Force Transfer Mechanism of Headed Anchorage Bar in Exterior Beam Column Joint with Finite Element Method and Strut and Tie Model

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***Abstract*—In structural concrete, the provisions for anchorage of straight bars and hooks sometimes present detailing problems due to the long development lengths and large bend diameters that are required. Occasionally, the requirements for straight bar anchorage and lap splices cannot be provided within the available dimensions of elements. Hooked bars can be used to shorten anchorage length, but in many cases, the bend of the hook will not fit within the dimensions of a member or the hooks create congestion and make an element difficult to construct. This congestion may lead to high fabrication effort needed and poor concrete placement, resulting in decrease of concrete quality at the joints. An alternative is the use of headed anchorage bar, which allows for extremely small development lengths, that can reduce congestion without compromising the integrity of the structure. As a result, designing and detailing the structure are made easier and more efficient. Headed bars are formed by the attachment of a plate or the forging of an upset bearing surface at the end of a straight reinforcing bar. Such bars are anchored by a combination of bond along the straight bar length and direct bearing at the head. This papers presents strut and tie models explaining force transfer mechanism of headed anchorage bar in exterior beam-column joint under monotonic loads. The proposed model is derived from beam-column joint specimen which have been tested experimentally. Stress and strain generated by modeling the beam column joint with finite element-based program, ATENA 3D. The result of the analysis explaining the behavior of headed anchorage bar is CCT nodes (compression-compression-tension). The model is consists of a strut with the nodal zone at the head for head bearing and a fan-shaped stress field for bond stresses along the development length.**

Keywords— *headed bar, hooked bar, CCT nodes, compression fields, tension fields, joint shear crack, ATENA 3D*

I. INTRODUCTION

In structural concrete which designed for seismic forces, the detailing of the reinforcement has the major role to make good performances. For region with high seismic risk, Indonesian Concrete Code recommends the use of special moment resisting frame, with tight detailing requirement. Special moment resisting frames (SMRF) require full ductility and stability of concrete structures with respect to cyclic loads. SMRF has a very strict detailing requirement, this is because the system of SMRF has to produce a very good energy dissipation mechanism in reinforced concrete structure.

The provisions for anchorage of straight bars and hooks sometimes present detailing problems due to the long development lengths and large bend diameters that are required, particularly when large-diameter reinforcing bars are used. Hooked bars usually be used to shorten anchorage length, a standard 90-degree hook has often been used to anchorlongitudinal reinforcement terminated within exterior or corner beam-column joints. A standard hook as an anchorage device in such regions, however, is likely to result in steel congestion with the difficulty of steel fabrication and concrete placement. As concrete and reinforcing bars of higher strengths are applied, the dimensions of reinforced concrete members become smaller with the longer development lengths of reinforcing bars and, therefore, the anchorage of reinforcing bars becomes more difficult.

This congestion of reinforcement commonly occurs at the exterior beam-column joints. And it may lead to high fabrication effort needed and poor concrete placement, resulting in decrease of concrete quality at the joints. Under seismic loading, beam-column joint core is subjected to horizontal and vertical forces which are many times larger than the beam or column elements. If the joint core is not carefully designed and detailed, it may become the weak link amongst the structural elements (Bing Li *et al.*, 2002)

Various innovations for concrete reinforcement have been developed with the purpose to get the more effective and efficient design and installation of reinforced concrete structures. One of them is a reinforcement bar with head or named as Headed Anchorage Bar (or headed bar). Headed bars are created by the attachment of a plate or nut to the end of a reinforcing bar to provide a large bearing area that can help anchor the tensile force in the bar. This material is an alternative option to replace a standard 90-degree hooked bar, is effectively applicable to exterior beam-column joint. The anchorage mechanism of headed bar mobilized by the head can replace the function of hooked bar that have been regulated in many concrete codes.

Using headed bars can reduce a space needed for the embedment of the hooked bars and make the reinforcement installation simpler and easier.

