PARAMETRIC STUDY ON THE EFFECTIVENESS OF A NOVEL FLAT TRUSS SHAPE PUNCHING SHEAR REINFORCEMENT USING FINITE ELEMENT MODEL

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By

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I hereby declare that all corrections and comments made by the supervisor(s)and examiner have been taken into consideration and rectified accordingly.

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ABSTRAK

Kajian ini bertujuan untuk mendapatkan pemahaman terhadap kelakuan model papak-tiang yang berkaitan dengan ubah bentuk dan tegasan tetulang keluli apabila dikenakan daya pada permukaan atas tiang tersebut. Tujuannya adalah untuk membuat simulasi kegagalan ricih tebukan papak rata di dalam bangunan dengan menggunakan perisian ANSYS *Static Structure* R14. Konteks kajian ini adalah untuk mencegah kegagalan ricih tebukan dengan menambah tetulang ricih tebukan baru berbentuk kekuda rata dan kesan mengubah bilangan segmen kekuda terhadap kelakuan ricih tebukan papak tersebut. Sebanyak lima model telah dibangunkan untuk kajian ini. Kerja menentusahkan model ANSYS (M_1) dengan dimensi papak 1050 mm x 1050 mm x 100 mm berbanding data ujikaji menunjukkan persamaan yang baik dan perbezaan peratusan telah dikira sebagai kurang dari 20%. Untuk tujuan meletakkan tetulang ricih tebukan berbentuk kekuda rata (FTSPSR), ketebalan papak telah ditingkatkan menjadi 150 mm (model M_2). Model papak-tiang dengan FTSPSR yang mempunyai empat segmen (model M_3) telah mengurangkan pesongan maksima sebanyak 6.02% berbanding model M_2. Selanjutnya, tegasan maksima tetulang pada beban kenaan maksima juga telah berkurangan sebanyak 2.81% berbanding model M_2. Adalah diperhatikan menggunakan lebih segmen kekuda pada FTSPSR meningkatkan kekakuan model. Fenomena ini adalah benar untuk model M_4 (lima segmen) dan M_5 (enam segmen) kerana pesongan maksima telah dikurangkan masing-masing sebanyak 5.33% dan 10.57% untuk model M_4 dan M_5 berbanding model M_3. Sementara itu, tegasan maksima tetulang juga berkurangan masing-masing sebanyak 8.19% dan seterusnya kepada 13.01% untuk model M_4 dan M_5 berbanding model M_3. Adalah dapat disimpulkan bahawa FTSPSR yang baru mempunyai potensi untuk digunakan di dalam pembinaan papak rata.

ABSTRACT

This research aims to gain understanding of the behaviour of a slab-column model in terms of deformation and stress in the steel reinforcement when subjected to force at the top column surface. The intention is to simulate the punching shear failure of a flat slab in a building using ANSYS Static Structure R14 software. The context of this study is the prevention of punching failure by addition of novel flat truss shaped punching shear reinforcement (FTSPSR) and the effect of varying the number of segments in a truss to the punching behaviour of the slab. A total of five models were constructed for this study. A validation work using ANSYS model (M_1) with slab dimension 1050 mm x 1050 mm x 100 mm against past experimental data exhibited good agreement and the overall percentage difference was calculated to be less than 20 %. In order to accommodate the FTSPSR, the thickness of the slab was increased to 150 mm (model M_2). The slab-column model having FTSPSR with four segments (model M_3) reduced the maximum deflection by approximately 6.02 % compared to model M_2. Moreover, the maximum rebar stress at highest applied load was 2.81 % lesser than that of M_2. It was also noted that incorporating more truss segment FTSPSR increased the stiffness of the model. This phenomenon is particularly true for model M_4 (five segments) and model M_5 (six segments) because the maximum deflection was reduced by 5.33 % and 10.57 % respectively for model M_4 and M_5 compared to model M_3. Meanwhile, the maximum rebar stress reduced by 8.19 % and further to 13.01 % for model M_4 and M_5 respectively when compared to model M_3. It can be concluded that the novel FTSPSR has the potential to be used in flat slab construction.

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LIST OF ABBREVIATIONS

FE	**F**inite **E**lement
FTSPSR	**F**lat **T**russ **S**haped **P**unching **S**hear **R**einforcement

NOMENCLATURES

E_{cm}	Elastic Modulus of Concrete
E_s	Elastic Modulus of Steel
f_{ck}	Concrete Compressive Cylinder Strength
$f_{ck,cube}$	Concrete Compressive Cube Strength
v_c	Poisson’s ratio of Concrete
v_s	Poisson’s ratio of Steel
γ_c	Density of Concrete
γ_s	Density of Steel
f_c	Concrete Stress
f_s	Steel Stress
ε_c	Concrete Strain
ε_s	Steel Strain
ε_o	Maximum Strain
f_{yk}	Yield Strength of Steel
f_t	Tensile Strength of Steel

CHAPTER 1

INTRODUCTION

1.1 Overview of Flat Plate Construction

Flat plate is a two-way reinforced concrete slab supported directly on column without the provision of beams and transfers the load directly to the columns. Engineers tend to use flat plate in many buildings due to its advantages over the conventional reinforced concrete slab. Transfer plate is a type of flat plate. A transfer plate is concrete slab used to transfer the floor loads from above to the column. It normally appears in between two floors with different functions such as carpark podium and residential floors. Table 1.1 shows the advantages and disadvantages of flab plate construction.

Table 1.1 Advantages and disadvantages of flat plate (Paul, 2014a)

Advantages	**Disadvantages**
Building height can be reduced	Higher slab thickness
Less construction time	Middle strip deflection is critical
Flexibility in room layout	Large span is not allowed

1.1.1 Punching Shear Failure of Flat Plate

Flat plate is prone to fail in punching shear. This failure occurs most commonly in the slab-column connection in a flat plate. It is a catastrophic failure that occurs when the column breaks through the portion of surrounding slab. When the load is distributed over the slab in real situation, the column reaction generated underneath pushes through the slab at relatively small surface area of the column cross section and induces cone-shaped perforation from the top surface of slab (Paul, 2014b). The reason is due to a smaller surface area that induced high pressure when a force is acting on it. Figure 1.1 illustrates the punching shear failure mechanism. Figure 1.2 shows the sketch of a transfer slab. The red circled parts of the figure indicate the points where punching shear failure occurs.

