ANALYSIS OF THE STAGGERED CROSSBEAM OF PIER DESIGNED BASED ON DEEP BEAM DESIGN CONCEPT

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SCHOOL OF CIVIL ENGINEERING
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by

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ABSTRAK

Konsep rasuk dalam mempunyai kelakuan pindahan beban yang berbeza dengan konsep rasuk lazim. Rasuk dalam menghasilkan zon ketegangan pepenjuru yang melanjutkan dari titik bebanan ke titik sokongan, dan menyebabkan retak ricih dan menyebabkan keruntuhan struktur. Alang berperingkat pada tiang jambatan dalam sebuah projek yang sudah siap telah terjadi retak ricih yang dalam kerana kurangnya pertimbangan tentang konsep rasuk pada peringkat reka bentuk. Hal ini mengakibatkan kerja perbaikan yang rumit perlu dijalankan untuk menyelesaikan masalah ini. Oleh itu, kajian ini memfokuskan analisis pada alang berperingkat yang direka berdasarkan falsafah reka bentuk yang mapan. Dalam kajian ini, dua alang berperingkat dengan dimensi yang serupa direka berdasarkan kaedah topang dan pengikat (strut and tie method) dan konsep rasuk lazim masing-masing. Hasil menunjukkan bahawa pengukuhan yang diberikan oleh kaedah opang dan pengikat lebih banak daripada yang diberikan oleh konsep rasuk lazim. Selain itu, analisis unsur terhingga dilakukan pada alang berperingkat yang berbeza ketinggian alang untuk menilai kelakuan konkrit tetulang dan kecukupan bar tetulang yang disediakan ketika dikenakan beban tertumpu. Model dibahagikan kepada lima kategori dengan ketinggian palang kanan yang berbeza dan disediakan enam set kumpulan tetulang untuk setiap model. Model dianalisis dengan perisian analisis unsur terhingga ABAQUS. Parameter seperti tegasan mampat maksimum, tegasan tegangan maksimum dan corak agihan tegasan model difokuskan dalam kajian ini. Hasil analisis menunjukkan bahawa kecukupan pengukuhan untuk alang berperingkat pada tiang jambatan berkurang apabila perbezaan ketinggian palang meningkat. Kecukupan pengukuhan untuk alang berperingkat diperoleh berdasarkan model dengan mempunyai zon ketegangan yang paling sedikit dalam corak agihan tegasan.

ABSTRACT

The deep beam concept has different load transferring behaviour from the simple beam concept. Deep beam develops diagonal tension zone extends from loading point to support point, causing the shear cracking and leading to failure of the structure. The staggered crossbeam in the pier in an existing completed project had occurred the deep shear cracking due to lack of consideration of deep beam concept during the design stage, resulting in the heavy and complicated remedial works. Therefore, this study focuses on analysing the staggered crossbeam of pier designed based on established design philosophy. In this study, two staggered crossbeams of the pier with similar geometrical dimensions were designed based on the STM and simple beam concept, respectively. The reinforcements provided by these two methods were compared and evaluated. The result showed that the reinforcement provided by the STM is more than that designed based on simple beam concept. Moreover, the finite element analysis was conducted for staggered crossbeam pier with varied crossbeam elevation differences to assess the behaviour of reinforced concrete and the adequacy of reinforcement provided when subjected to concentrated vertical loads. The models were divided into five categories with a different elevation of right crossbeam and provided six reinforcement groups for each model. The models were analysed with ABAQUS finite element analysis software. The analysis result indicated that the adequacy of reinforcement for staggered crossbeam of the pier is reduced when the variation of crossbeam elevation increases. The adequacy of reinforcement for the staggered crossbeam of the pier was obtained based on the model with the least tension zone in the stress distribution pattern.

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
CIRIA	The Construction Industry Research and Information Association
EC	Eurocode
FEM	Finite Element Model
RC	Reinforced Concrete
STM	Strut and Tie Method

LIST OF SYMBOLS

A_s	The required area of reinforcement
$A_{s,req}$	The required area of reinforcement
A_{sw}	The required area of reinforcement
b	Overall width of the cross-section of crossbeam or column
b_w	Width of the cross-section of the crossbeam
c	Concrete cover
d	The effective depth of the crossbeam
DF	Distribution factor
e	Eccentricity
f_{ck}	Characteristic strength of RC
f_{yk}	Characteristic strength of steel reinforcement
h	Overall depth of cross-section of column
i	Radius of gyration
I_b	Moment of inertia of crossbeam
I_c	Moment of inertia of column
K	Relative column stiffness
k_b	Stiffness of column
k_c	Stiffness of crossbeam
L_b	Length of crossbeam
L_c	Length of column
l	Span of crossbeam
l_o	The effective length of the column
M_{Ed}	Designed bending moment of the crossbeam
M_{max}	Maximum designed bending moment of the crossbeam