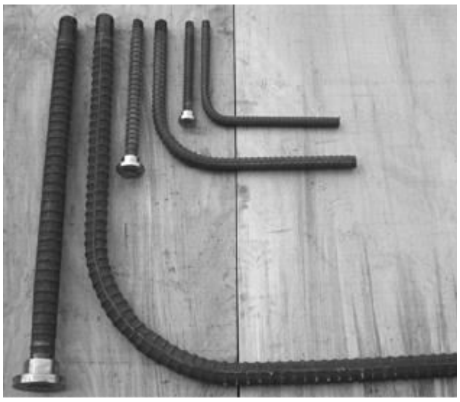


Figure 1. Comparison of the form of headed bar and hooked bar

Several codes like ACI 318, have made a design requirement for structure that used headed bars. The design requirement for headed bars is specified on development length in tension and concrete cover. The requirements are described in ACI 318 section 12.6 as follows:

- Bar yield strength shall not exceed 420 MPa
- Bar size shall not exceed No. 36
- Concrete shall be normal weight
- Net bearing area of head Abrg shall not be less than 4Ab
- Clear cover for bar shall not be less than 2db

Figure 2 shows the development length definition by ACI 318-11.

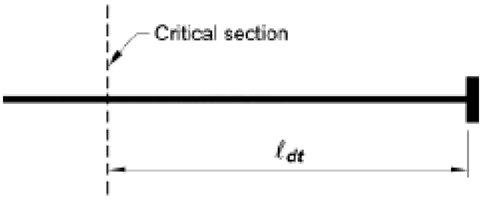


Figure 2. Development length of headed bars by ACI 318-11

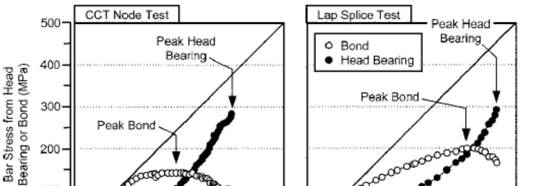


Figure 3. Bond and head bearing components

The anchorage of a headed bar is a combination between head bearing and bond along the bar (Thomson *et al.*, 2006). Initial anchorage is carried primarily by bond. As additional stress is applied to the bar, bond achieves peak capacity and begins to decline. As the process of bond deterioration occurs, bar anchorage is transferred to the head, causing a rise in head bearing. During loading, the load is initially beared by the bond along the bar. If the slip occurs, the head starts to bear the load (Thompson et al., 2006). This pattern is shown in Figure 3.

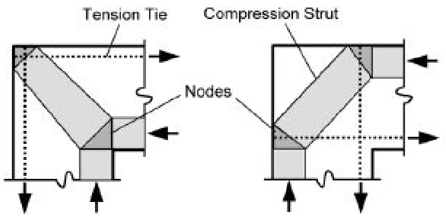
This paper presents a strut and tie model for development of headed anchorage bar in an exterior beam-column joint with finite element method approach. Strut and Tie Modeling (STM) is a simple method which effectively expresses complex stress patterns as triangulated models. STM is based on truss analogy and can be applied to many elements of concrete structures. STM method is used to study the force transfer mechanism that occurs in exterior beam-column joint with finite element method approach using ATENA 3D.

II. BACKGROUND ON STRUT AND TIE MODELING

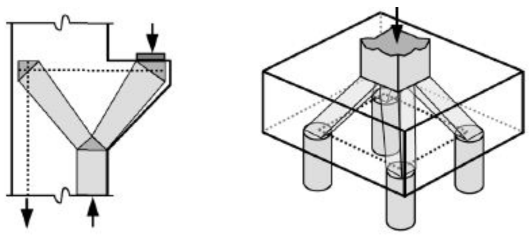
Strut and Tie Modeling (STM) is a detailing and ultimate strength calculation procedure for discontinuity regions within structures. When point loads are introduced into structural members or abrupt changes in cross-section are introduced, conventional methods of plane section analysis are no longer sufficient Such locations (termed disturbed regions) are generally detailed using rules of experience or empirical guidelines based on limited research data. Such methods are not based in structural mechanics for ultimate strength determination. Empirical methods are limited to the experience base from which the method derives. It is possible to analyze disturbed regions using complex analysis procedures such as finite elements.