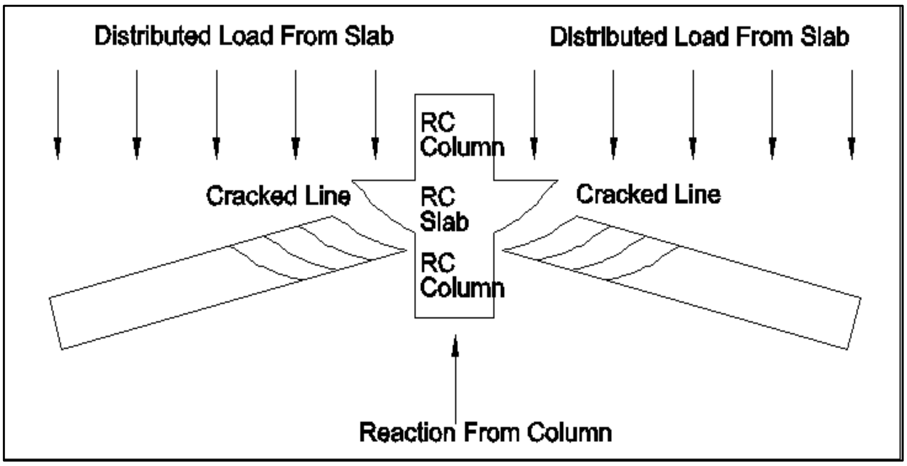


Figure 1.1 Punching shear failure mechanism at flat plate

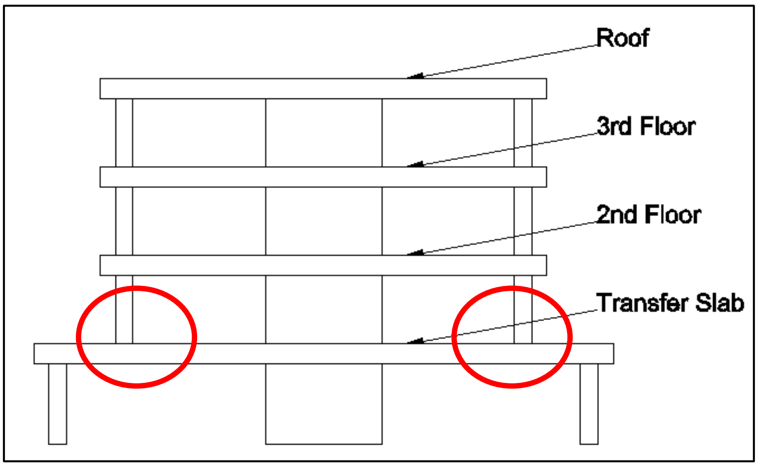


Figure 1.2 Punching of a transfer plate

On 20th March 1997, the Pipers Row Multi-Storey Car Park collapsed at midnight due to an impact of 120 tonne section from the top floor. Wood (1997) reported that the failure was due to initial punching shear failure at one of the columns and the failure progressively spread. This catastrophic spread happened due to the unbalance of the whole structure redistributing the force to other members who exceeded their own designed capacity. Figure 1.3 shows the punching shear failure happened at Pipers Row Car Park, Wolverhampton.

4th floor had
collapsed due
to punching

Figure 1.3 Collapse of Pipers Row Car Park, Wolverhampton (Wood, 1997)

Skyline Plaza apartment building in Virginia, U.S.A was another example of catastrophic collapse of a 30 storey reinforced concrete structure while under construction on 2nd March 1973. Leyendecker and Fattal (1977) reported that slab around few columns at 23rd floor experienced shear stress higher than the shear capacity of concrete slab and trigger the punching shear failure. The high shear stress developed in slab was due to the removal of shoring work underneath the slab. As a result, the adjacent columns on that storey were over-stressed leading to the whole 23rd floor falling onto the floor below. The increased weight on the 22nd floor due to collapsed load eventually led to a progressive collapse to the ground level. Figure 1.4 shows the view of failure zone of Skyline Plaza.

Figure 1.4 View of the failure zone of Skyline Plaza (Leyendecker and Fattal, 1977)

1.1.2 **Ways to Increase Punching Shear Capacity**

A precise calculation on the punching shear capacity is a major consideration in designing the flat slab. Engineers use several ways to resist the punching shear failure in flat plate. Several parameters such as the cost, practicality and effectiveness must be considered before the decision is made. Table 1.2 summarizes the disadvantages of three conventional ways in practice to increase the punching shear capacity which are the increment of the slab depth, provision of drop panel and increment of the reinforcement percentage. These three methods are applied by manipulating the respective design formulae embedded in the design code.

Table 1.2 Disadvantages of the conventional ways to increase punching shear capacity

Ways to Increase Punching Shear Capacity	**Disadvantages**
Increment of the slab depth/thickness	• Cost increases • Building weight increases
Provision of column head/drop panel	• Increase overall floor height • Complex construction
Increment of the reinforcement percentage	• Cost increases • Subjected to allowable maximum percentage

Besides, the incorporation of punching shear reinforcement in between the orthogonal reinforcement of the slab is another option to increase the punching shear capacity. Unlike the abovementioned conventional methods, the adoption of punching shear reinforcement will not tamper with the building-by-law requirement, design constraint, additional dead load and architecture perspective. Moreover, (Lips et al., 2012) reported that the provision of even a small amount of punching shear reinforcement significantly improves the punching shear capacity as well as the deformation behaviour of a slab.

1.2 Problem Statement

Flat plate or transfer plate structure is subjected to high punching shear stress. Although the punching shear failure of these structures is not common in the construction industry but if triggered, it co lead to catastrophic type failure. The current method to increase the punching shear capacity of these structures is by introducing a thick drop panel or incorporating additional punching shear reinforcements as shown in Figure 1.5.

(a) (b)

Figure 1.5 Enhancement of punching shear capacity in a flat plate using (a) drop panel (John, 2013) and (b) shearail (Punching shear reinforcement Shearail, n.d.)

Drop panel will either increase the floor to floor height or reduce the head room clearance of a building. The introduction of drop panel increases the difficulty in the construction work and is not aesthetically appealing. On the hand, introducing additional patented punching shear reinforcement can be costly. This study aims to numerically investigate the possibility of using a novel flat truss shape punching shear reinforcement (FTSPSR). FTSPSR can be assembled using ordinary reinforcement that can be easily found from the reinforcement bar waste at site as shown in Figure 1.6.

Figure 1.6 Reinforcement bar waste at construction site
(*Reinforcement bar waste collected*, 2015)

1.3 Objectives

The objectives of this research are as follows.

1. To determine the effectiveness of a novel flat truss shape punching shear reinforcement (FTSPSR) in enhancing the punching shear capacity of a slab-column structure.
2. To analyse the effect of varying the number of truss segments

The knowledge gained from this study serves as a platform for further research to improve the resistance of flat slab to punching with a novel method.