s	Spacing of reinforcement
s_{cl}	Spacing of link
s_{min}	Minimum spacing of reinforcement
V_{Ed}	The designed shear force of the crossbeam
V_{max}	The maximum designed shear force of the crossbeam
$V_{Rd,max}$	The maximum designed shear resistance of the crossbeam
z	The inner lever arm of the crossbeam
σ_{Ed}	Designed strength of the strut
$\sigma_{Rd,max}$	Maximum allowable strength of the strut
θ	The angle between compression strut and beam axis perpendicular to shear force
ρ	Required tension reinforcement ratio
ρ_o	Reference reinforcement ratio
ρ'	Required compression reinforcement ratio
ϕ_{bar}	Reinforcement diameter

CHAPTER 1

INTRODUCTION

1.1 Background

A reinforced concrete beam is the structural element that withstands the loads laterally to its axis. It can be classified into a simple beam and a deep beam. A deep beam is a structural component having a span that is less than three times the depth of its overall section (CEN, 2004). Usually, a simple beam has support at each end while the middle section is suspended, which having a span that is more than three times the depth of its overall section.

Hammerhead pier or tee type pier is a typical pier shape for bridges constructed in urban areas. It consists of a single solid concrete portion as the column with a concrete crossbeam on top. The crossbeam that supports the bridge deck forms a cantilever shape to the column. It will exhibit a moment to the bridge pier or column that will resist at the crossbeam-column area. When the moment and tension exceed the column's resistance, the cracks will occur, which may lead to the bridge pier's critical failure. In most bridge piers, a weak connection between the crossbeams and the column causes the cracking at joint, leading to the failure due to the loss of integrity of the concrete structure. Therefore, the bridge pier's reinforcement shall be adequate to resist the moment and tension at the crossbeam. Figure 1.1 shows a sample of hammerhead bridge pier. Figure 1.2 shows the components of a typical hammerhead pier.

Figure 1.1: Hammerhead Bridge Pier (United Forms Corporation)

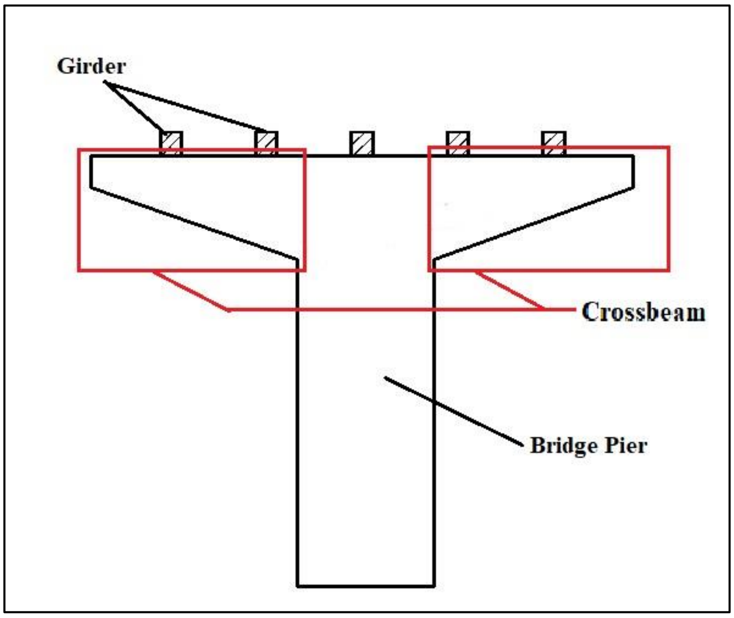

Figure 1.2: Component of the Hammerhead Bridge Pier

However, due to specific requirements, a staggering crossbeam pier may support the bridge decks in different elevations. For the staggered crossbeam pier, the rebar required in moment resistance and stress resistance is different from that of the hammerhead bridge pier. It is because of the presence of varying crossbeam elevation, causing changes of moment. Thus, the design of the rebar arrangement should be different in the staggered crossbeam pier. Therefore, the effect of implementing the rebar arrangement in the tee type pier to the staggered crossbeam pier needs to be studied to understand their relationship and find out the solution to mitigate this defect. Figure 1.3 shows a staggered crossbeam bridge pier.

Figure 1.3: Staggered Crossbeam Bridge Pier

According to Najafgholipour and Arabi (2021), the transverse reinforcement at the joint panel at the beam to the column cannot significantly enhance the strength against joint shear failure. Therefore, the other reinforcement arrangement, such as longitudinal reinforcement, should be provided in the crossbeam-column area. The implementation of shear reinforcement can enhance the joint shear strength at the crossbeam-column area (Kadarningsih et al., 2014). However, a minimum and adequate transverse reinforcement is also required to avoid joint shear failure in the structure (Niroomandi et al., 2014).

