EFFECT OF THE VERTICAL AND HORIZONTAL WEB REINFORCEMENT ON DEEP BEAM WITH STRUT-AND-TIE MODEL WITH FINITE ELEMENT ANALYSIS

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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

Laporan kajian ini adalah mengenai tinglah laku struktur ricih konkrit bertelulang dengan nisbah tetulang web menegak dan mendatar yang berlainan. Objektif utama penyelidikan ini adalah untuk mengkaji kesan pengukuhan web menegak dan mendatar pada tindak balas beban-pesongan, dan pengagihan tekanan dalam nisbah rentang ricih kepada kedalaman 1.67 apabila tertakluk kepada beban dua titik. Oleh kerana pendekatan numerik penyelidikan yang terhand, penyelidikan dijalankan dalam analisis ubah bentuk linear yang bahannya tidak melampaui titik hasilnya, ubah bentuk plastic struktur yang mengalami ubah bentuk non-linear geometri tidak akan dipertimbangkan dalam kajian ini. Kajian ini dijalankan dengan mengesahkan pemodelan unsur terhingga dengan hasil eksperimen. Sejumlah lima (5) rasuk termasuk satu rasuk kawalan dengan kekuatan mampatan 85MPa dengan dimensi panjang 1800mm, lebar 100mm dan kedalaman 400mm, dengan 550mm rentang ricih dan 330 kedalaman berkesan memberikan rentang ricih kepada nisbah kedalaman 1.67 yang dimodelkan sebagai perletakan sederhana dalam analisis tiga dimensi (3D) oleh analysis unsur terhingga (FEA), ANSYS 18.2. Dalam penyelidikan, tetulang yang digunakan adalah 6T16 untuk bar bawah, 2T12 untuk bar atas, T8 sebagai bar tetulang web menegak atau pautan ricih dan T6 sebagai bar tetulang web mendatar atau midbar. Dengan membandingkan dengan rasuk tanpa sebarang tetulang web, rasuk dengan 0.56% dan 1.26% tetulang web vertikal menyebabkan pengurangan sebanyak 7.43% dan 15.60% pesongan pertengahan rentang. Di antara rasuk dengan tetulang mendatar 0.22%, 1.26% tetulang web menegak menyebabkan pengurangan 11.33% pesongan pertengahan rentang berbanding dengan rasuk dengan 0% tetulang web menegak. Di antara rasuk tetulang menegak 0.56%, dan 1.26%, nisbah tetulang mendatar 0.22% menyebabkan penurunan 0.11% dan 2.93% dalam pesongan pertengahan rentang

berbanding rasuk dengan tetulang web mendatar. Berbanding dengan kawalan rasuk, 0.56% dan 0.22% gabungan tetulang menegak dan mendatar web telah menyebabkan pengurangan sebanyak 7.53% pada pesongan pertengahan, dan 1.26% dan 0.22% gabungan tetulang web menegak dan mendatar yang menyebabkan pengurangan 18.01% dalam pesongan pertengahan. Terdapat persetujuan yang baik mengenai rasuk FEA yang dimodelkan oleh ANSYS 18.2 dengan hasil eksperimen dalam tindak balas beban-pesongan dan pengagihan tekanan dalam rasuk yang mendalam apabila dikenakan beban.

ABSTRACT

The research was carried out to study the shear structural behaviour of reinforced concrete deep beams with different ratio of vertical and horizontal web reinforcement. The main objectives of the research are to study the effect of vertical and horizontal web reinforcement on load-deflection response, and stress distribution of deep beam with shear span to depth ratio of 1.67 when subjected to two-point loading. Due to limited research numerical approach, the research was conducted in linear deformation analysis which the material did not go beyond its yield point, the plastic deformation that structure undergo geometric non-linearity deformation will not be considered in this study. The study was conducted by validating the finite element modelling with experimental results. A total of five (5) beams including one control beam with compressive strength of 85MPa with dimension of 1800mm length, 100mm width and 400mm depth, with 550mm of shear span and 330mm of effective depth giving shear span to depth ratio of 1.67 were modelled as simply supported beams in three-dimensional (3D) analysis by finite element analysis (FEA) software, ANSYS 18.2. In the research, reinforcement used was 6T16 for bottom bar, 2T12 for top bar, T8 as vertical web reinforcement bar or shear link and T6 as horizontal web reinforcement bar or midbar. By comparing with beam without any web reinforcement, the beam with 0.56% and 1.26% of vertical web reinforcement caused reduction of 7.43% and 15.60% of mid-span deflection. Among beam with 0.22% horizontal reinforcement, the 1.26% of vertical web reinforcement caused reduction of 11.33% of mid-span deflection compared to beam with 0% vertical web reinforcement. Among beams of vertical reinforcement of 0.56%, and 1.26%, 0.22% of horizontal reinforcement ratio caused 0.11% and 2.93% reduction in mid-span deflection respectively compared to beam with horizontal web reinforcement. Compared to control beam, 0.56% and 0.22% of combined vertical and horizontal web reinforcement caused 7.53% reduction in mid-span deflection, and 1.26% and 0.22% of combined vertical and horizontal web reinforcement caused 18.01% reduction in mid-span deflection. There is good agreement on FEA beam modelled by ANSYS 18.2 with the experimental results in load-deflection response and stress distribution in deep beam when subjected to loading.