1.4 Scope of Work

The numerical analysis in this study will be conducted using ANSYS Static Structure R14 software package. This software can analyse the response of reinforced concrete structure subjected to static loading. Prior to the actual simulation incorporating various types of punching shear reinforcement, a validation exercise will be performed in order to ensure the correct usage of ANSYS Static Structure R14 commands and produce reliable results thereafter. In this case, only one suitable experimental data from a previous research work will be selected. The numerical analysis incorporating various types of punching shear reinforcements will be focusing on the measurement of deflection at the slab mid-span and axial stress in the reinforcement. The results will be discussed accordingly.

1.5 Dissertation Outline

This dissertation consists of five chapters and is organised as follows:

Chapter 1: Introduction

This chapter describes the background and objectives of this study. Besides, the scope of work of this study is briefly described.

Chapter 2: Literature Review

This chapter describes the reviews from the open literature relevant to the relationship between the current punching shear design methods and the slab-column structure behaviour in experimental work. In addition, the numerical analysis on the response of slab-column structure in previous research is also discussed.

Chapter 3: Methodology

This chapter describes the development of a slab-column structure by incorporating the material properties, dimensions, reinforcement and boundary condition to obtain outcome corresponding to the objectives. The procedure to derive the material properties is also discussed.

Chapter 4: Result and Discussion

This chapter presents the validation of previous research's outcome and the effect of the FTSPSR in term of deflection at the slab mid-span and steel axial stress using finite element analysis. It also includes a parametric study on the FTSPSR to investigate the change in slab central deflection and steel axial stress.

Chapter 5: Conclusion

This chapter summarizes the main findings and reviews of the objectives of the research before conclusions are drawn. Recommendations for future work are also presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Flat plates are common in floor construction especially in multi-story building. The ultimate capacity of flat plate is often determined by punching shear failure load which is generally smaller than flexural failure load (Theodorakopoulos and Swamy, 2002). Due to this fact, significant amount of research has been conducted on the punching shear failure analysis of concrete flat plate experimentally but few of them have been carried out using numerical analysis. The literature reviewed in this chapter is divided into three main groups which are the punching shear failure mechanism in flat plate, the use of various types of punching shear reinforcement in concrete slab and the numerical analysis on punching shear using software.

2.2 Punching Shear Failure Mechanism

When a load is applied to the slab which is monolithically connected to the column, the slab-column system implies a series of punching shear event thereafter. Theodorakopoulos and Swamy (2002) reported that a roughly circular crack around the column periphery on the tension surface of the slab is formed at first and the crack subsequently propagates into the compression zone of concrete. Following that, new lateral and diagonal flexural cracks are formed. Finally, inclined shear crack is observed near mid-depth of the slab at about 50-70 % of the ultimate load. The inclined shear crack develops towards the compressive zone and the tension steel. However, the propagation is hindered by the compression zone above the top of the crack near the column face and by the dowel action of the tension reinforcement. At this stage, the slab tension steel close to the column yields. Eventually, the punching shear failure occurs in the compression zone before yielding extends beyond the vicinity of the column. The failure in the compression zone occurs by splitting along the line AA' and BB' as shown in Figure 2.1.

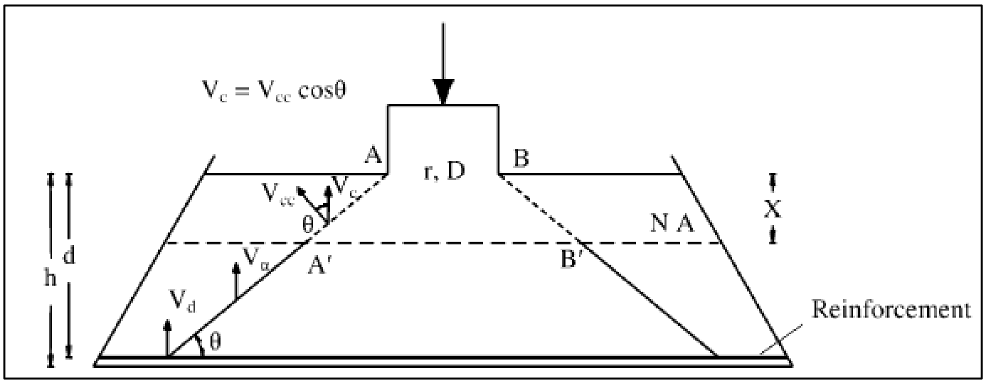


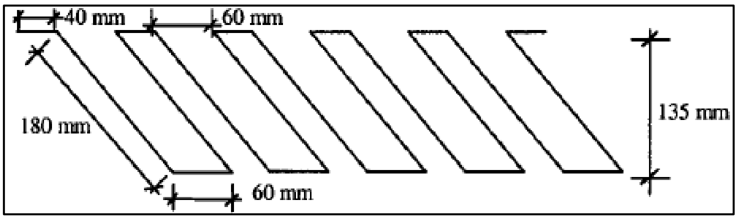
Figure 2.1 Punching shear mechanism (Theodorakopoulos and Swamy, 2002)

2.3 Types of Punching Shear Reinforcement

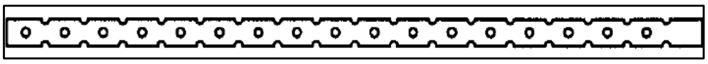
Lips et al. (2012) reported that even a small amount of punching shear reinforcement is capable in resisting punching shear reinforcement. Traditionally, punching shear reinforcement should be provided either at an angle or perpendicular to the main flexural reinforcement (Pilakoutas and Li, 2003). There are many types of patented punching shear reinforcement available in the market. This following sub-sections describe some of the punching shear reinforcements and their effectiveness in resisting punching shear failure.

2.3.1 Shearband Reinforcement

Pilakoutas and Li (2003) developed a new concept in shear reinforcement namely the shearband system which consisted of elongated thin steel strips punched with holes as shown in Figure 2.2.



(a)



(b)

Figure 2.2 (a) Shearband reinforcement and (b) Steel strip with punched hole (Pilakoutas and Li, 2003)

The authors aimed to validate the effectiveness of this patented shear reinforcement for reinforced concrete flat slab experimentally. Symmetric point loads were applied at eight locations on a circle of diameter 1.7 m as shown in Figure 2.3. The authors also reported that the shear reinforcement had little effect before the initiation of inclined shear crack. The shearband transferred much of the shear force across the shear crack and delayed the further widening of shear crack only after the development of inclined shear crack. Besides, the slabs reinforced with shearband exhibited ductile behaviour after achieving full flexural potential thereby proving the effectiveness of shearband. Hassan et al. (2017) reported that the ductility of flat slab increased by 79 % in the experiment conducted using shearband in enhancing the punching shear capacity.