The established design philosophy in this project refers to the simple beam concept and the deep beam concept. The simple beam design and deep beam design can be referred to EC 2: Design of concrete structures (CEN, 2004). The deep beam design is different from simple beam design as it has different considerations to the assumption of the structure's condition. The STM is one of the design methods for deep beams. The presence of numerical girders loaded above the crossbeam form numerical concentrated loads along the span. The amount of reinforcement can be different when considering the crossbeam span act as a simple beam or deep beam. The transmission of the loading across the deep beam concrete span is different from that in the simple beam concept. The shear cracking will happen diagonally from the point of load to the support in a deep beam.

1.2 Problem Statement

For one case of staggered crossbeam bridge pier that happened in Malaysia, a project is hereby referred to as Project A in this final year project due to private and confidential concerns. Project A had constructed a staggering crossbeam pier. The staggered crossbeam pier had a deep cracking problem at the diagonal of the beam-column joints. According to the result of inspection and forensic, the major reason that causing the deep cracking at the bridge pier was the inadequate tension reinforcement. The staggered crossbeam in Project A was designed based on the simple beam concept. However, in the mechanism of load transfer in deep beam, the span is considered as the distance of the point of load to the support for cantilever structure. The span of the crossbeam is less than 3 times the overall section depth. The misinterpretation of the clause to classify the elements of a beam structure was causing the wrong decision in designing the staggered crossbeam bridge pier using a simple beam concept rather than a deep beam concept. As result, the deep crack formed in the pier designed with simple beam concept. Therefore, this project focuses on the evaluation of different in reinforcement designed based on deep beam concept and simple beam concept. Furthermore, the focus of study extends to the adequacy of reinforcement in crossbeam bridge pier when the crossbeam has different crossbeam elevation. Figures 1.4 and 1.5

show the picture of the staggering crossbeam pier mentioned above, which has a deep cracking problem. Due to private and confidential issues, the background of the photo is blurred to avoid the disclosure of further information about the project.

Figure 1.4: Staggered Crossbeam Pier with Cracking Problem (Red circle mark the cracking position)

Figure 1.5: Staggered Crossbeam Pier with Cracking Problem (View from Middle Bridge Deck)

Regarding the problem stated above, extended learning is required to differentiate the staggered crossbeam in pier designed based on strut and tie method and normal beam method to understand the amount of reinforcement proposed under both conditions. Moreover, a comparison between the design methods for staggered crossbeams is required to justify the performance of the RC structures. The adequacy of reinforcement to the staggered crossbeam in various elevation need to be investigated in this project.

1.3 Objectives of Study

The objectives of the project on analysis of staggered crossbeam of pier designed based on deep beam design concept are as follows:

1. To evaluate the reinforcement of staggered crossbeam pier designed based on normal beam method (simple beam concept) and strut and tie method (deep beam concept).

2. To evaluate the adequacy of rebar of the staggered crossbeam in the pier with different crossbeam elevations designed based on strut and tie method.

1.4 Scope of Work

The scope of this study is to mitigate the possible cracking and potential failure of the staggered crossbeam in piers due to the lack of reinforcement when designed based on the simple beam method and deep beam method. A fixed uniformly distributed vertical load is applied to the staggered crossbeam in piers with similar reinforcement arrangements but different crossbeam elevations throughout the work. A modified amount of reinforcement is used in the modelling to simulate the adequacy of reinforcement in the staggered crossbeam of piers.

This research focuses on the distribution of stresses along the crossbeam at the staggered crossbeam pier. The pattern of distribution of the tension forces across the joint panel is reflecting the weak point of the flexural component where the cracking of structures due to shear failure is likely to occur. The relationship of the ultimate flexural strength and the stresses indicate the tensile strength and flexural capacity of the staggered crossbeam pier provided by its reinforcement. Thus, the adequacy of the rebar of the staggered crossbeam pier can be justified.

1.5 Dissertation Outline

In this final project report, the contents are divided into five chapters. Chapter 1 is the introduction to the topic in this project. The content includes the background of the study, problem statements, objectives of the project, and scope of work. Chapter 2 is the literature review of previous research that comprises the summary of the previous researches according to the related subject and the overall outline. Chapter 3 is the methodology of this project. The content describes the method to be used in this project and the detailed step for the operation. Chapter 4 presents the analysis of the research outcome and findings of the research. Chapter 5 is the conclusion and recommendation for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The staggered crossbeam of the pier consists of column member, crossbeam member, beam-column joint panel, longitudinal reinforcement and transverse reinforcement. Thus, the previous research that covers the stated areas are chosen as the references for this project.