However, the computer software necessary for such computation is not readily available to many designers. Furthermore, the cost and time of such analysis, which might constitute a large percentage of the designer's effort, does not always reflect the material and construction cost of the disturbed regions, which may represent only a minor part of the cost of a complete construction project. STM represents an in between design method for complex structural details that has abasis in mechanics but is simple enough to be readily applied in design.

STM is a method involving the idealization of a complex structural member into a simple collection of struts, ties, and nodes representing, in a general manner, the flow of stress paths within the member. Figure 4 shows some typical structural components for which STM could be applied. STM is ideal for deep members, joints, supporting brackets or corbels, dapped beam ends, anchorage zones for post tensioning, and many other complex structural components .STM is derived from plasticity theory. STM is a lower bound solution method. According to the theory of plasticity, any statically admissible stress field that is in equilibrium with the applied loads and in which stress levels are on or within the material yield surface constitutes a lower bound solution. Plastic material behavior is a primary assumption of plasticity theory. Strain capacity of the materials is a fundamental requirement to fully satisfy that a lower bound solution occurs. Though plain concrete lacks considerable plastic stress-strain behavior, properly detailed, confined concrete can sustain ductile compressive strains (Figure 5). Plasticity theory has been applied to the design of reinforced concrete but only with the proviso that strain limits within the concrete are limited or adequate detailing is provided to enhance the ultimate strain limits of the material.



(a) Knee Joint



(b) Corbel (c) Deep Pilecap

Figure 4. Example of strut and tie modelling

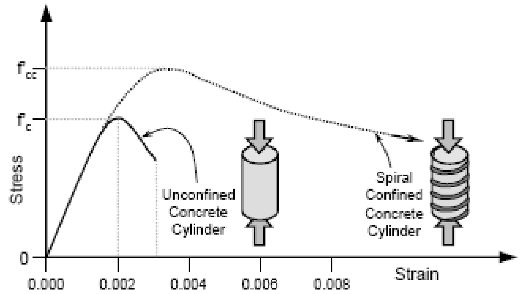


Figure 5. Deformation response of unconfine and confine concrete

STM involves the construction of a truss mechanism contained within the boundaries of the member being analyzed. The truss mechanism is composed of struts that model concrete compression fields, ties that model tensile steel reinforcement, and nodes that represent the localized zones in which the tensile steel is anchored into the concrete and strut forces are transferred into the ties. The struts and ties carry only uniaxial stresses. This truss mechanism must be stable and properly balance the applied loads. Failure of the truss mechanism is dictated by yielding of one or more ties or by excessive stresses within the struts or nodes or by an anchorage failure of the reinforcement at one of the nodes. When used properly to detail a structural member, only the first of the aforementioned failure modes should occur. The choice of acceptable concrete stress levels for struts and nodes is an empirical add-on to conventional plastic theory designed to allow for the use of concrete. Allowable stress levels are chosen to prevent local crushing or splitting of struts and nodes and are generally based on the degree of confinement available to the concrete.

III. STRUT AND TIE MODEL DEVELOPMENT FOR HEADED BARS IN C-C-T NODES

Thompson et al. suggested that the development of a headedbar is due to the combination of head bearing plus bond along the anchorage length of reinforcement between the point of maximum bar stress and the head. For distinction between embedment length and anchorage length, he proposed that strut and tie model (STM) be used when detailing headed bars.