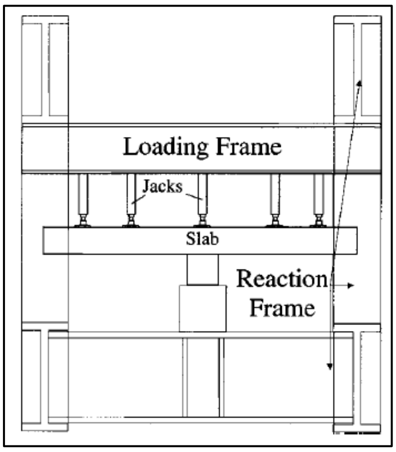


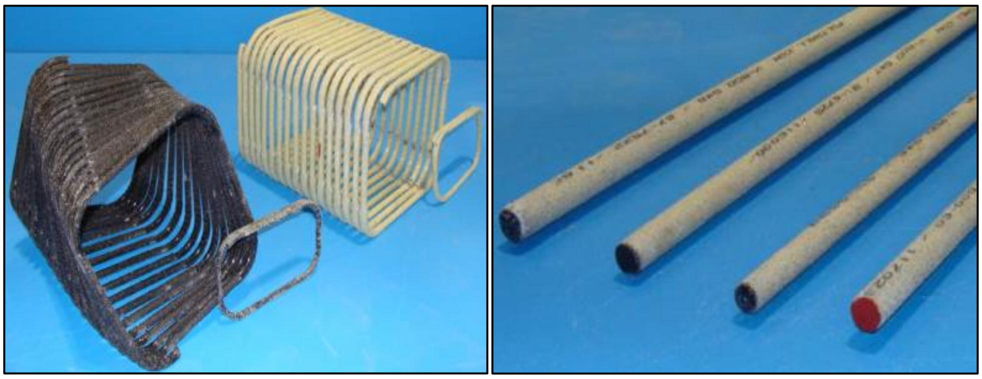
Figure 2.3 Schematic representation of test setup (Pilakoutas and Li, 2003)

According to the authors, the benefits of shearband were as follows.

- Can be applied in thin slabs and simple to place due to small thickness
- Preventing brittle punching shear failure
- Improving ductility of slab but not increasing the flexural capacity of slab. Hence, it does not cause brittle failure of slab.

2.3.2 **Fibre Reinforced Polymer (FRP) Reinforcement**

Mohamed et al. (2015) assessed the effectiveness of glass fibre reinforced polymer (GFRP) bars as flexural reinforcement and glass/carbon FRP stirrups as shear reinforcement as shown in Figure 2.4. The authors' idea was that FRP bars can effectively eradicate the problem of steel corrosion. The FRP bars can extend the service life of RC slab especially in parking garage thereby reducing maintenance cost.



(a) (b)

Figure 2.4 (a) glass/carbon FRP stirrup and (b) GFRP bar (right) (Mohamed et al., 2015)

The experimental setup is shown in Figure 2.5. Concentric loading was applied on the column stub from the bottom of the specimen. The specimens were held against the laboratory's rigid floor and simply supported along four edges by a rigid steel frame with 100 mm width that was supported by eight tie rods that were 38 mm in diameter.

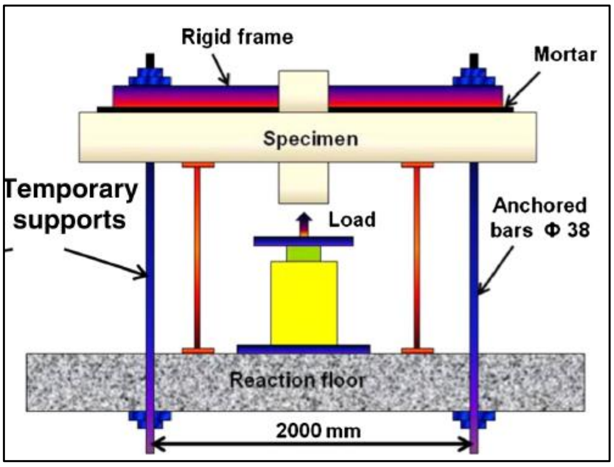
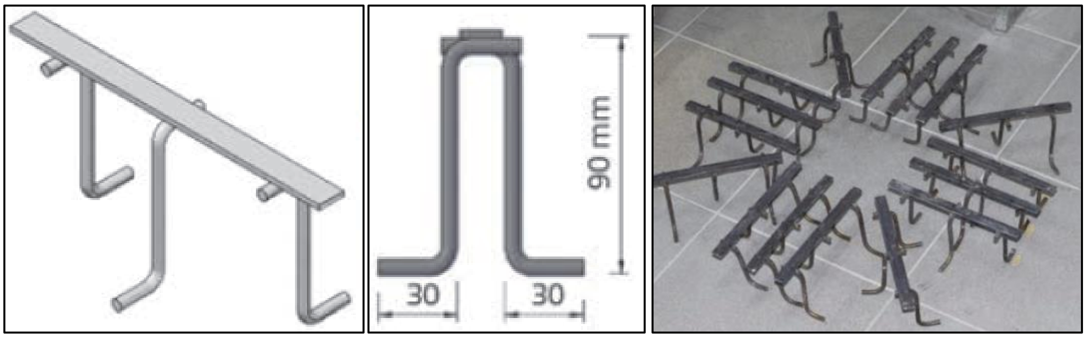


Figure 2.5 Schematic representation of test setup (Mohamed et al., 2015)

The test result revealed that FRP stirrups as shear reinforcement increased the punching shear capacity and deformation capacity of the test slabs. More shear cracks in the slab with shear reinforcement were observed rather than one single critical crack existing in slab proving the FRP stirrups functioned in preventing failure along the critical plane. The authors highlighted that the FRP stirrups transferred most of the forces across the shear cracks which could increase the punching shear capacity.

2.3.3 Z-Shaped Shear Reinforcement

Bartolac et al. (2015) investigated the performance of a z-shaped shear reinforcement systemin flat slab as shown in Figure 2.6 to resist punching shear. The system was believed to be the best alternative currently to simulate the headed shear studs which was patented material and costly. Besides, the authors also presented the design models using three different codes which were Eurocode 2, ACI code 318 and Fib Model Code 2010 and compared the predictions from the codes their own experimental results.