2.2 Review of the Design of the Deep Beam Based on Different Codes

The deep beam design and simple beam design can be referred to the established design codes or guidelines, such as Eurocode, ACI code and CIRIA guide.

2.2.1 Eurocode 2

According to Section 9.7 Clause (1) in EN 1992-1-1:2004, a deep beam should normally be provided with an orthogonal reinforcement mesh near each face, with a minimum of $A_{s,dbmin}$. According to Section 9.7 Clause (2) in EN 1992-1-1:2004, the distance between two adjacent bars of the mesh should not exceed the lesser of twice the deep beam thickness or 300 mm. According to Section 9.7 Clause (3) in EN 1992-1-1:2004, the reinforcement should be fully anchored for equilibrium in the node by bending the bars, by using U-hoops or by anchorage devices, unless a sufficient length is available between the node and the end of the beam permitting an anchorage length of l_{bd} (CEN, 2004).

2.2.2 CIRIA Guide 2

According to CIRIA Guide 2 – The Design of Deep Beams in Reinforced Concrete (CIRIA, 1977), the design of reinforced concrete deep beams over two or more supports using this guideline should satisfy the following conditions:

1. The beam is a flat plate.
2. Holes in the beam are not such as to interfere with the stress pattern significantly.
3. There is no appreciable different movement of supports under load.
4. There are no concentrated loads.
5. There are no indirect loads or supports.

CIRIA Guide 2 includes the supplementary rules for the analysis of deep beams and the detailed procedures on the design and analysis of the behaviour of designed deep beams, such as elastic analysis, flexural failure, shear capacity, bearing failure, deformation, deflection, and reinforcement.

2.2.3 ACI Codes

According to ACI 318-08 (ACI, 1985), a deep beam is the member loaded on one face and supported on the opposite face so that a compression strut can develop between the loads and the supports. A deep beam should have either a clear span equal to or less than four times the overall member depth or regions with concentrated loads within twice the member depth from the face of the support. The deep beam design in

ACI 318-08 is focusing on the strut and tie method. A minimum flexural tension reinforcement and shear reinforcement is provided in the design.

2.2.4 Conclusion of Different Code and Guides on Deep Beam Design

Eurocode 2, CIRIA Guide 2 and ACI Code are introduced design method of deep beams. However, these three codes and guides have their own different preconditions for the structure and condition of deep beams. The deep beam considered in CIRIA Guide 2 must be a flat plat with no concentrated load had limiting the design for other types and conditions of deep beam. ACI codes and Eurocode 2 have different definition of deep beam in the span-depth ratio. Therefore, their design methods are different, and they are not suitable for interspersed use.

2.3 Review of the Parameters Considered in Both Design Approaches

In this project, the tensile stress and compressive stress are the main parameters to be evaluated in the designed crossbeam bridge piers.

2.3.1 Tensile Stress

Tensile stress is the quantitative parameter to the behaviour of structures under stretching or tensile forces. The behaviour of a structure under tension is known as tensile. This tensile force act along the axis of force, causing the structure to stretch. Generally, tensile stress is defined as the magnitude of force applied along an elastic material divided by its cross-sectional area in a direction of perpendicular to the force (Byju’s Classes, n.d.b). The elastic modulus of the material can affect the capability of the material to withstand tensile stress. A ductile material such as steel bar can withstand the high tensile stress, while a brittle material such as concrete fails easily when subjected to the high tensile stress.

2.3.2 Compressive Stress

Compressive stress is the force that causes a material to deform, which lead to the reduction in the volume of the material. Generally, compressive stress is defined as the magnitude of force applied along a material divided by its cross-sectional area in a direction parallel to the force (Byju’s Classes, n.d.a). When compressive stress is applied to brittle materials, the stored energy is suddenly released, causing the materials to break. When compressive stress is applied to ductile materials, they compress but do not fail.

2.4 Previous Researches

The design philosophies involved in this research is the concept of the deep beam and simple beam. A deep beam possesses different characteristics as compared to a simple beam. This is because the geometrical dimension of the deep beam eases the development of non-linear strain distribution, causing significant shear deformation in the deep beam (Jamal, 2017). Therefore, the deep beam design usually uses the strut and tie method (STM) to cater for the shear deformation in the beam. The related studies on the deep beam are presented in Section 2.4.1.

A staggered crossbeam pier consists of two beams-column joint panels. According to the problem statements, the cracks appear at the diagonal of the joint and extend to the column. As general knowledge, the joint panel of the beam to the column is the most crucial part of the whole superstructure because the transmission of load through the different components of beam and column resulting in a great shear and inelastic deformation (Hao et al., 2019). Reinforcement across the joint panel certainly has an important stabilizing effect on the structure. The related studies on the beam-column connection are described in Section 2.4.2.