STM are assumed to fail due to yielding of ties, crushingof struts, failure of nodal zones connecting struts and ties, oranchorage failure of ties. Intended behavior of most STM assumes the yielding of ties excluding bond-related failuremodes and, hence, a head or an anchor plate at the end of atie needs to be supplied for formation of singular nodes. The key to the treatment of bond in STM is how to model the deviation of force at nodes involving tension ties such as compression-compression-tension (C-C-T).

The proposed STM reasonably predict the ultimite loads and provide the basic concept for consistent strut and tie modeling for a headed bar application in bond related structural concrete components such as a beam with a dapped end (Figure. 7(a)), a corner joint (Figure. 7(b)), a beam with suspended load (development of a hanger bar) (Figure. 7(c)),a prestress transfer region of a pretensioned beam (Figure. 7(d)), an exterior beam column joint without transverse reinforcements (Figure. 7(e)), and an exterior beam-column joint with transverse reinforcements (Figure. 7(f)).

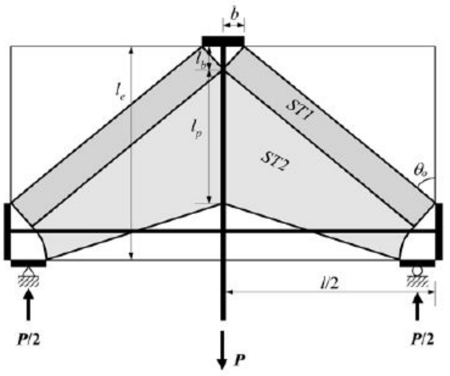


Figure 6. Strut and tie model for headed bar developed in C-C-T nodes

Strut and tie model for the development of headed bars in an exterior beam column joint is proposed that investigate realistic forces transfer by headed bars within the joint. The tensile force in a headed bar is considered to be developed by head bearing together with bond along a partial embedment length. Strut and tie model presents how to decompose the tensile force developed in headed bars into direct strut action and fan action and their effects on joint strength.

IV. NUMERICAL ANALYSIS

A headed bar has been considered as an alternative to a standard 90-degree hooked bar, but a failure mechanism and a design method for a headed bar have not been clearly established. This paper presents STM for headed bar development in C-C-T nodal zones (C-C-T nodes). The modeling clarifies the load transfer and failure modes of a headed bar anchored in an exterior beam-column joint. The description of the forces transfer mechanism in beam-column joint will be studied approach by finite element method.

Finite element method (FEM) is a numerical technique to find approximate solutions for boundary value problems, for partial differential equations and also for integral equations. These differential equations are solved by either eliminating the differential equations completely or by rendering these differential equations into ordinary differential equations which are then numerically integrated using standard techniques. FEM is a good choice for solving partial differential equations over complex domains. The technique of FE Method is described by: discretizing the continuum, selecting interpolation functions, finding and assembling the material properties to obtain the system equations, imposing the boundary conditions, solving the system equations, and making additional computations if desired. In fact, the nonlinear fracture models based on the numerical approach are relatively more involved in the computations as ATENA program. For this reason, probably, the fracture models based on the modified linear elastic fracture mechanics may bridge the gap between the computational efficiency and the model predictive capability of results; because, they are relatively more computationally efficient, but have limited capacity to predict the fracture parameters.

FEM is well suited for superimposition of material models for the constituent parts of a composite material. Advanced constitutive models implemented in the finite element system ATENA serve as rational tools to explain the behavior of connection between steel and concrete. Nonlinear simulation using the models in ATENA can be efficiently used to support and extend experimental investigations and to predict behavior of structures and structural details. Several constitutive models covering these effects are implemented in the computer code ATENA, which is a finite element package designed for computer simulation of concrete structures. The graphical user interface in ATENA provides an efficient and powerful environment for solving many anchoring problems. ATENA enables virtual testing of structures using computers, which is the present trend in the research and development. Because of material properties play an important role in modeling of structural elements, each material inside the program is defined; concrete is represented by solid brick element and reinforcement by bar elements.