(a) (b) (c)

Figure 2.6 (a) Z-shaped shear reinforcement with its (b) dimension and (c) arrangement prior to installation (Bartolac et al., 2015)

The concrete slab was discretely positioned into a frame consisting of eight steel columns of circular cross section via spatially hinged supports. The column supports were placed at a radius of 75 cm from the slab centre. The load was applied continuously through a steel column at the centre of slab. Figure 2.7 shows the experimental setup of the author's model.

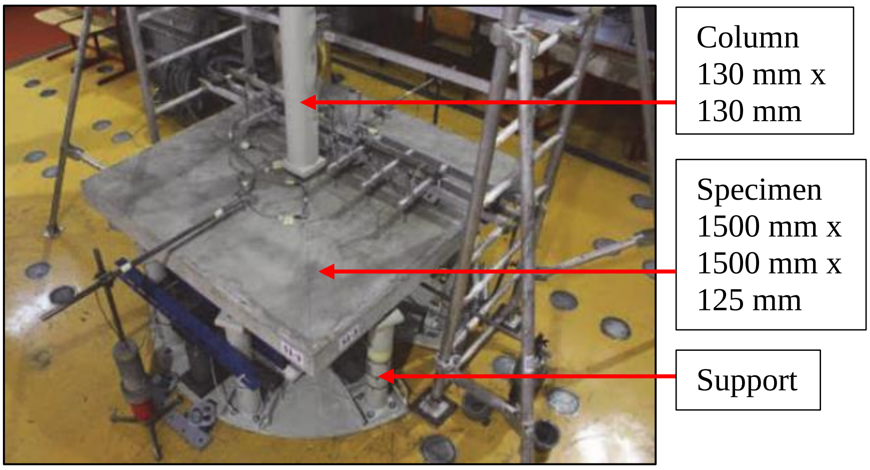


Figure 2.7 Punching shear experiment setup (Bartolac et al., 2015)

The authors reported that the slab strengthened with this kind of reinforcement exhibited punching shear force that was on average 17% greater than the slab without shear reinforcement. The deformation capacity of the slab also was increased by 36%.

The authors highlighted that all studied design models without shear reinforcement based on the three abovementioned codes underestimated the real carrying capacity of slab subjected to punching shear. Eurocode 2 predicted the punching shear force most accurately and closely to the experimental model among the three codes. However, the use of relatively low thickness slab resulted in increased punching force as the punching force results were highly sensitive to specimen size effect. Consequently, the result implied that the codes were conservative.

As to slab with shear reinforcement, it was found out that Eurocode 2 overestimated punching shear capacity. Fib Model Code 2010 showed the best correspondence with experimental result. On the other hand, ACI 318 again proved to be the most conservative in predicting punching shear capacity.

2.3.4 **Conventional Vertical Stirrups**

Mabrouk et al. (2017) studied the contribution of vertical stirrups on the punching behaviour of concrete flat slab. The parameters considered in the experiment were spacing between vertical stirrups, stirrups width and flexural reinforcement ratio. The authors also compared the experimental results against values estimated from international code E.C.P (203-2007) and ACI 318-14. The slab specimen was supported at the four corners using rigid plate which laid above roller support. The load was applied from the column top surface as shown in Figure 2.8.

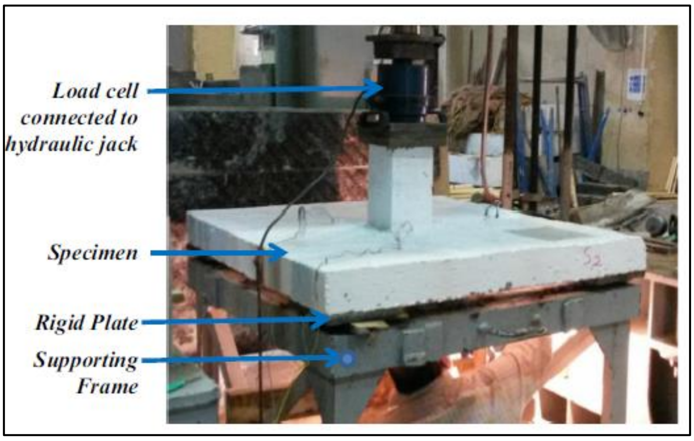


Figure 2.8 Punching shear experiment setup (Mabrouk et al., 2017)

The authors reported that adding vertical stirrups improved the punching shear capacity of the slabs by 23 % in case of 100 mm spacing and 36 % in case of 50 mm spacing. The result showed that smaller stirrups spacing led to a higher area of steel resisting the punching stress at the critical section. The close spacing between stirrups assisted in grabbing the potential shear cracks in the punching area. Besides, increasing the stirrup width also proved to increase the cracking load. The punching capacity increased by 6 % when the flexural reinforcement ratio increased by 20 % and higher subsequent increment ratio led to higher punching capacity increment. The punching capacity estimated from the codes were less than that resulted from experiment with E.C.P (203-2007), the Egyptian code being more conservative than ACI 318-14.

2.3.5 Other Types of Punching Shear Reinforcement

This section discusses on other types of punching shear reinforcement, apart from the conventional punching shear reinforcement as reported in the open literature.

2.3.5.1 U-Shaped Shear Reinforcement

Marzouk and Jiang (1997) discovered that U-shaped stirrups as shown in Figure 2.9 did not provide sufficient increment in ultimate loading capacity as they could not be properly anchored to the flexural reinforcement though they were advantageous during installation.

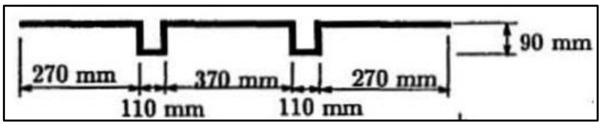
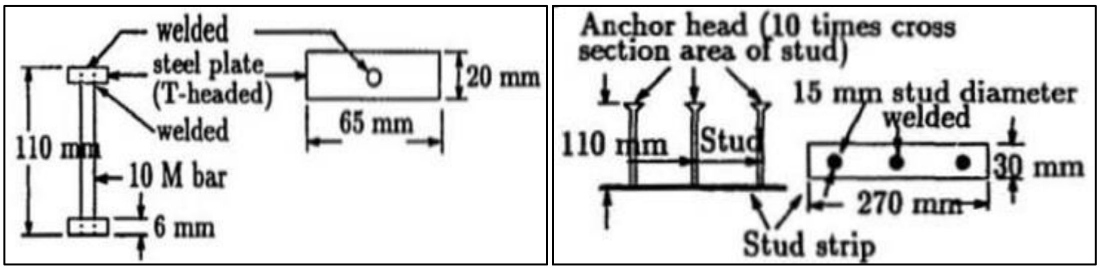


Figure 2.9 U-shaped stirrup (Jiang, 1994)

However, the authors suggested that punching shear failure could be controlled by T-headed shear reinforcement and shear stud as shown in Figure 2.10 (a) and (b) respectively.