A concrete possesses high compressive strength because of the high adhesiveness attributed to its constituents such as the aggregates and cement (Ashish, 2019). However, the tensile strength of concrete is considered weak due to the easy formation of micro cracking between its particles within the concrete structure when it is subjected to the tensile force (Ashish, 2019). The crossbeam of the concrete structure is easy to crack since it subjected to bending action which involves both tensile and compressive stresses at the same time (Prasad, 2021). The reinforcement embedded in concrete provides tensile strength and flexural enhancement to the entire structure including the beam-column joints in staggered crossbeam pier. The related studies on the steel reinforcement in concrete columns are presented in Section 2.4.3.

The structural behaviour of an reinforced concrete (RC) structure is essential to safety and durability. However, few parameters such as the bonding of reinforcement to concrete, the distribution of stress in concrete and steel reinforcement, the flexural capacity, and ductility are studied in previous researches. These parameters need to be studied in the research to propose a good structure behaviour of staggered crossbeam pier. The related studies on the structural behaviour of reinforced concrete are discussed in Section 2.4.4.

A finite element software named ABAQUS was used to carry out a finite element simulation for the staggered crossbeam pier under the load for this research. Therefore, the application of the finite element software in the research and the validation of the finite element analyses results are required to be reviewed. Due to the uncertainties associated with the modelling based on computer programs to the real condition, the validation or verification of the finite element analyses results is of considerable importance. The related studies using ABAQUS finite element software are summarized in Section 2.4.5.

2.4.1 Related Studies on Deep Beam

de Mello and de Souza (2016) had studied the deep beam design approach using the stringer-panel method. A stringer-panel method is an alternative approach to the deep beam design instead of the STM and finite element model (FEM) design. According to the explanation in this research, the stringer-panel design caters to shear deformation by separating the beam into two elements where the stringers absorb the normal forces while the panels absorb the shear forces. Through the comparison on the deep beam designed and the analysed results on its behaviours based on a manual calculation of stringer-panel method and STM with the validation of the result using non-linear analysis software that is SPanCAD and ATENA 2D, the researchers concluded the suitability of stringer-panel method as an alternative to design deep beam. Other than that, the researchers had mentioned that the STM produces a more concentrated reinforcement in the considered ties while the stringer-panel method produces a more distributed reinforcement in considered panels.

Hussein et al. (2018) had studied the effect of loading and the supporting area on the shear behaviour and size effect of the concrete deep beam. In this research, the experiment was done on nine specimens of the concrete deep beam to investigate the concrete behaviour under the variation in beam height and loading and supporting plate length. The crack pattern, deflection response by loading, cracking, and ultimate strength are the main observations in the experiment. Based on the observation, the crack pattern is the diagonal shape with that the width of shear crack increases and elongates toward the loading and supporting area when the loading is raised. The ultimate shear stress can be greatly increased and the size effect reduced by maintaining a ratio of 0.2 between the length of the loading and supporting plates and the total beam depth. Based on the failure pattern observation, the researchers concluded that the loading and supporting plate dimension could affect deep beams' failure behaviour, such as avoiding the web compression that forms a very brittle behaviour to the deep beam and transforming it to diagonal tension that is too less brittle.

Wu et al. (2018) had studied the shear models for the concrete deep beam. This research focus on a concrete deep beam made up of lightweight aggregate only. The concrete deep beams with various effective span to depth ratios and shear span to effective depth ratios were tested experimentally under concentrated loading until failure. Based on the results, the deep beam forms more flexure failure when the effective span to depth ratio increases, but the deep beam's brittleness after the diagonal shear cracking happened raises when the effective span to depth ratio decreases. The experiment on the concrete deep beam with increasing effective span to depth ratio and shear span to effective depth ratio shows the reduction of strength provided from the concrete strut and the longitudinal reinforcement, whereas the increase of stresses in vertical web reinforcement had become more significant. Therefore, the vertical reinforcement becomes the main contribution of shear strength to avoid cracking for the deep beam when the effective span to depth ratio and shear span to effective depth ratio of the deep beam is high.

Chen et al. (2019) had studied the optimal strut and tie model for irregular concrete deep beams. In this research, two irregular concrete deep beams were designed based on the different strut and tie model, followed by casting and experimentally testing in the laboratory. The irregular concrete deep beam was tested under stepped loading. The amount of reinforcement, the load-carrying capacity and the failure pattern of the deep beams were being focused on. Based on the results, the researchers concluded the optimum typology of strut and tie model for each irregular deep beam where the least but effective amount of steel reinforcement contributes the highest load-carrying capacity. In addition, the experiment affirmed the importance of the typology of the reinforcement in strut and tie model to the mechanical performance of the deep beam.