V. PROPOSED MODEL

The specimen model to be analyzed is exsterior beam-column joint or "T" joint which derived from research that have been done by [1]. Specimens were positioned with column in vertical position. There are 2 specimens that are exterior beam-column joint using hooked bar (HK-22) and headed bar (HD-22).

Column and beam size were 400 mm x 450 mm and 250 mm x 350 mm respectively. All of column used 4 longitudinal reinforcement diameters 25 mm with 1.26% reinforcement ratio. Column flexural strength to beam flexural strength ratio was 2.30. So it could be assured the flexural failure wouldn't be happen at the column. As transversal reinforcement, column used 13 diameter deformed bar with spacing 100 mm. Column transverse reinforcement designed according to section 21.6.4.3. Column clear concrete was 30 mm.

Both specimen beam which use hooked bar and headed bar will use longitudinal reinforcement diameters 22 mm. Beam longitudinal reinforcement ratio was 0.85% longitudinal diameter. The transverse reinforment designed according section 21.5.3.2, used10 diameter deformed bars with 75 spacing along twotimes of beam depth from the face of column. Then according section 21.5.3.4, used 150 spacing for the rest length.

The specimen with headed bars modeled according to ACI 318 section 12.6. The clear concrete cover was 40 mm. The clear concrete cover between longitudinal reinforcement and the surface of the concrete was 50 mm. Spacing between headed bars also satisfy *4Ab*. The development length, according to section 12.6.2 was not less than 305.36 mm and the development length will use 350 mm. The head placed exceed the development length to the far side of the confined joint core, in accordance with ACI 352R-02 that recommends the back

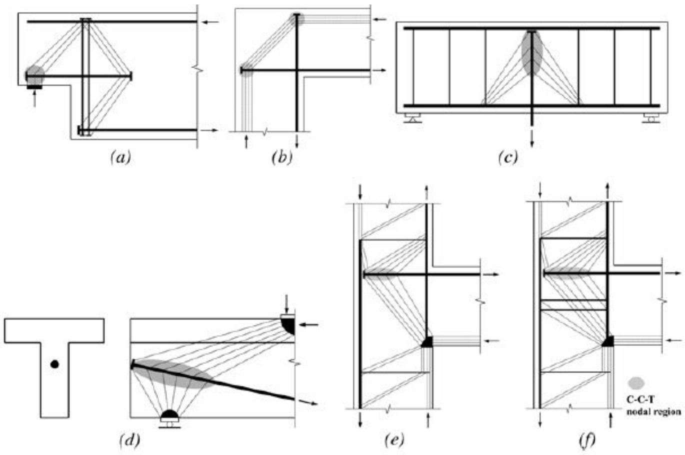


Figure 7. examples of headed bars developed in C-C-T nodes and strut and tie models

of the head is placed not greater than 50 mm from far end of joint core. Detailing reinforcement of beam and column shows in Figure 8.The typical specimen with headed bars and hooked bars are shown in Figure 9 and Figure 10.

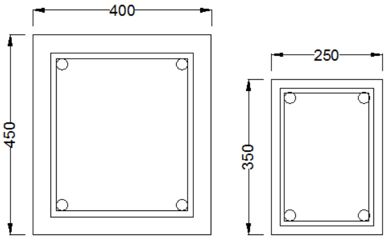


Figure 8. Detailing reinforcement of column (left) and beam (right)