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LIST OF ABBREVIATIONS

3-D	**T**hree-**D**imensional
ACI	**A**merican **C**oncrete **I**nstitute
BS	**B**ritish **S**tandard
C-C-C	**C**ompression-**C**ompression-**C**ompression
C-C-T	**C**ompression-**C**ompression-**T**ension
C-T-T	**C**ompression-**T**ension-**T**ension
D-regions	**D**isturbed **R**egions
EC	**E**urocode
FEA	**F**inite **E**lement **A**nalysis
LVDT	**L**inear **V**ariable **D**ifferential **T**ransducer
RC	**R**einforced **C**oncrete
STM	**S**trut-and-**T**ie **M**odel
T-T-T	**T**ension-**T**ension-**T**ension

NOMENCLATURES

γ	Angle between Strut Axis and Reinforcement
α	Angle
a	Shear Span
A_s	Area of Reinforcing Steel
A_v	Area of Shear Reinforcement Perpendicular to the Flexural Tension Reinforcement
A_{vh}	Area of Shear Reinforcement Parallel to the Flexural Tension Reinforcement
b_s	Width of Specified Beam
b_w	Width of Beam
d	Effective Depth of Beam
D	Overall Depth
E	Young Modulus
f	Stress
f_{cu}	Effective Compressive Strength
f'_c	Concrete Compressive Strength
f_u	Ultimate Strength
f_y	Yield Strength
F_{ns}	Strut Capacity

h	Height
l_b	Width of Column
l_{dh}	Development Length
ℓ_n	Clear Span Length
l_{dh}	Development Length
p_h	Ratio of vertical web reinforcement
p_v	Ratio of horizontal web reinforcement
s	Spacing
s_i	Spacing of Specified Beam
V_n	Maximum Allowable Shear Force
V_u	Designed Shear Force

CHAPTER 1

INTRODUCTION

1.1 Background

Reinforced concrete (RC) deep beam is a common structural member that used in offshore structures, pile caps, and transfer beam in tall building. In tall building, deep beam is act as supporting element to support the discontinuous column and transfer the its loads to the surrounding columns.

A deep beam is a structural member that has clear span length equal to or less than four times to overall member depth as stated in ACI-318-2008. A deep beam is a non-flexural member when it subjected to load, it behaves differently from an ordinary beam as its shear action rather than flexural bending, as its strength is controlled by shear rather than flexure. To design a solid reinforced concrete deep beam, the use of strut-and -tie model (STM) is required to model the Disturbed regions (D-regions) into idealized truss. The STM is a powerful tool, which is a multiple step and powerful tool to design reinforced concrete deep beam. A D-regions is a region that discontinuity in the stress distribution occurs at a change in the geometry of a structural member, which the plane sections assumption of flexure theory could not be applied. STM provide guidance to designers where empirical equation lose validity.

In this study, the shear stiffness of reinforced deep beams will be investigated with different vertical and horizontal web reinforcement under linear deformation analysis before the plastic stage which the yielding of material occurred, in finite element analysis (FEA) software, ANSYS. The experimental works of RC deep beams have been carried out by Ismail (2016). Firstly, the ANSYS modelling technique will be verified by comparing the model load-deflection response to the experimental work studied by Ismail (2016). A detail design of control deep beam with shear span to depth ratio of 1.67 will be performed with STM as per ACI-318-2008. Then FEA by ANSYS 18.2 software will be carried out to investigate the shear stiffness of RC deep beams under 4-points bending configuration with different ratio of vertical and horizontal web reinforcement. The stress distribution of deep beam under two-point loading will also modelled with the von Mises stress contour.

1.2 Problem Statement

RC deep beams are common and useful application in various building but their detail design does not cover by British Standard (BS) and Eurocode (EC), which are widely practiced by structural engineers in Malaysia as structural code. In BS 8110-1:1997, it stated “other relevant specialist literature may be used providing the resulting design” for deep beam design. EC provide brief guideline on minimum reinforcement area of reinforcement mesh, distance between two adjacent bars of mesh and reinforcement pattern without establish the STM. Currently, ACI-318-2008 is the main structure code by providing the most comprehensive and recommendation to design deep beam by using STM for analysis and design of concrete members, reinforcement and anchorage.

According to research done by (Beshara et al., 2015), the corresponding beams modelled in FEA software ANSYS could produce accurate analytic result in determining the load-deflection response compared to experimental results. Therefore, this study is conducted to study the behavior of RC deep beam with different ratio and configuration vertical and horizontal web reinforcement by validating the result with that in experimental works. Premature structural failure and over deformation takes places in deep beam with lack of adequate reinforcement. In this study, the configuration and amount of vertical and horizontal web reinforcement were chosen as study parameters. The RC deep beams with different ratio of vertical and horizontal web reinforcement to the minimum requirement for web reinforcement as per design code ACI-318-2008.

1.3 Objectives

The objectives in this study are:

1. To design the deep beam with STM as per design code ACI-318-2008.
2. To validate the FEA model by comparing the result obtained with the experimental works in linear deformation static analysis.
3. To determine the shear stiffness of RC deep beams with different configuration and amount of vertical and horizontal web reinforcement in linear deformation static analysis.
4. To study the stress distribution of RC deep beam when subjected to two-point loading.

1.4 Scope of Work

The scope of work performed in this study consists of:

1. To design the deep beam with STM as per design code ACI-318-2008.
2. Validation of FEA model in software ANSYS by comparing the analytic result obtained with the experiment works result in linear deformation static analysis.
3. Analyse the result from variable of configuration and amount of vertical and horizontal web reinforcement in RC deep beams.

4. Study the von-Mises stress distribution pattern of deep beam when subjected to two-point loading.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Reinforced Concrete Deep Beam

Reinforced concrete (RC) deep beam is a structural member that has clear span length equal to or less than four times to overall member depth as stated in ACI-318-2008. Deep beam failure is mainly governed by shear rather than flexural failure in the ordinary beam. The difference between a deep beam and shallow beam can be based on either beam action or tied arch action. RC deep beams are commonly applied in transfer beam in tall buildings, offshore structures and foundations. RC deep beams have a function to convert the structural system between upper and lower part of the structure. Since deep beams should support the whole upper part of structure, its structural behaviour can influence on stability and safety of structure remarkably (Noh et al., 2005).

