Punching Shear in Reinforced Concrete Flat Slabs in Multi-Storey Car Park Building Structure

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Abstract. Punching shear failure had been the cause of some fatal accidents that had occurred in the past in flat slabs of car park structure. A number of such failure reports had identified the underlying reasons being in the use of outdated or obsolete standards which have been phased out. Therefore, the design and analysis of punching shear strength in reinforced concrete flat slab is a key procedure that requires precision and accuracy. Over the years, although researchers had done a lot of experimental studies on the behaviour of flat slab structures, but the punching shear failures still happened despite many precautions being taken when designing for the car park structure. In this paper, some data that had been presented by previous researchers are used to identify the few design criteria for multi storey car park structure, and these results will also be compared with Eurocode 2 and two other standards, namely the phased out BS8110 and ACI318. From there the analysis for punching shear in multi storey car park structure is carried out using the Eurocode 2 approach considering the varying design parameters such as the sizes of column, slab thickness, span between columns and shapes of column. These parameters played a major role in assessing the punching shear strength in multi storey car park structure. In the model simulation, it was found that among the four selected parameters for study, the thickness of slab and the column size adopted are key factors that can enhance the punching shear strength capacity. On the other hand, the use of square column was proven to have an average of 27\% higher punching shear strength than circular column. Besides that, the span between columns in two plane directions are best to range around 6m and 7m but due to car park functional expectations, a flat slab bay area of 8m x 6m and 9m x 6m can be recommended for the purposes of accommodating more car park spaces.

1. Introduction

Concrete slabs are one of the core structural members in a building structure. The function of a slab member or platform is to transfer loadings on it to a column support. This can be done directly without the presence of a beam or to go through the beam first as a load path. There are two main types of slab, the conventional beam-slab connection and the slab column connection which is the flat slab structure.

For flat slabs, the load is transferred from the slab directly to the column, the foundation and finally to the foundation. Comparatively, reinforced concrete flat slabs provide savings in floor-to-floor headroom compared to the conventional beam-slab arrangement. Although flat slabs have a number of advantages for aesthetic and economic reasons, the likelihood of punching shear failure has been and is a continuing concern when it comes to design of the flat slabs for reinforced concrete structures.

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such as for multi-storey car park. Punching shear usually happens when a high magnitude load applied on a slab is transferred to a small contact surface area in the vicinity of a column support.

Normally, punching shear is observed to occur at the slab-column connection. This is highly likely when a high shear force happens at this connection causing punching shear failure to take place. Lateral loads such as wind load and earthquake may cause unbalanced moments to be transferred between slab and column, which in turn would cause additional instability resulting in punching shear failure at the slab-column connections. [1]

Over the years, news and reports have been published with regards to the accidents and failures of flat slabs in multi-storey car park caused by punching shear failure. It is a major concern to safe design of flat slabs as it can result in catastrophic accidents and loss of lives if the design and construction are not properly carried out.

2. Problem statement

In an article by Wood [2], it was reported that a number of car park structural failures were likely due to human error at the design stage as well as during the construction phase. Although it is known that the British standards for concrete design [3] has been replaced by the Eurocode 2 [4] in 2010 but a number of practicing engineers in Malaysia are still using the phased out British Standards [3] to design for the reinforced concrete structure. This is unfortunate and it needs to be rectified because standards of design practice evolved over a period of time with changing technology and updated information for safe design practices in the construction industry.

Hence it is always vital to learn and be informed of any recent and latest developments of research into methods of design and application in overcoming such potential failures and catastrophes such as those due to punching shear failures in reinforced concrete flat slabs. In view of many multi-storey car parks being built of reinforced concrete flat slab design, there is a need to address the potential failures due to punching shear, since by function and nature of usage, car park areas support high static and moving loading on the floor slabs.

The purpose of this study is to look into the configuration of car parks of flat slab design which can result in potential punching shear and its mitigation, such as column shape and sizing, spans of column supports as well as the concrete grade and thickness of slabs.

3. Literature review

Boon Tiong [5] carried out a research study on the punching shear capacity of the flat slab column connection with the aid of 3D non-linear finite element analysis. In this research the author discussed on the behaviour of reinforced concrete slab when punching shear occurs, which include how the first crack patterns will appear surrounding of the slab-column connection.

The first crack normally features a rough circular-like shape which formed around the perimeter of loaded slab column connection area due to the negative bending moment which takes place in the radical direction. It was also shown that the crack will propagate slowly from the top of the slab and end up on to the soffit of the slab. And these series of cracks formed are mainly due to the punching shear occurring in the vicinity of the slab-column connection.