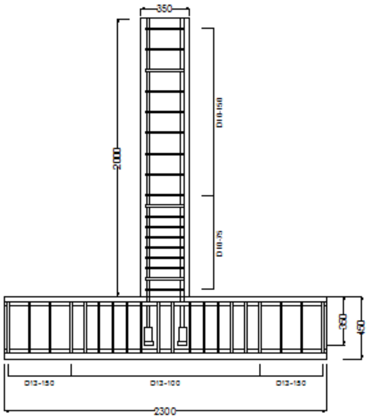


Figure 9. Specimen beam-column joint with headed bar

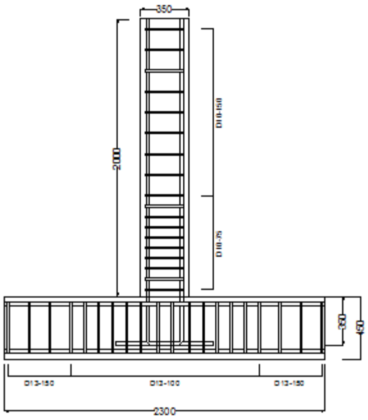


Figure 10. Specimen beam-column joint with hooked bar

Concrete strength derived from concrete compressive test result which is shown in Table 1 and tension test result for headed bars are shown in Table 2.

Table 1. Concrete compressive strength

Age (days)	fc' (MPa)
7	24.05
14	28.45
28	31.12

Table 2. Bars Tensile Test Result

Test Specimen	Yield Strength (MPa)	Tensile Strength (MPa)
Headed Bar D22	446	651
Hooked Bar D22	445	632
Column Bar D25	460	620

Figure 11 shows the conditions of headed bars before and after tensile test. The bar heads are steel pipe that formed by a cold treatment. The head pressed to the bar to get the friction strength. The ratio of net head-bearing area to the cross-sectional area of the bar was 1.95 for 22 mm bars.

(a)

(b)

Figure 11. Bar condition (a) before test and (b) after test

Table 3 shows the specification of headed bar, where Ab is bar diameter, Ah is area of head, Aobs is area of obstruction, and Anh is net bearing area of head.

Table 3. Headed Bar Specification

D22 Headed Bar	
Ab	380.13 mm^2
Ah	3117.25 mm^2
Aobs	2375.83 mm^2
Anh	741.42 mm^2
Rnh	1.95

Figure 12. Headed bar material

VI. FEM MODELING OF SPECIMENS IN ATENA 3D

In ATENA 3D, the concrete material is modeled as constituitive model which is consist of two parts, constituitive SBETA and fracture plastic constituitive model. Element geometric modeling of concrete has been done using 3D solid brick element with 8 up to 20 nodes. The 3D solid brick elements having three degree of freedom at each node: translations in the nodal x, y and z directions. This is an isoperimetric element integrated by Gauss integration at integration points. This element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The most important aspect of this element is the treatment of non-linear material properties. The parameters of concrete model will shown in Table 4.

Table 4. Material properties

Concrete Material Properties	
Cylinder compressive strength	31.12 MPa
Initial Elastic Modulus	32870.96 MPa
Poisson's Ratio	0.3
Tensile strength	2.646 MPa

Perfect bond between concrete and reinforcement is assumed in this model. No bond slip can be directly modeled except for the one included inherently in the tension stiffening. However, on a macro-level a relative slip displacement of reinforcement with respect to concrete over a certain distance can arise, if concrete is cracked or crushed. This corresponds to a real mechanism of bond failure in case of the bars with ribs.

Reinforcement modeling could be discrete or smeared. In our work, a discrete modeling of reinforcement has been done. The reinforcement has been modeled using bar elements in ATENA 3D. Reinforcement steel is a 3D bar element, which has three degrees of freedom at each node; translations in the nodal x, y and z direction. Bar element is a uniaxial tension-compression element. The stress is assumed to be uniform over the entire element. Also plasticity, creep, swelling, large deflection, and stress-stiffening capabilities are included in the element.