(a) (b)

Figure 2.10 (a) T-shaped shear reinforcement and (b) shear stud reinforcement (Marzouk and Jiang, 1997)

2.3.5.2 Hat-Shaped Stirrup

Yamada et al. (1992) tested several types of shear reinforcement with regards to the punching shear capacity of monolithic slab-column structure and reported that hat-shaped stirrup (refer Figure 2.11) was not effective due to lack of anchorage and wide spacing. As the model was assumed to have perfect bond between concrete and steel, the possible anchorage problem was ignored according to the author.

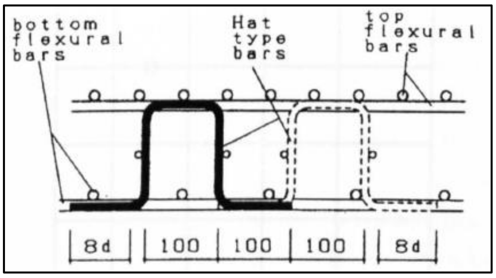


Figure 2.11 Hat-shaped shear reinforcement (Yamada et al., 1992)

2.3.5.3 Hook Type Shear Reinforcement

Yamada et al. (1992) also tested the hook type shear reinforcement and varied the spacing by placing it at every node of longitudinal reinforcement grid (interval=1) and at every second node (interval=2). These intervals indicated a difference in percentage of shear reinforcement. All the shear reinforcements were placed within 170 mm from the column. Figure 2.12 shows the hook bar at different intervals and its dimension.

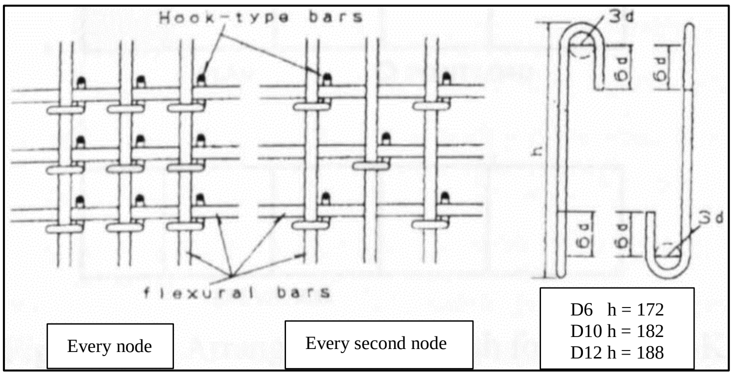


Figure 2.12 Hook bar at every node (left), every second node (middle) and its dimension (right) (Yamada et al., 1992)

A downward load was applied symmetrically at eight points distributed at a perimeter of 750 mm around the column centre. The numerical analysis showed that punching occurred outside the shear reinforcement region. The authors reported that a stronger concrete compressive strength and providing extra shear reinforcement within the perimeter of 170 mm from column would not have increased the failure load further as the failure load occurred outside the reinforced zone.

2.4 Numerical Analysis on Punching Shear Using ANSYS Software

ANSYS is a software that comes with two different variants which are ANSYS APDL (Ansys Parametric Design Language) and ANSYS Static Structure R14. ANSYS APDL uses scripting language to automate common task or to build a parametric model. On the other hand, ANSYS Static Structure R14 allows users to save time in performing simulation by linking with major external CAD tools efficiently. ANSYS Static Structure R14 has complete environment which is user-friendly on the geometry import, modifications, meshing, contact detection and general model setup (Thieffry, 2010). ANSYS Static Structure R14 analysis determines the displacement, stress, strains and forces in structures caused by loads that do not include inertia and damping effects. The structure response is assumed to vary slowly with steady loading with respect to time (ANSYS, 2009).

2.4.1 Element Type in ANSYS

There are many elements defined in ANSYS. An element is defined by a name consisting of group label and a unique identifying number. Those elements are selected to define a certain material for use in analysis. This section will discuss the element normally used for concrete and steel reinforcement.

2.4.1.1 SOLID 186 For Concrete

SOLID 186 as shown in Figure 2.13 is a higher order 3-D 20 node solid element that exhibits quadratic displacement behaviour. Each node has three degrees of freedom with translation in x, y and z direction. This element supports plasticity, hyper elasticity, creep, stress stiffening, large deflection and large strain capabilities. It can incorporate one concrete material property and rebar's up to three rebar materials. The rebars are assumed to be well distributed through the concrete element in a defined region of the FE mesh (*SOLID 186 Element Description*, n.d.).

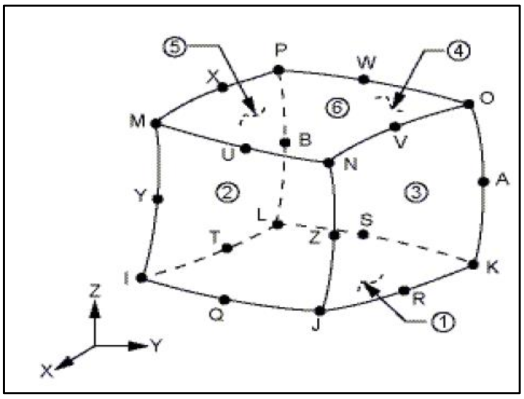


Figure 2.13 SOLID 186 for concrete (*SOLID 186 Element Description*, n.d.)

2.4.1.2 BEAM 188 For Steel Reinforcement

The element is a linear, quadratic, or cubic two-node beam element in 3D. BEAM 188 as shown in Figure 2.14 has six or seven degrees of freedom at each node with translations in x, y and z directions and rotations about x, y and z directions. The element includes stress stiffness terms which enable the elements to analyse flexural, lateral and torsion problem. A cross-section using this element can be a built-up section with more than one material (*BEAM 188 Element Description*, n.d.).

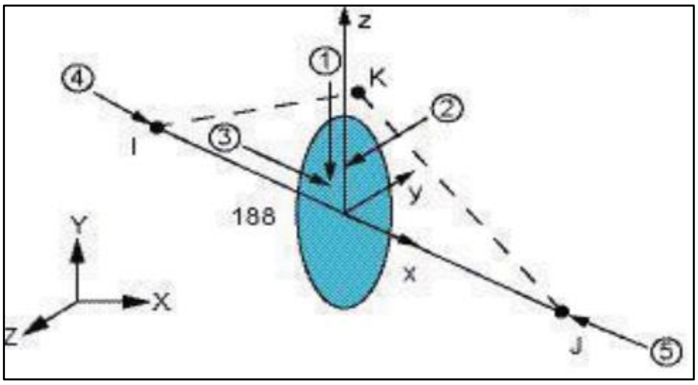


Figure 2.14 BEAM 188 for steel reinforcement (*BEAM 188 Element Description*, n.d.)