Although it is known that the punching shear occurred at the slab-column connections and many past researchers had developed numerous empirical equations for analysis and design, it was found [5] there are very little effort to go in-depth to understand the mechanism of punching shear failure. Waleed [6] have done some research on the failure mechanism of punching shear failure and concluded that the unbalanced moment which is transferred between slab and column will produce additional shear stress and torsion which will enhance and even accelerate the punching shear mechanism at the slab-column connection joint.

Wood [2] have carried out a full quantitative study of the cause of the partial collapse of the Piper’s Row Car Park due to flat slab failure in 20th March 1997. In the report, after intensive investigation had been conducted, it concluded that the punching shear failure had occurred at the slab-column connections. The underlying reasons for this failure of the car park structure were mainly due to aspects of incorrect design and construction practices which had reduced the factors of safety.
involved. In addition, the ongoing partial repair has caused some deterioration leading to punching shear failure at one column which in turn caused progressive collapse at a top floor section.

The structure was built in 1965 and had repairs carried out in 1996 due to parts of deck slab collapse and this led to the punching shear collapse later in 1997. The inspection of the repaired area of the deck slab gave rise to a conclusion that the repair material used were not well compacted around the reinforcement area with inadequate bonding to the substrate concrete. The slab thickness of average 239mm did not comply with the specified designed thickness of 230mm which is the design of the car park structure itself.

Moreover, the concrete quality was found to be much lower than the actual design which led to a loss of more than 20% of the dead load capacity of the car park structure and that most of the concrete in the areas were not up to the specified design strength of 20.5 N/mm². These various factors have played a major role in reducing the punching shear strength and leading to the punching shear failure and collapse.

4. Research methodology

In this research paper, some data of the studies were compiled from previous works of researchers who had studied the punching shear analytical approach using various design standards such as the BS8110 [3] and Eurocode 2 [4], the replacement code of practice in UK and Malaysia. Visitations were made by the authors to various multi-story car parks of flat slab design to observe the conditions of the structures, as well as the configurations of column sizing, locations, spans in between supports and slab thicknesses.

Following from there, by inserting changing parameters of the design configurations observed, a number of model simulations were carried to study the structural behaviours and outcomes on how some of the design factors may affect the punching shear strength in the multi-storey car park structures. These simulations were carried out based on given design provisions from selected international standards of concrete design.

The following describes the proposed formulas used in determining the punching shear strength capacity in reinforced concrete flat slabs – both for slab/column connections with and without shear reinforcement in place. Prescribed formulas in three design standards are used in this study (Table 1-Table 3), which are the withdrawn British Standard BS 8110 [3], the Eurocode EC 2 [4] and the American Concrete Institute ACI 318 [7]. These form part of the procedures adopted in the model simulation to be carried out on the outcome of structural behaviours based on different inputs of design parameters observed.

Table 1. Slabs without shear reinforcement formula

| Design Standard   | Formula                                                                 |
|-------------------|-------------------------------------------------------------------------|
| Eurocode 2        | $V_{EC2,\text{Rd,c}} = 0.18udk(100p_{c,k})^{1/3}$                      |
|                   | $k = 1 + \left(\frac{200}{d}\right)^{1/3}$                           |
| BS8110            | $V_{BS8110,\text{Rd,c}} = 0.27(100p_{c,k})^{1/3}(k)^{3/2}ud/y_m$       |
|                   | $k = \frac{400}{d} \geq 1$                                            |
| ACI 318           | $V_{ACI318,\text{Rd,c}} = \frac{1}{3} (f_{c,k} \times u \times d)$     |
Table 2. Slabs with shear reinforcement formula

| Design Standard | Formula |
|-----------------|---------|
| Eurocode 2      | \[ V_{ECC, Rd, cs} = 0.75V_{ECC, Rd, c} + 1.5 \left( \frac{d}{S_T} \right) \left( A_{pe} f_{yw}d_{ef} \frac{1}{bd} \right) \sin \alpha \] (6) |
| BS8110          | For \( V \leq 1.6 V_{BS8110,Rd,c} \), \[ V_{BS8110, Rd, cs} = V_{Rd,c} + 0.95f_{yv} \sum A_{yv} \sin \alpha \] (7) |
|                 | For \( 1.6 V_{BS8110,Rd,c} \leq V \leq 2V_{BS8110,Rd,c} \), \[ V_{BS8110, Rd, cs} = 1.42V_{Rd,c} + 0.27f_{yv} \sum A_{yv} \sin \alpha \] (8) |
| ACI 318         | When inclined stirrups are used, \[ V_{sr} = A_v f_{yv} \frac{(\sin \alpha + \cos \alpha) d}{S_T} \] (9) |
|                 | When single bar or a single group of parallel bars are used, \[ V_{sr} = A_v f_{yv} \sin \alpha \leq \frac{1}{4} f_{ck} u d \] (10) |