2.2 Strut-And-Tie Model

Strut-and-tie model (STM), has been proposed for analysis and design of non-linear structure with generalization of the truss analogy (Schlaich and Schafer,1991). STM consist of three parts which are strut, tie and nodes. In RC deep beam, the distribution of strains across depth of the cross section will be nonlinear and significant amount of load is carried to the support by a compression strut joining the load and reaction (Nagarajan and Pillai, 2007). Deep beam entire structural element belongs to Disturbed regions (D-regions) which can’t be designed or analysed by simple numerical calculation. STM provide a flexible and intuitive option for designing such structural member.

Ties are resultant of tension stress that carried by reinforcement. Its cross-section follows from the tie force in the ultimate limit state and the design yield strength of the steel (Schlaich and Schafer,1991). There are three types of struts in STM as shown in Figure 2.1, which are prism, fan and bottle type of struts. Nodes are the transition zone where the strut-and-tie converge. Nodes are the regions where the forces are deviated over a certain length and widths. Safe anchorage of ties in the nodes have to be assured with minimum radii of bent cars and anchorage length of bars. The bar must be extended to another end of node region (Schlaich and Schafer,1991). Nodes are commonly in triangle shape and its size is affected by bearing size and loading area size, location and distributions of reinforcements, and anchorage. According to Schlaich and Schafer (1991), there are four types of nodes were shown in Figure 2.2:

a) Compression-compression-compression (C-C-C) node experiences compression on all three nodal faces (Figure 2.2 (a))
b) Compression-compression-tension (C-C-T) node experiences compression on two face and tension on one face (Figure 2.2 (b))
c) Compression-compression-tension (C-T-T) node experience compression on one face and tension on two faces (Figure 2.2 (c))
d) Tension-tension-tension (T-T-T) node experiences tension on all three nodal faces (Figure 2.2 (d))

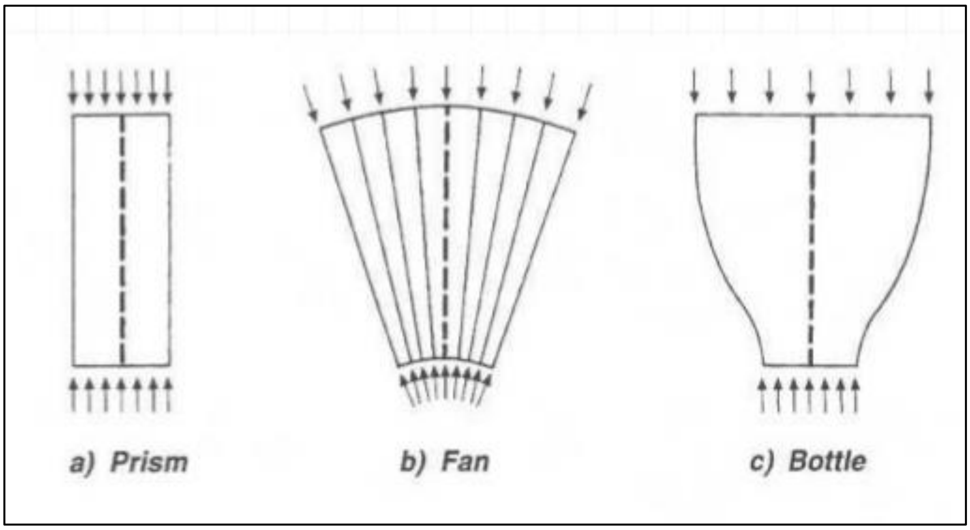

Figure 2.1: Three types of struts in STM (Schlaich and Schafer, 1991)

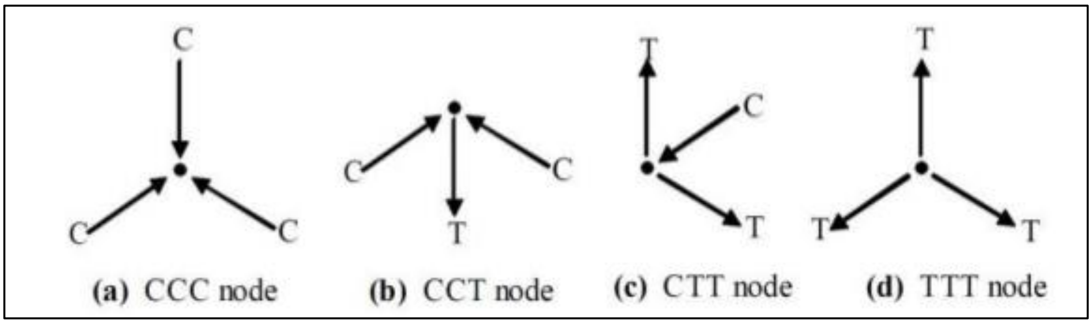

Figure 2.2: Four types of nodes in STM (Schlaich and Schafer, 1991)

2.2.1 American Concrete Institute Code (ACI-318-2008)

The ACI-318-2008 define deep beam as beam that have (a) clear span equal to or less than four times the overall member depth; or (b) regions with concentrated loads within twice the member depth from the face of the support.