2.4.2 **Verification Against Experimental Data Using ANSYS APDL**

Mabrouk and Hegab (2017) studied the contribution of flexural reinforcement and vertical stirrups to punching behaviour of flat slab using ANSYS APDL 15.0. Before that, the authors verified the previous experimental results using ANSYS APDL 15.0 to test its reliability. It can be observed from Figure 2.15 that the authors meshed the slab and column specimen respectively into cubical elements of same size. The optimum size of meshing that would be used for analysis was determined using mesh convergence study. The point where the result started to converge to a value when the increment in the mesh density had negligible effect on the result would be the mesh size chosen.

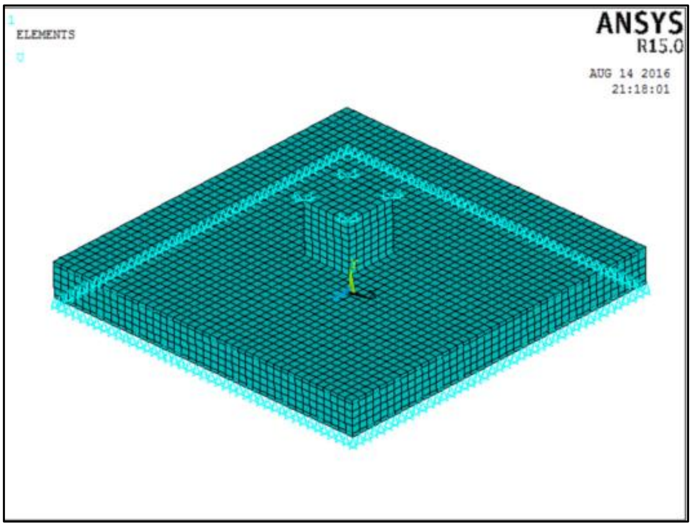


Figure 2.15 Meshing of ANSYS APDL model (Mabrouk and Hegab, 2017)

The percentage error between the experimental and FE data for ultimate load and its corresponding deflection did not exceed 10 % and 16 % respectively which the authors considered acceptable. The load-deflection curves were plotted for experimental and FE data as shown in Figure 2.16. A good correlation was observed between both experimental and FE data. Hence, the authors reported that ANSYS was reliable to study the punching behaviour of flat slab in more details which could not be monitored in laboratory.

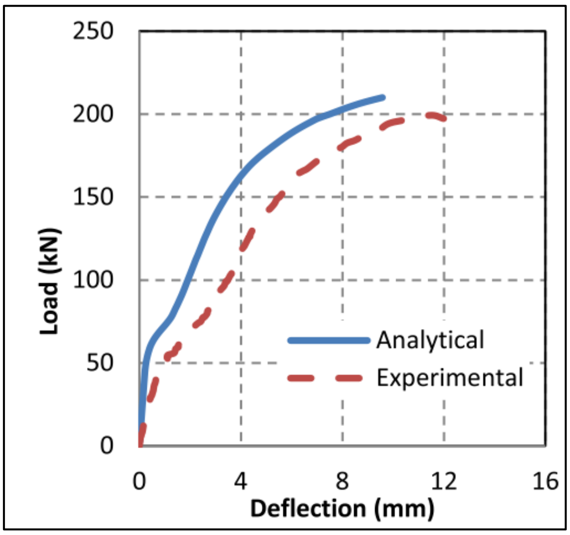
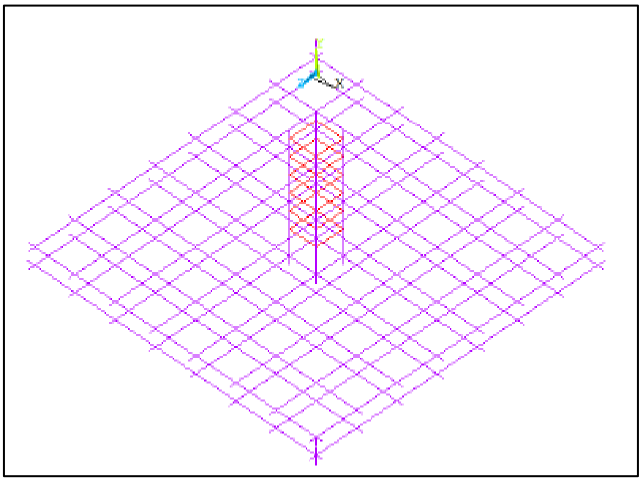
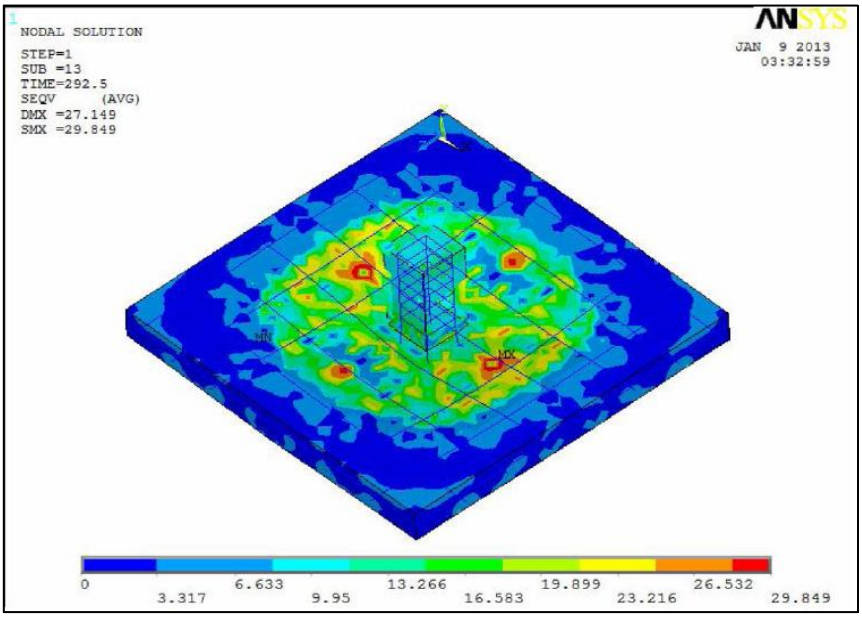


Figure 2.16 Load-deflection curve for experimental and FE data
(Mabrouk and Hegab, 2017)

Ragab (2013) studied the behaviour and punching shear capacity of flat plate produced from steel fibre reinforced self-compacting concrete by application of ANSYS APDL as well. The FE model was divided into small cubical elements and sharing nodes option was used in ANSYS to interconnect the concrete and steel reinforcement elements. Figure 2.17 (a) and (b) show the steel reinforcement and stress intensity of flat plate modelled from ANSYS APDL.