Santos et al. (2019) had studied the RC deep beam behaviour for a different design of strut and tie model and in-plane stress field method. The strut and tie model in this research formed a concentrated arrangement of reinforcement within the sizing zones of the deep beam, while the in-plane stress field model formed continuously distributed reinforcements along the entire deep beam. In this research, the researchers used the non-linear finite element analysis to investigate the cracking pattern and strain energy developed in the different models of the deep beam under ultimate conditions. The results showed that the higher amount of distributed reinforcement in the deep beam contributes to lower strain energy in the RC deep beam. Furthermore, from the analyses on the crack pattern in these models, the researchers concluded that both models have contributed to reducing cracking propagation, where the strut and tie model focuses the reinforcement in the direction of maximum tensile stress. In contrast, the in-plane stress field model adheres to a uniformly distributed reinforcement.

Ghali et al. (2021) had studied the shear behaviour in the T-shaped RC deep beam with openings. In this research, the investigation is focusing on the effect of the variation of flange dimension, concrete strength, stirrup, and shear span to depth ratio to the deep beam. Based on the investigation, the shear capacity and stiffness of the deep beams were increased by increasing the flange depth, while the flange width had only a minimal influence on the deep beam's shear capacity and stiffness. Furthermore, the shear capacity of deep beams was increased by reducing the shear span-to-depth ratio at the same location of openings. The behaviour of deep beams is significantly affected by lowering the shear span to depth ratio by 41.7 per cent. In addition, the initial cracking load and ultimate shear capacity of the RC deep beam were improved by increasing the concrete compressive strength. As a result, the use of high-strength concrete can improve the behaviour of deep beams significantly.

2.4.2 Related Studies on Beam-Column Connection

Kadarningsih et al. (2014) had investigated the application of the King-cross steel profile at the beam-column connection parts to strengthen the seismic capacity of RC structures. The study focused on investigating the joint shear strength developed by transverse reinforcement designed based on established design philosophy and after replacing it with the King-cross steel profile at the joint section. High ductility and shear strength are essential for inelastic capacity development in the beam-column joint that will help resist the earthquake effects by dissipating the seismic energy. However, this study demonstrated that ordinary transverse reinforcement's joint shear strength and ductility in large beam-column structures is insufficient to resist the seismic loads. Thus, the researchers attempted to implement the diagonal cross bracing bars to a specific beam-column joint design in a moment-resisting frame with a King-cross steel profile. The results showed that their proposed King-cross steel profile could enhance the seismic strength by the increased joint shear strength, stiffness and ductility in beam-column joint.

Niroomandi et al. (2014) had investigated the beam-column joint without transverse reinforcement at the joint panel. The beam-column joint without transverse reinforcement is considered a non-ductile structure due to inadequate amounts of steel reinforcement causing the structure weak to resist seismic effects due to more brittle behaviour. Therefore, the presence or absence of joint transverse reinforcement is essential for the prevention of brittle failure from seismic damage. This research investigated the joint shear strain, joint shear strength, capacity curve, and crack pattern of the FEM under the loading. By comparing the model predictions with experimental results, the joint aspect ratio and the beam-strengthening ratio directly impact the beam-column joint action. The joint becomes brittle as the reinforced concrete contains a higher joint aspect ratio. Thus, the joint shear strength also reduces. Concerning the reinforcement ratio of the joint, the increase of ratio has only little effect on the enhancement of joint shear strength, but it does affect the joint brittleness.

Asran et al. (2016) had investigated the general behaviour of different classifications of RC beam-column joints. The beam-column structure involves members that intersect in three-axis making it the most important part of the structure for stability. In this research, the beam-column structures had been divided into six categories, including interior connection, exterior connection, corner connection, which were separated into connections at the middle or roof of the building. The effect of reinforcement configuration, eccentricity and joint aspect ratio of the beam-column structure was studied to understand its relationship to shear strength development at the joint panel. Other than that, the compressive column axial load and concrete compressive strength was also investigated in this research. According to the results, the joint shear strength of beam-column joints was not affected much by the column axial force as well as the joint shear reinforcement ratio. On other hand, the compressive strength affected significantly on joint shear strength development in RC. In addition, the significant improvement for seismic behaviour of joints showed that transverse reinforcement is essential in the beam-column joint structure.