The ACI-318-2008 defines shear design of deep beam as follows:-

- Deep beam shall be designed using STM. (Section 11.7.2: ACI-318-2008)
- Nominal shear strength, $\boldsymbol{V_n}$ shall not exceed $10\sqrt{f'_c}b_w d$, where f'_c is concrete compressive strength of, b_w is width of beam and d is effective depth of beam. (Section 11.7.3: ACI- 318-2008)

- The area of shear reinforcement perpendicular to the flexural tension reinforcement, A_v, shall not be less than $0.0025b_w s$, and s shall not exceed the smaller of d/5 and 304.8mm, where s is the spacing. (Section 11.7.4: ACI-318-2008)
- The area of shear reinforcement parallel to the flexural tension reinforcement, A_{vh}, shall not be less than $0.0015b_w s_2$, and s_2 shall not exceed the smaller of d/5 and 304.8mm, where s_2 is the spacing. (Section 11.7.4: ACI-318-2008)

2.3 Effect of Vertical Web Reinforcement to Shear Stiffness of Reinforced Concrete Deep Beams

According to Beshara et al. (2015), the load carry capacities and loading-deflection response improve with an increase in ratio of vertical shear reinforcement (ρ_v). In RC deep beams without vertical web reinforcement, the sudden failure occurred due to crushing of the concrete compression struts. When vertical reinforcement is sufficient, crack fans develop under the loads, and over the interior support, and the stiffness of beam also increase. Cracking load at mid-span show minor reduction and increased deflection in tested beam without vertical shear reinforcement. The study result indicated deep beam without vertical web reinforcement or stirrup had very little ductility, and with heavy vertical web reinforcement has improved its ductility, while light vertical web reinforcement will be brittle.

Increase of amount of vertical web reinforcement increase the strain and reduce the mid-span deflection at a given loading. Rao et al. (2015). When vertical web reinforcement increase, the vertical web reinforcement will share the loading and allow the concrete to sustain more cracking strain. The more vertical web reinforcement, the more diagonal strains due to increasing share of shear that is resisted by reinforcement. Other than that, when quantity of shear reinforcement is increased, more confinement is offered to sustain greater web strains and crack widths. The reinforced concrete deep beams show an increase in ductility with increase in percentage of shear reinforcement.

In the study by Seo et al. (2014), among the deep beam with shear span to height ratio, a/h from 0.5 to 1.0, the mid-span deflections decreased with an increasing of web reinforcement. The shear stiffness deep beam without web reinforcement dropped significantly after diagonal crack. The reinforced concrete deep beams with shear reinforcements satisfying the requirement as in ACI-318-2002 Code showed effective behaviour for crack control and ductile behaviour after yield. The strain of vertical and horizontal shear reinforcement was similar after yield of longitudinal reinforcement for deep beam with shear span-to-overall height ratio a/h= 1.0. But for case of a/h=0.5, the horizontal reinforcement showed higher strain than vertical reinforcement after formation of initial diagonal cracks. It concluded that when a/h is low, the horizontal reinforcement has higher contribution.

2.4 Effect of Horizontal Reinforcement to Structural Behaviour of Reinforced Concrete Deep Beams

According to Beshara et al. (2015), the horizontal shear reinforcement has moderate effect on improvement of the measure load-deflection response of tested reinforced concrete deep beams. The test show reduction in first diagonal cracking load and ultimate total load for test beam with horizontal shear reinforcement (ρ_h) of 0.00 compared to test beam with horizontal shear reinforcement (ρ_h) of 0.0033. The tested beam with horizontal shear reinforcement (ρ_h) of 0.0048 found increase in its first diagonal cracking load, ultimate total load and first flexural cracking load compared to test beam with horizontal shear reinforcement (ρ_h) of 0.0024.

Asin & Walraven (1995) had found that the tested RC deep beams show decrease in failure load when only horizontal web reinforcement was present when comparing the that designed with original calculation with vertical reinforcement only. The experiment shows the horizontal web reinforcement become more effective in increasing shear stiffness for mall shear span ratio of deep beam than vertical web reinforcement.

Deep beam with horizontal web reinforcement behave stiffer in load-deflection response than deep beams without horizontal web reinforcement (Mohamed et al., 2014). The flexure stiffness of deep beam with horizontal bars have higher flexure stiffness than deep beam without horizontal bars due to higher gross-sectional inertia in presence of horizontal bars. However, the presence of only horizontal bars without vertical bars will weaken the compression zone near the loading points and cause decrease in deep beam capacity compared to deep beam without web reinforcement.

In the experimental carried out by Ahmed et al. (2009), increasing of longitudinal reinforcement steel ratio will increase the shear stiffness of beam, hence the deflection of tested deep beams also decreases. This is because the increasing of longitudinal web reinforcement will increase the neutral axis depth in deep beam and cause reduction in tension reinforcement strain. When the horizontal web reinforcement is closely spaced, it has pronounced effect in deflection control, and widely spaced horizontal web reinforcement was not effective in controlling deflection.

2.5 Effect of Combined Vertical and Horizontal Web Reinforcement to Shear Stiffness of Reinforced Concrete Deep Beams

Study by Ismail (2016) had found that shear reinforcement including vertical and horizontal web reinforcement has no significant effect on shear capacity but could effectively reducing the principal tensile strain and the deformation on reinforced concrete. The concrete compressive strength has more influence on reinforced concrete than shear reinforcement due to strut and tie action is primary mechanism of shear stress transfer in deep beam. However, the presence of vertical web shear reinforcement is crucial in controlling crack propagation and providing ductility to deep beams.

Combination of both horizontal and vertical reinforcement proved to be most effective in enhancing the shear strength and stiffness of RC deep beams (Asin & Walraven, 1995), albeit the expense of more reinforcement. The well distribution of both horizontal and vertical web reinforcement is recommended for practical purposely as it could limit the crack widths.

2.6 ANSYS Finite Element Analysis Model

Finite element analysis (FEA) simulation is one of the methods to analyse the nonlinear behaviour of reinforced deep beam with web openings with analytical solution. FEA is a computer modelling and capable to solve complicated stress problems by numerical solutions. ANSYS is selected as FEA software as its comprehensive and reputable capability for FEA for various design of mechanical engineering and civil engineering related projects. ANSYS offers user a user-friendly experience with its well-developed graphic and interface, Workbench.