Table 3. Model simulation formulas

| Design Standard | Formula |
|-----------------|---------|
| Eurocode 2      | \[ V_{ed} = F_{d} \times u_{o} \times n \] (11) |
|                 | \[ V_{ed, eff} = V_{ed} \times \beta \] (12) |
|                 | \[ V_{ed, max} = \left( 0.5 \times u_{o} \times d \times \frac{F_{ck}}{1.5} \times \left( 0.6 \times \left( 1 - \frac{F_{ck}}{250} \right) \right) \right) \times 10^{-3} \] (13) |

5. Results and discussion
The following sections present the punching shear strength analysed based on selected standards used in North America and Europe, given differing parameters applied. These values are then compared with test results published by various past researchers who had conducted the experimental testing in their research work. [8-11]

5.1. Comparisons of outcome of punching shear from codes of practice and experimental values obtained

5.1.1. Shapes of Column
From Figures 1(a) and 1(b) above, it showed the experimental data from past researchers [8-11] in comparison with the predicted values by the three standards. It can be seen clearly from the figure that Eurocode 2 [4] gave a more accurate prediction with the plotted points close to the equi-diagonal line which acts as a guide for the accuracy of punching shear strength as predicted by the standards against the experimental data values. A number of results from BS8110 [3] are zeros due to the standards
being limiting the concrete strength ($F_{ck}$) value to 40 MPa so that any data which have over 40 MPa of $F_{ck}$ then the values cannot be predicted by the BS8110 [3].

**Figure 1.** Experimental punching shear strength vs punching shear strength predicted by standards for (a) square columns, and (b) circular columns, in slabs without shear reinforcement

### 5.1.2. Slab thickness

From the Figures 2(a) and 2(b) above for varying slab thickness without shear reinforcement as design parameter [8-11], Eurocode 2 [4] again provide a more accurate prediction of analysed results compared to experimental data. Although it is only 50mm difference in thickness but 200mm slab thickness clearly has a higher punching shear strength when comparing to the 150mm slab. Other than that, those values from BS8110 [3] are zeros due to the standards are limiting the concrete strength ($F_{ck}$) value to 40MPa so that any data which have over 40 MPa of $F_{ck}$ then the values cannot be predicted by the BS8110 [3].

**Figure 2** Experimental punching shear strength vs punching shear strength predicted by standards for different thicknesses 150 mm and 200 mm in slabs without shear reinforcement

From the Figures 3(a) and 3(b) above for varying slab thickness with shear reinforcement [8-11], it can be seen that the value predicted by Eurocode 2 [4] are nearer to the diagonal line than the other two standards which can be concluded that Eurocode 2 [4] are predicted the value of punching shear strength are more accurate than the other 2 standards. From the graphical results shown, it is obvious that the 500mm slab thickness has almost five times the punching shear strength than the 125mm slab. Not only that, when comes to comparing with earlier Figures 2(a) and 2(b), the thinner 125mm slab with reinforcement has a higher punching shear strength compared to its 150mm thick counterpart slab without shear reinforcement.
Figure 3 Experimental punching shear strength vs punching shear strength predicted by standards for different thicknesses 125 mm and 500 mm in slabs without shear reinforcement

5.2. Model simulation results
In this model simulation, there is a total of 400 data compiled with various different dimension, shapes of column, slab thickness and span between columns [8-11].

5.2.1. Sizes of Column
The first factor that can control is the variable size of column. The sizes of column studied are from 300mm, 350mm, 400mm, 450mm to 500mm in determining the influence of sizes of column to the punching shear strength.

From the Figure 4 above, it is clearly seen that the higher the sizes of column, the punching shear failure occur will reduce due to the increment of the punching shear strength. In term of punching shear strength, 500mm have minimum maximum punching shear strength of 1MN while 300mm only at 0.58MN.

Figure 4. Percentage of punching shear failure and passing with different column sizes

5.2.2. Slab thickness
Then, the second factor that can control the punching shear capacity is the varying slab thickness. The slab thickness is ranged from 150mm, 200mm, 250mm to 300mm in determining the influence of slab thickness to the punching shear strength.

From the Figure 5 above, it is clearly seen that thicker of the slab thickness, the punching shear failure occur will reduce due to the increment of the punching shear strength. It is obvious from 150mm to 200mm the results showed the punching shear failure reduced effectively. In term of
punching shear strength, the 300mm slab has a maximum punching shear strength of 1.35MN while the 150mm slab has a minimum value at 600kN.

