction.

(b) Use fiber-reinforced polymer or steel-reinforced polymer strips to strengthen the slab. The strips can be overlapped at the corners of the opening, with less interference with the floor surface than anchored steel plates but, requiring more highly skilled labor.

(c) When shear strengthening is required around columns, a steel or concrete collar is installed around the columns to increase the perimeter of the critical section for punching shear.

(d) Systems that incorporate epoxy adhesives must be protected, as they can lose strength rapidly at elevated temperatures.

5.0 METHODOLOGY

A base line study of 50 shopping arcade structures in Kampala was carried out. It was found out that 40 of them had openings of various shapes and dimensions. A questionnaire was prepared and distributed to various consultants with the aim of obtaining data for comparison of the appropriateness of the current methods of analysis. A one to one interaction with members of consultancy firms was carried out. Original copies of approved structural plans of shopping arcade structures were collected from KCC and their duplicates made. This was followed by a careful study of detailing.

6.0 FINDINGS

6.1: Questionnaire results

There was little cooperation from some respondents since by its nature the project indirectly affected them, others claimed not to have time to attend to the researcher, while others completely refused on fears of alleged hidden agenda. All refused to fill the questionnaires but some were willing to have a one to one discussion, from which the following information was obtained;

- All consultants surveyed use computer programs in analysis and design because it is economical,
- The Hillerborg strip method which is a lower bound theorem is a strong tool in analyzing and designing slabs with openings but it is not used,
- For Maxpan slabs, consultants include a slab beam around openings,
- Consultants not bothered by the effect of openings on structural integrity due to seismic loads,
- Slab beams act as stiffeners but due to their low depth, they are liable to deflection for large spans, and
- The shape of the opening (i.e. rectangular, circular, etc) is not considered.

6.2 A Study of selected approved structural plans

20 structural plans with openings were studied; 19 of the 20 plans studied had “maxspan” slabs. In 16 of these plans the designers had provided strong bands (slab beams or beams) around openings, while in four, these appear to have had the slab designed as a cantilever. Plans submitted to KCC are not submitted with calculations therefore a clear picture of what the designer may have had in mind could only be assumed. None of 20 plans had diagonal bars around the corners of openings to take care of cracking caused by stress concentrations.

But 17 out of 20 plans studied avoided sharp corners and had their ends rounded as seen in Figure 4 and 5. Panels with holes had the same distribution of reinforcement as those without, therefore there was no evidence that the bars taken from the openings have been concentrated in the space adjacent the opening as recommended by most codes. There was no clear evidence of provision of ties (systematic continuity of reinforcement in all directions) in all the slabs as seen in Figure 4. Some openings left in shopping arcades are not included on the approved structural details.

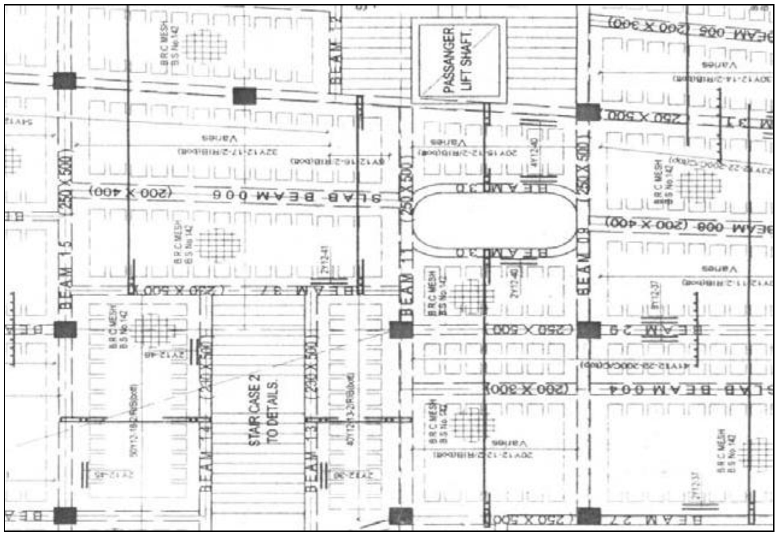


Figure 5: Slab with edge beams or strong bands around openings

7.0 CONCLUSIONS

Methods employed in designed slabs with holes were studied, in addition methods employed to strengthen existing slabs in which holes are made were considered. Discussions were held with willing consultants and approved structural plans were obtained from KCC and examined with special emphasis on detailing. From discussions held with consultants; all consultants surveyed use computer programs in analysis and design, consultants include a slab beam, around holes in maxspan slabs, consultants do not consider effect of openings on seismic structural integrity, and the shape of the opening is not put into consideration.

From a study of selected approved plans; 95% of plans studied were of maxspan slabs, 80% of plans studied had openings surrounded by strong bands or beams, diagonal (skew) reinforcement at corners was missing in all slabs considered but most slabs had rounded edges, area taken from holes was not distributed around the holes as recommended by codes, there was no clear evidence of provision of ties in all the slabs, some openings in shopping arcades are not included on the approved structural details, and some slabs appear cantilevered from supporting beam.

8.0 RECOMMENDATIONS

- Torsion should be considered in beams surrounding openings, re entrant corners should be avoided, where these are provided, they should be provided with diagonal bars,
- For large openings, the slab should be stiffened by use of beams around the opening,
- The reinforcement that is interrupted by the opening should be added to the sides of the opening,
- Any changes in plans should be submitted and separately approved,
- Measures to cater for reduced resistance to fire spread should be put in place for slabs with holes,