In the study by Haider (2013), the FEA shows fair agreement with experimental data despite the complexity of problem caused by irregular stress when introduction of various size of openings in deep beam. Ashraf et al. (2013) concluded that ABAQUS FEA software can capture the response reasonably with its model validation with experimental work from literature.

In the study carried out by Sabale et al. (2014) on analysis on deep beam by ANSYS with having different length to depth ratio, ANSYS shows its capacity of idealizing any continuum finer mesh to enhance the result obtained with high speed of operation.

Nonlinear FEA program, ANSYS 10.0 shows good agreement in predicting the result of load-deflection response as well as cracking patterns (Beshara et al., 2015). The program could accurately determine the ultimate loads, displacement ductility, stiffness changes, and failure mechanism for RC deep beams with different variables.

2.6.1 Material Concrete in ANSYS

SOLID186 element is used for 3D modelling of RC in ANSYS. SOLID186 possess properties of concrete which has capability for quadratic displacement behaviour, supports plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain capability. It also has capability of modelling behaviour of reinforcement with addition of rebar. SOLID186 is defined by 20 nodes, and each node having 3 degrees of freedom, translation in x, y, and z directions.

SOLID186 is selected the element for concrete in this analysis because of its capability to incorporate one material property for concrete and up to many reinforcement bars. The reinforcement bars are assumed to be uniformly distributed through the concrete element in defined region of finite element mesh. The use of

SOLID186 in reinforcement model is mainly used in analysing structure which have large volume such as deep beam as in this study.

SOLID186 homogenous Structural Solid is the default element for concrete in ANSYS 18.2 Workbench. It is suitable to model irregular meshing. The geometry, node locations and the coordinate system for element SOLID186 homogeneous Structural Solid geometry was shown in Figure 2.3.

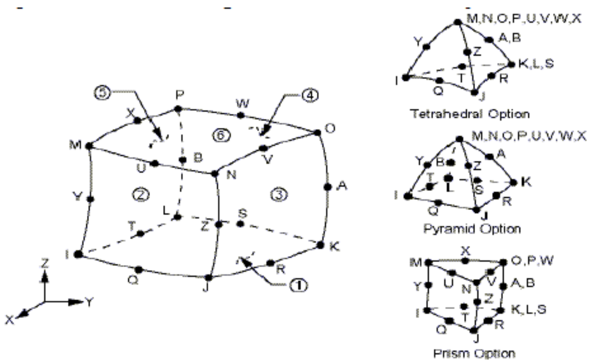

Figure 2.3: Geometry of SOLID186 in ANSYS

2.6.2 Material Reinforcement Bar and Shear Link in ANSYS

BEAM188 element is used for 3D modelling of reinforcement bar and shear links in ANSYS. BEAM188 could be used to model trusses, sagging cables, links and spring in the FEA analysis. BEAM188 possess properties of reinforcement bar and shear links which is linear, large rotation, and large strain nonlinear application. BEAM188 is a linear beam element in 3-D with six degrees of freedom at each node, translation in nodal x, y and z directions, and rotations about x, y and z direction.

The element BEAM188 can include stress stiffness terms by default, in any analysis with large deflection. With provided stress stiffness, element BEAM188 enable to analyse flexural, lateral and torsion stability problem by using Eigen value buckling. This element in model can support elasticity, plasticity, creep and nonlinear material. Geometry of element BEAM188 was shown in Figure 2.4.

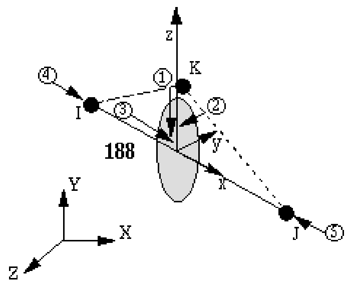

Figure 2.4: Geometry of BEAM188 in ANSYS

2.7 Summary

In summary, design of deep beam could be designed with STM model as per ACI-318-2008. Many research studies have been done on deep beam with different ratio of vertical and horizontal web reinforcement. Deep beams are commonly used in offshore structure and transfer beam in tall building, excessive deflection will impact the aesthetic and safety of the building. When deep beams are installed with different ratio of vertical and horizontal web reinforcement, it could affect their shear stiffness and their deflection when in service stage. Researchers including Beshara et al. (2015) and Rao et al. (2014) concluded vertical web reinforcement improve load-deflection response and increased beam stiffness. Rao et al. (2015) found deep beams shows increase in ductility when percentage of vertical web reinforcement increase. There are researchers such as Beshara et al. (2015), Mohamed et al. (2014) and Ahmed et al. (2009) found the horizontal web reinforcement have improved load-deflection and the shear stiffness of deep beams. Asin and Walraven (1995) found the horizontal web reinforcement is more effective in improving shear stiffness of deep beam when shear span ratio is small, and combined horizontal and vertical web reinforcement proved to be most effective in enhancing the shear stiffness of deep beams. However, Ismail (2016) concluded web reinforcement has no significant effect on shear capacity as concrete strength has more influence on deep beam shear stiffness. To study the FEA on effect of shear stiffness of deep beam with different ratio of web reinforcement, researchers such as Sabale et at. (2014) and Beshara et al. (2015) concluded FEA ANSYS software capable to capture structure behaviour of deep beam.