![Graph showing slab thickness vs punching shear failure/passing]

**Figure 5.** Number of punching shear failure and passing with different slab thickness

5.2.3. *Span between columns*

The third factor studied is the variable spans between column supports as shown in the Figure 6 above, in determining the influence of span between columns to the punching shear strength. From the Figure 6, it can be seen that given shorter spans in both direction of the slab, the occurrence of punching shear failure will reduce due to the increment of the punching shear strength.

On the other hand, due to the function of the car park structure that needs to accommodate as many parked vehicles as possible, the right span between columns are needed to be chosen wisely. In this case, 8m x 6m and 9m x 6m are highly recommended to be used in the car park structure. In term of punching shear strength for both of the recommended spans between columns, 9m x 6m span configuration have minimum maximum punching shear strength of 770 kN while a 8m x 6m span configuration would yield a 900 kN punching strength capacity.

![Graph showing span between columns vs punching shear failure/passing]

**Figure 6.** No. of punching shear failure and passing with different span between column supports

5.2.4. *Shapes of columns*

Last but not the least, the final variable and factor is the shape of column section. The shapes of column considered here are the circular and square columns. Both shapes of column are studied to determine the influence of their shapes on the punching shear strength.

From the 400 sets of data compiled for the model simulation, there are only 83 numbers of tested models which had failed in punching shear but among of the 83 failed test models, 60 numbers of the column failed are of circular in shape.
This proved that with a smaller cross-sectional area, circular columns would provide less resistance to punching compared to the square shaped columns. From the previous results with column shapes with varying slab thickness, sizes of column and span between column, taken into consideration, it was found that square column have 27% more in punching shear strength capacity than the circular column shapes.

In term of punching shear strength for both shapes of column, the square columns have minimum maximum punching shear strength of 780 kN while circular columns showed punching resistance at 600 kN.

6. Conclusions
The main objective of the research was to investigate the punching shear resistance in reinforced concrete multi-storey car park structure. The objective was achieved where the analysis using model simulation to complete for analysis of multi storey car park structure with varying design parameters (such as sizes of column, slab thickness, span between columns and shapes of column).

Before the model simulation commences, the first objective was to determine the accuracy of Eurocode 2 in analysing the flat slab structures for their punching shear resistance. Numerous data and results collected from past technical reports, journals and researches [12-15] were compared with the predicted values from three selected standards (Eurocode 2 [4], BS8110 [3] and ACI318[7]) to ascertain the accuracy in predicting the values of punching shear strength of flat slabs. With numbers of analysis carried out, the Eurocode 2 was found to be the most accurate in predicting the punching shear strength.

Hence the Eurocode 2 approach was adopted to carry out the model simulation. In the model simulation, four parameters were chosen as variables, which are the size of column, slab thickness, span between columns and the shapes of column which can affect the punching shear strength of the multi storey car park structure.

On completion of the simulation, it was found that four parameters which can affect the design factors are linked and interdependent on each other in order to cater for the suitable design configuration for a multi storey flat slab car park structure in terms of punching shear resistance.

7. References
[1] Robertson Ian 1997 Analysis of Flat Slab Structures Subjected to Combined Lateral and Gravity Loads, *ACI Structural Journal* 94 723-729
[2] Wood J G M 2003 Pipers Row Car Park Wolverhampton: Quantitative Study of the Causes of the Partial Collapse on 20th March 1997 *Brit. HSE, Final Report (March)* 114
[3] BS8110-1. 1997 Structural use of concrete — Part 1: Code of practice for design and construction (London: British Standard Institution) pp 168
[4] BS 1992-1-1 2002 Eurocode 2: Design of concrete structures Part 1-1: General rules and rules for building (London: British Standard Institution) pp 226
[5] Lim B T 1997 Punching Shear capacity of Flat Slab-column Junctions ( A study by 3-D Non-linear Finite Element Analysis) PhD Thesis (Glasgow: University of Glasgow) pp 514
[6] Waleed E E 2016 Review Article on Ductility of Reinforced Concrete Structures, *El-Mansoura University Publication, January*
[7] ACI Committee 318 2014 *Building code requirements for structural concrete (ACI 318-14) : an ACI standard : commentary on building code requirements for structural concrete (ACI 318R-14), an ACI report* ( Machigan, United State: American Concrete Institute) pp 524
[8] Akobo I, Georgewill V and Ngekpe B 2019 Punching Shear Failure of Reinforced Concrete Flat Slab System-A Review *Euro. J. Adv. Engg. Tech.* 6(2) 10-16
[9] Bartolac M, Damjanović D and Duvnjak I 2015 Proboj ravnih ploča s posmičnom armaturom i bez takve armature. *Gradjevinar,* 67(8) 771–786
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