Najafgholipour et al. (2017) had investigated the accuracy of the finite element analysis model simulating the shear behaviour of RC beam-column joint with experimental results using finite element analysis software ABAQUS. In their research, the transverse reinforcements were excluded from the joint panel design to emphasize the beam-column joint’s brittle behaviour when the structure is subjected to seismic activity. The structures to be investigated included exterior beam-column connection and interior beam-column connection in this research. Throughout the experiment and finite element analysis, the joint shear forces were obtained and the deformation and cracking pattern of the structures under the seismic condition. As result, the analysis revealed the tensile damage at the beam-column joints. Diagonal tensile cracking formed and spread rapidly in proximity to the column, causing compressive damage to the concrete diagonal compressive strut as well as yielding joint longitudinal reinforcement. In short, transverse reinforcement at the joint panel would provide tensile resistance to the beam-column structure and increase the resistance to the seismic damage.

Li et al. (2017) had investigated the application of mechanical anchorage reinforcement to the beam-column joints to study its relationship to the strength of structures against anchorage failure. There is a problem of premature failure with top floor T-shaped beam-column joints due to the anchorage failure induced by column longitudinal rebar. This research focused on the hysteresis behaviour of the reinforced concrete and the crack pattern of the concrete. They also focused on dislodging the concrete cover until the reinforcements are exposed to the atmosphere when subjected to loading. The stress distributed at the anchorage and the reinforcements in the beam-column joint panel were also analysed. The results showed that the amount of joint shear reinforcement does not affect the hysteresis behaviour of the RC beam column. However, it had been proved to affect the capability of the reinforcement to withstand the high stresses to prevent anchorage failure. Therefore, the joint shear reinforcement and the anchorage are important factors in maintaining the joint shear strength in top floor beam-column joint structures.

Ali and Al-Rammahi (2019) had investigated the flexural properties of the beam-column joints. Exterior beam-column structures are subjected to uniaxial or biaxial loading where one of the sides is not resisted by the beam component. However, the research was focusing on the hybrid reinforced concrete that was made up of different types of materials such as reactive powder concrete and hybrid reinforcement. Carbon fibre reinforced polymer was one of the materials to be used in the concrete mix for this hybrid concrete. The beam-column joint was chosen as the portion to be investigated because this part in a moment-resisting frame is the most critical when the load transmits through the structural components. The result of cracking, which included the shear crack and flexural crack, were analysed at the experiment’s end. The ultimate load and the failure mode of the structures under static load can be studied from the cracking patterns. The data of ductility factor and absorption of energy were also analysed in this research to study the flexural behaviour of beam-column joint structures.

Abuzaid (2020) had investigated the performance of RC beam-column joints under influence of construction joints and effects cycling loading. The interface element at the surface of the RC beam-column joint panel was one of the factors that would be focused on in this research as it is inferred to be capable of influencing the effectiveness of beam-column joints. Reinforcement at the joint panel was investigated to study its implementation on the stiffness of the structures. Cycling load was simulated to be applied to the joint structures. The research was carried out with the assistance of a modified three-dimensional nonlinear finite element analysis program. According to the results, the interface element at the beam-column joint has a significant impact on the stiffness of the RC structures. The thinner interface element can provide a higher stiff response to the joint structures. Besides, the amount of steel reinforcement around the joint panel would also affect the stiffness of the structures. The strains in the joint reduced, and the deflection of structure decreased when the steel percentage applied at the joint increased.

Murad (2020) had developed the joint shear strength model for exterior RC beam-column joints under the biaxial cyclic loading using gene expression programming. The RC beam-column joint is one of the most critical and fragile components of an RC structure, and its failure may have a significant effect on the structure. Shear failure is a form of brittle failure that frequently occurs at the joint structure that occurs suddenly and without indication. For example, shear failure may occur when there is inadequate transverse reinforcement or when the material properties have degraded because of ageing. This research purposely investigated accurate modelling to predict the joint structure behaviour under the influencing factor. The developed model showed four main parameters that influence the joint shear strength: the compressive strength of the reinforced concrete to be used, the transverse reinforcement at the beam-column joint panel, the depth of the column and the width of the joint panel.

Feng and Fu (2020) had investigated the shear strength of interior RC beam-column joints using an algorithms machine learning-based approach. RC structures are a three-dimensional structural framework in which RC beam-column joints are exposed to a complicated stress condition that can cause the structure to collapse under extreme loading conditions. Biaxial and uniaxial loading condition was the focus of this research. While the biaxial cycling loading designed column-beam joint structures were seriously damaged as compared to uniaxial cycling loading designed joint structures. The uniaxial connections have higher joint shear strength than the biaxial connections. Simulation and modelling had been done to indicate the accuracy and prove for these phenomena. According to the research results, the gradient boosting regression tree (GBRT) model performed the best and most accurate in predicting the structure behaviour. This GBRT model showed that the concrete strength has a major influence on the shear strength of the beam-column joint structures.