(a)



(b)

Figure 2.17 (a) Steel reinforcement in model and (b) 3D view for stress intensity of flat plate from ANSYS (Ragab, 2013)

The author verified the FE model using test results of experimental data before conducting a parametric study on the effect of flexural reinforcement ratio and upper reinforcement ratio. The bar chart in Figure 2.18 shows that the theoretical result from finite element analysis indicated a general good agreement with the experimental result. The author thus highlighted that models made with ANSYS finite element program gave reliable result and that the design errors at design stage or wrong material selection which could be made during experiment could be avoided.

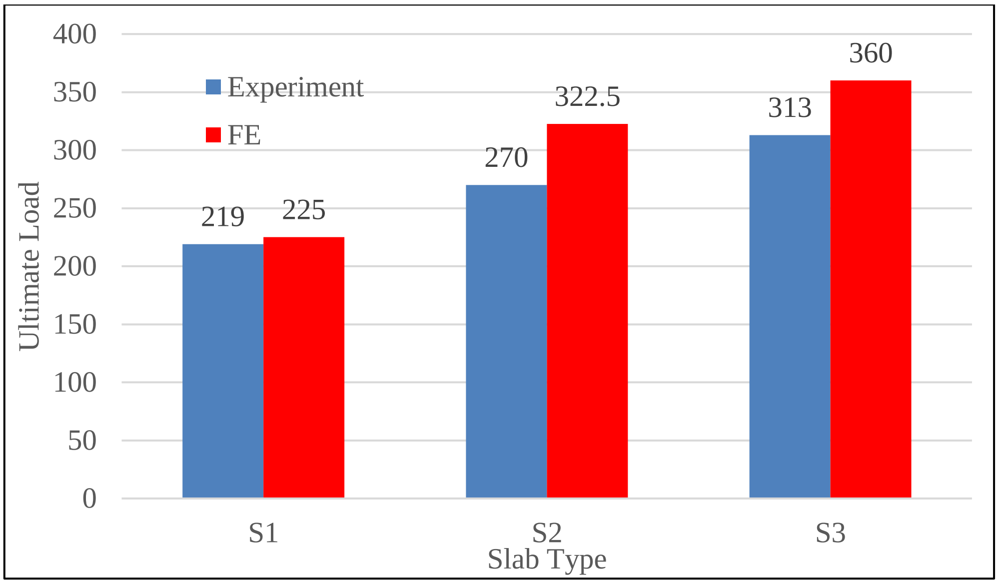


Figure 2.18 Comparison between FE and experimental result (Ragab, 2013)

Zhang (2004) studied the application of finite element method for numerical modelling of slab-column connection reinforced with glass fibre reinforced polymer (GFRP) using ANSYS APDL. The author constructed a quarter of the full-sized slab-column model in ANSYS as shown in Figure 2.19 for modelling to reduce computational time and computer disk space requirements. In the study, a total displacement was divided into several displacement steps and applied to the column stub for simulating the experimental process instead of using applied force. Sufficiently small displacement steps were required to determine particularly the change of behaviour of reinforced concrete connection. The author also highlighted that FE model represented by load-deflection plot at slab centre showed good agreement with test data, but the FE model was slightly stiffer than the test model.

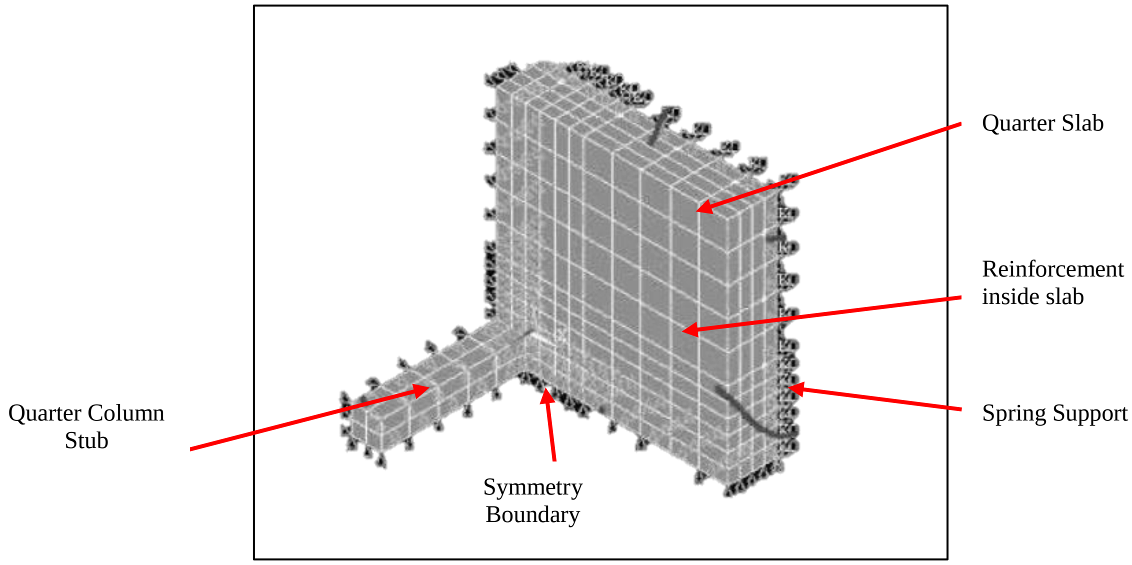


Figure 2.19 ANSYS numerical quarter model representation of experimental specimen (Zhang, 2004)

2.4.3 **Verification Against Experimental Data Using ANSYS Static Structure R14**

Figure 2.20 (a) and (b) show the results from ANSYS Static Structure R14 FE model for a full-sized beam. A comparison of deflection at slab mid-span was made between the FE result and the experimental data (*Finite Element Analysis*, n.d.). The author reported that the specimen modelled with ANSYS Static Structure R14 showed higher values of ultimate load and deflection (about 5 % increment) when compared to experimental result. In other words, it could mean that the ANSYS model was stiffer than the experimental model. However, the general behaviour of the FE model represented by load-deflection plot at mid-span showed good agreement with the test data from full-scale beam test.