CHAPTER 3

METHODOLOGY

3.1 Introduction

To achieve the objectives of this research study, the finite element analysis (FEA) was carried out to determine the shear stiffness of five deep beams, Beam A1, Beam A2, Beam A3, Beam A4 and Beam A5, which have dimension of 1800mm length, 100mm width and 400mm height of deep beams. The sample beams have shear span of 550mm and 330mm of effective depth giving shear span to depth ratio of 1.67. The result obtained will be compared and to validate the outcome of experimental works study carried by Ismail's test (2016).

The detail of designing the deep beam as per ACI-318-2008, FEA modelling and analysis will be discussed as in Figure 3.1. The material properties of concrete and reinforcement bars were shown in Table 3.1 and Table 3.2.

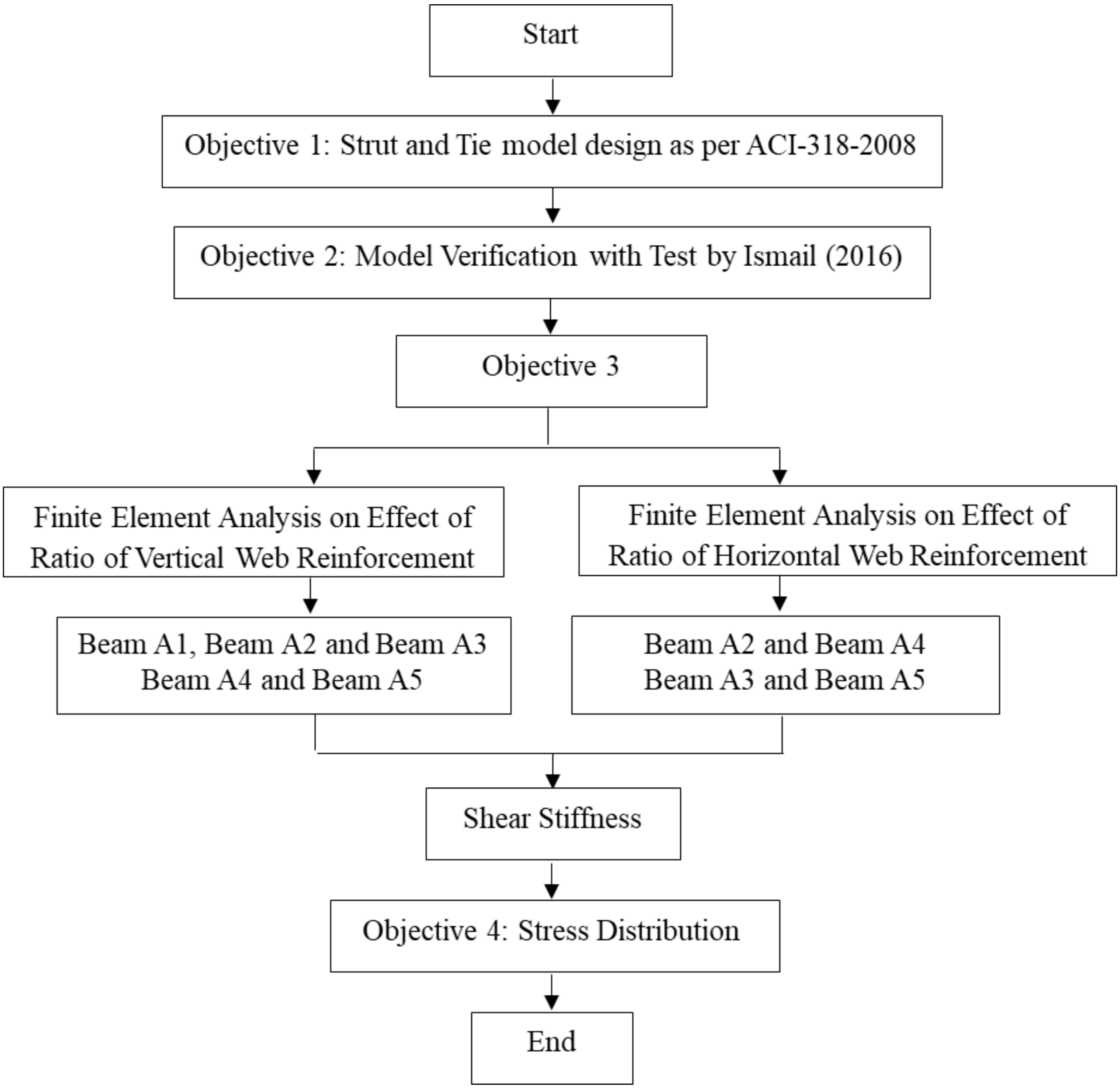

Figure 3.1 Methodology flow chart

Objective 1: Strut and Tie model design as per ACI-318-2008

Objective 2: Model Verification with Test by Ismail (2016)

Objective 3: FEA on Effect of Ratio of Vertical and Horizontal Web Reinforcement on Deep Beams' Shear stiffness

Objective 4: Stress Distribution of Deep Beams

Table 3.1: Material properties for concrete modelled in ANSYS

Density	2400 kg/m^3
Compressive Strength, f'_c	85.0 MPa
Young Modulus, E	30000 MPa
Poisson's Ratio	0.2

Table 3.2: Material properties for reinforcement bars modelled in ANSYS

Diameter Size (mm)	Density (kg/m^3)	Young Modulus, E (MPa)	Poisson's Ratio	Yield Strength, f_y (MPa)	Ultimate Strength, f_u (MPa)
6	7850	200000	0.3	577	660
8	7850	200000	0.3	448	693
12	7850	200000	0.3	404	635
16	7850	200000	0.3	364	550

3.2 The Strut-and-Tie Model in Design of Deep Beam as per ACI-318-2008

The strut-and-tie model (STM) was developed using optimisation technique that represent load mechanism and stress path in a reinforced concrete (RC) deep beam under designed ultimate load. It is also a simple equilibrium model based on lower bound solution of the plasticity theory that can used to design RC deep beams which is consisted of Disturbed regions (D-regions). ACI-318-2008 was chosen as design standard because the strut-and-tie model approach is incorporated in ACI-318-2008 for the design of RC deep beams. By following the specification outlined in ACI-318-2008, it allows designers to perform design and detailing of RC deep beams. Guan & Doh (2007) successfully performed the detail design of RC deep beam, and predicted accurately the load-carrying capacity and failure characteristic of designed RC deep beams by indicate the location of struts, ties and nodal zone in deep beam by strut-and-tie model outlined in ACI-318-2008.