Najafgholipour and Arabi (2021) had investigated the seismic structural behaviour of RC beam-column joints affected by the transverse reinforcements.

Transverse reinforcement acts as part of the reinforcement at the joint of beam-column structures, affecting the strength of the structures. Brittle failure due to the absence of transverse reinforcement in the joint structure adversely affects the ductile response and leads to widespread instability of the flexural frame, and causes collapse. This research was conducted using finite element analysis software ABAQUS to simulate the beam-column structures under seismically loading. The amount of transverse reinforcement used in the analysis was the crucial factor to evaluate. According to the results, the transverse reinforcement has no enhancing effect on the ultimate strength of the joint and therefore has little impact on avoiding joint shear failure. Nonetheless, the transverse reinforcement can increase the ductility of the joint and thus strengthen the nonlinear deformation capacity of the joint. It supports the yielding of beam flexural reinforcement and thus indirectly prevents joint shear failure of the beam-column structures.

2.4.3 Related Studies on Steel Reinforcement in Concrete Column

Pothisiri and Panedpojaman (2012) studied bonding between steel reinforcement and concrete under thermal loading. The mechanical properties of concrete and reinforcement, and even their bonding properties, can be greatly decreased at high temperatures due to the thermal expansion. This deterioration can influence the flexural capacity of the RC structures in bonding behaviour. The study focused on the thermal expansion of reinforcement in concrete and its bond strength to concrete under the influence of the concrete cover, the compressive strength of the concrete and the temperature applied to the concrete. From the conclusion, the reduction in bond strength due to thermal expansion can be affected by the concrete cover and by the compressive strength of concrete. The pull-out forces produced by the steel reinforcement and the concrete when the thermal expansion occurred could induce the thermal cracks. In addition, the thinner concrete cover had weaker resistance to degradation of the bond strength when subjected to high temperature.

Ha et al. (2016) studied the one-side headed shear reinforcement in RC columns under cycling loading. In an RC column, the heads could prevent the column bars from buckling, allowing the columns to keep their capacities. The type of anchorage crosstie was the major variable in this research. Different variables of anchorage crosstie applied in the shear reinforcement would give a different performance to the concrete column such as ductility and dissipation of energy. The research tested the conventional crossties using standard hooks and mechanical anchorage using heads that the crossties were anchored to 135-degree hook or 90-degree hook either enclosing the hoops or enclosing the longitudinal bars, and tested double-headed crossties with the heads enclosing the hoops. The outcomes of this research revealed that the headed crossties would effectively restrain the column reinforcement and core concrete, thereby enhancing the ductility and energy dissipation capacity of the concrete column.

Wu et al. (2018) studied the shear strength of composite column pier that combines RC pier with embedded steel tube. According to previous studies, shear failure was the most common reason to induce pier failure and it can be observed through the failure shape of the pier. Therefore, it is critical to increasing the shear capacity and the shear strength of piers to ensure the performance of the pier structures are safe. A shear capacity model for pier embedded steel tubes was developed. It showed that the RC piers reinforced by steel tube and rebar developed relatively satisfactory crack distribution. The patterns of failure in the piers indicated the ductile failure occurred when it was subjected to the loads. Therefore, the steel tube could enhance the deformation ability of the concrete pier to reduce the effect of the shear failure. The failure patterns of piers were also found to be shear diagonal compression failure. The embedded steel tube structure of the bridge piers had much more integrity. The steel tube and brace embedded in the concrete avoid concrete cracking and delay the transition from yielding to ultimate failure.

Ali et al. (2019) studied the concrete-filled fibre reinforced polymer tube. This research focused on the flexural behaviour of the concrete-filled fibre reinforced polymer tube under lateral cyclic load in the influence of bond and tube thickness. To investigate the effect of bonds on the concrete structures, the researchers carried out the lateral cyclic load test to column specimens with similar geometrical properties but different in the presence or absence of sand coating on the tube internal surface. To investigate the effect of tube thickness on the concrete structures, the researchers carried out a constant axial load test and lateral cyclic load test to the specimen columns that have similar mechanical properties but different in the exterior tube thickness. From the results of the experiments, the sand coating bonded concrete-filled reinforced polymer tube section enhanced the flexural capacity of the structures. This indicates that the composite action on the interior surface of the reinforcement and the concrete brings significant effect to the structure behaviours. Besides, the thickness of the tube affected the yielding of steel that can affect the flexural behaviour of the concrete-filled fibre reinforced polymer tube.

Rabi et al. (2020) studied the bonding of reinforcement in RC. The materials of the reinforcement to be investigated in this research were stainless steel and carbon steel. The bond behaviour of reinforcement to the concrete is important to the flexural capacity and ductility of the RC, thus influencing the safety and durability of the