The first step in designing STM is to establish a strut-and-tie layout as shown in Figure 3.2 by transfer the imposed loads to the supports, and Equation 3.1 is used to determine the strut angle, α_1 between strut and tie. The resultant force in each strut and tie were determined from force equilibrium equation from Equation 3.2, Equation 3.3 and Equation 3.4. Next step is to determine the effective compressive strength of concrete in node by Equation 3.5 and Equation 3.12, where Table 3.3 shows β_n = 1 for nodal zoned bounded by struts and bearing areas; 0.80 for nodal zones that anchoring one tie and 0.60 for nodal zones anchoring tension ties in more than one directions. Next step is to check the stress in base face, top face and vertical face of nodes in Equation 3.6, Equation 3.13 and Equation 3.14. The width of strut, which also defines the Node 1 height is determined in Equation 3.7 which was shown in Figure 3.3. In code, the effective strength of concrete was determined by Equation 3.8, where Table 3.4 shows β_n = 1 for prismatic strut in compression zones; 0.75 for bottle-shaped struts with crack control reinforcement; 0.6 for bottle-shaped strut without crack control reinforcement; 0.4 for struts in tension members and all other cases. The width of strut required to be determined before calculating its capacity, the widths of Strut 1-2 in Node 1 and Node 2 were determined in Equation 3.9 and Equation 3.15, which the dimension of Node 2 was shown in Figure 3.4. The loading point (Point 1 in Figure 3.2) is bounded by three struts and a bearing plate, therefore according to ACI-318-2008, the compressive strength of the strut can be determined in Equation 3.10 and Equation 3.16. The nominal shear strength of deep beam was limited to $10\sqrt{f'_c}b_wd$ which was shown in Equation 3.11. For the tie member 2-3 able to carry tensile force, the required cross-sectional area of steel reinforcement was determined by Equation 3.17. To ensure adequate anchorage, the development length is check through Equation 3.18 and Equation 3.19. In order to design the vertical and horizontal web reinforcement to control cracking, the web reinforcement in provided to fulfil the minimum ratio requirement where the angle between the axis and the horizontal web reinforcement and vertical web reinforcement were calculated in Equation 3.20 and Equation 3.21.

The important steps in designing reinforced concrete deep beam

1. Establish truss geometry and truss member forces
2. Check maximum shear force permitted in a deep beam
3. Node checking
4. Check anchorage at node
5. Provide minimum reinforcement in strut

Step 1: Establish truss geometry and truss member forces, where d_v is effective depth and a_v is shear span,

$$\tan \alpha_1 = (d_v / a_v) \qquad (3.1)$$

Code section A.2.5 stated the angle between any strut and tie should not be taken at angle less than 25 degrees. Figure 3.2 shows the layout of strut-and-tie layout for designed beam.

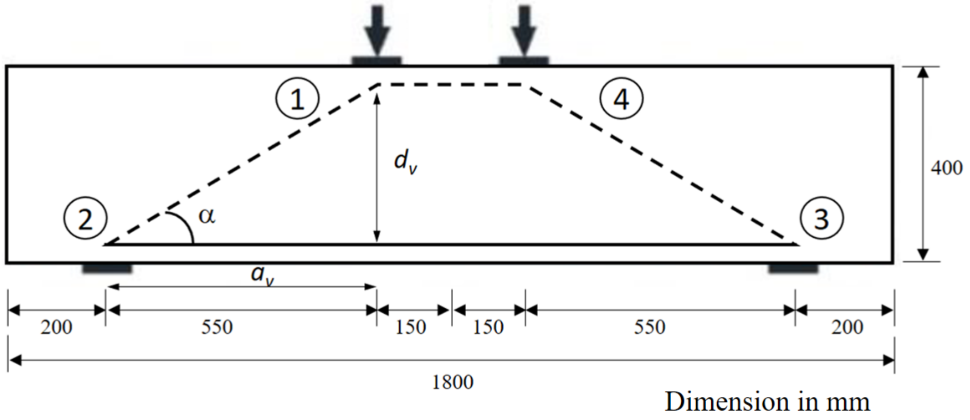

Figure 3.2: Deep beam dimension and general truss model assumed for the analysis

From equilibrium at Node 1, where T is the applied loading which is designed force.

$$\Sigma\,(Fy) = \mathrm{T} - F_{12}\,(\sin\alpha_1) = 0 \tag{3.2}$$

$$\Sigma\,(Fx) = F_{12}(\cos\alpha_1) - \mathrm{F}_{23} = 0 \tag{3.3}$$

$$\Sigma\,(Fx) = F_{14} - \mathrm{F}_{12}(\cos\alpha_1) = 0 \tag{3.4}$$

The effective compressive strength for node is defined as

$$f_{cu} = (0.85)\,\beta_n\,f'_c \tag{3.5}$$

Where f_{cu} is effective compressive strength, and f'_c is concrete compressive strength. In our case, Node 1 is a C-C-T node, so β_n = 0.8 as shown in Table 3.3. Thus, the effective compressive strength for Node 1 at nominal conditions is

$f_{cu}\,(1) = (0.85)\,\beta_n\,f'_c = (0.85)\,(0.80)\,f'_c$

Table 3.3: βn for different type of nodes

Type of Nodes	β_n
C-C-C	1
C-C-T	0.8
C-T-T, T-T-T	0.6

Use this nominal strength and $\phi = 0.75$ to check stress at the base of the node, where R_1 is the reaction force of support at Node 1, b_w is width of beam and l_{b3} is width of upper column.

$$f(\text{base}) = \frac{R_1}{(b_w)(l_{b3})} \tag{3.6}$$

f (base) < $\phi\, f_{cu}$ (1) (o.k.)

Also, find the $w_{14,}$ width of Tie 1-4, which defines the height of the Node 1,

$$w_{14} = \frac{F_{14}}{\phi(b_w)f_{cu}(1)} \tag{3.7}$$

β_s substituted for β_n. For Strut 1-2, use $\beta_s = 0.75$ as shown in Table 3.4,

$$f_{cu}\,(1\text{-}2) = (0.85)\,\beta_s\, f'_c = (0.85)\,(0.75)\, f'_c \tag{3.8}$$

Table 3.4: βn for different type of struts

Type of Struts	β_n
Strut of Uniform Cross-sectional Area Over its Length	1
Bottle-Shaped Strut with Crack Control Reinforcement	0.75
Bottle-Shaped Struts without Crack Control Reinforcement	0.40

Now, use the geometry of Node 1 to determine the w_s, width of Strut 1-2 in Figure 3.3, where l_{b1} is width of supporting column.

$$w_s\,(1\text{-}2) = w_{14}(\cos\alpha_1) + l_{b1}(\sin\alpha_1) \tag{3.9}$$

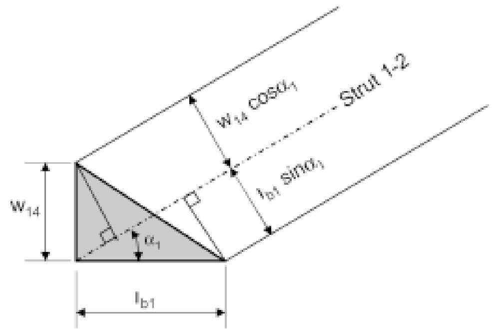

Figure 3.3: Geometry and dimension of Node 1 and Strut 1-2

Now check the $\phi F_{ns}(1\text{-}2)$, strut capacity at Node 1,

$$\phi F_{ns}(1\text{-}2) = \phi\, f_{cu} w_s(1\text{-}2) b_w \tag{3.10}$$

If $\phi F_{ns}(1\text{-}2) > F_{12}$ (o.k)

Step 2: Check maximum shear force permitted in a deep beam, where Vu is designed shear force and V_n (max) is maximum allowable shear force.

Code Section 11.8.3 defines an upper limit for the shear force permitted in a deep beam. With the centroid of Tie 3-4 established, the effective flexural depth of the beam d is $h - (w_{34}/2)$ Thus, the check of Code Section 11.8.3 requires

$$Vu \le \phi V_n\,(\text{max}) = \phi(10)\sqrt{f'_c}\,b_w d \tag{3.11}$$

Step 3: Node check (Node 2)

Sketch of the left side of Node 2 is given in Figure 3.4 The top dimension is set equal to 2/3 of the column dimension. The vertical dimension of the node was assumed in Step 3. Check the stress on the top face of Node 2 (C-C-C node) using $\beta_n = 1.0$

$$f_{cu}\,(2) = (0.85)\,\beta_n\, f'_c = (0.85)(1.0)\, f'_c \tag{3.12}$$

$$f(\text{top}) = \frac{R_1}{(b_w)(l_{b2})} \tag{3.13}$$

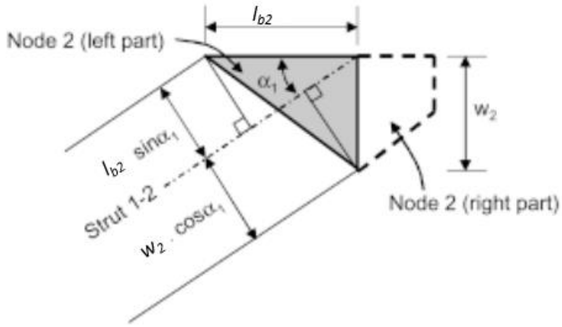

Figure 3.4: Geometry and dimension of Node 2 and Strut 1

Check stress on vertical face of left part of Node 2

$$f(\text{vertical face}) = \frac{R_1}{(b_w)(w_2)} \tag{3.14}$$

Determine w_s (1-2), width of Strut 1-2 at Node 2

$$w_s(1\text{-}2) = w_2(\cos\alpha_1) + l_{b2}(\sin\alpha_1) \tag{3.15}$$

Check the ϕF_{ns}(1-2), strut capacity of Strut 1-2 at Node 2 (critical end)

$$\phi F_{ns}(1\text{-}2) = \phi\, fcu(1\text{-}2) w_s(1\text{-}2) b_w \tag{3.16}$$

Step 4: Select reinforcement for Tie 1-4 as in Figure 3.2

Determine the A_s, required area of reinforcing steel:

$$\text{As(required)} = \frac{F_{14}}{\phi f_y} \tag{3.17}$$

Check anchorage at Node 1:

$$l_a = (w_{14})/(\tan\alpha_1) \tag{3.18}$$

Thus available anchorage length = $l_a + l_{b1}$ – concrete cover

l_{dh}, development length for Bar (Code section 12.5)

$$l_{dh} = (0.02\beta\lambda f_y / \sqrt{f'_c}) d_b \tag{3.19}$$

Development length must greater than $8d_b$ and 6inch or 150mm.