Discrete model of reinforcement is in form of reinforcing bars and is modeled by truss elements.In this cases the state of uniaxial stress is assumed and the same formulation of stress-strain law is used in all types of reinforcement.The reinforcement behavior will follow Multi-line Law. The multi-linear law consists of four lines as shown in Figure 13, Figure 14, and Figure 15. This law allows to model all four stages of steel behavior: elastic state, yield plateau, hardening and fracture. The multi-line is defined by four points, which can be specified by input. Stress-strain cuve will be approached by EPSH (Elastic Plastic-Curve with Strain Hardening) method. This method gives parabolic equation which described strain hardening behavior. The parameters of EPSH method are from previous study by Charles Pankow.

$$fs = fu - (fu - fy)\left(\frac{\varepsilon_{su} - \varepsilon_s}{\varepsilon_{su} - \varepsilon_{sh}}\right)^2 \qquad (1)$$

The parameters from Charles Pankow's study:
ε_{su} = 9% for reinforcement with yield strength 60 ksi
ε_{sh} = 1%

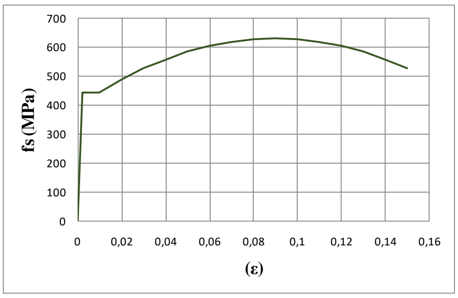


Figure 13. Stress – strain curve for hooked bar D22

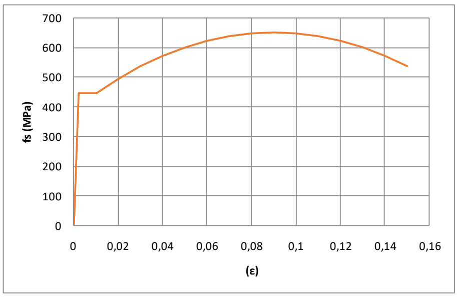


Figure 14. Stress – strain curve for headed bar D22

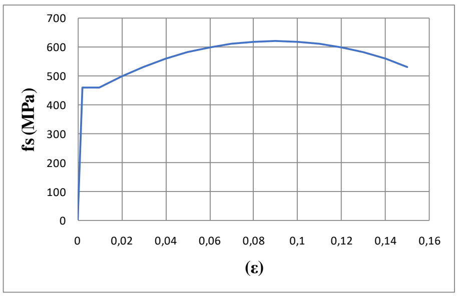


Figure 15. Stress – strain curve for column bar D25

There are two kinds of loading that will be applied to the model. First loading is a cyclic quasi-static with displacement control, this load is applied same as the previous study. Load applied sequentially from linear condition with small drift until reach nonlinear condition and being fail. The load pattern for cyclic loading is shown in Figure 16. The cyclic simulating load applied to beam edge at point 1650 mm from column top face (Figure 17). The load applied to get the behavior and performance of beam-column joint under seismic load. Second loading is monotonic loading, this loading will be applied gradually from small loads until the specimens have decreased strength, total steps in monotonic loading are 200 steps with 1 mm of displacement applied each step. The purpose to give monotonic load is for study about force transfer mechanism occurs at the beam-column joint.

The test set up model in ATENA 3D was arranged with column which each edge of column will be given hinge support that represent the condition of inflection point at column. This hinge also restrain column from moving transitionally, thus column edges will only move rotationally. Rolled support is given at the beam, so that the beam actually moves in transation due to displacement load (Figure 19).

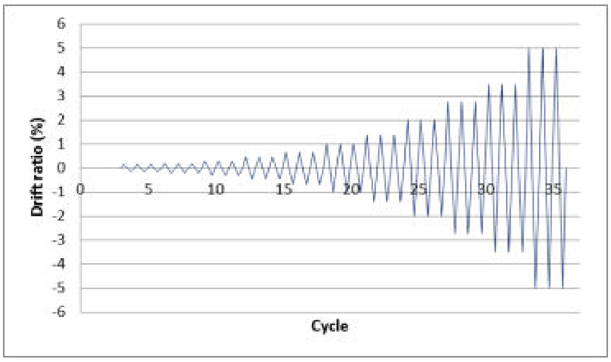


Figure 16. Cyclic loading

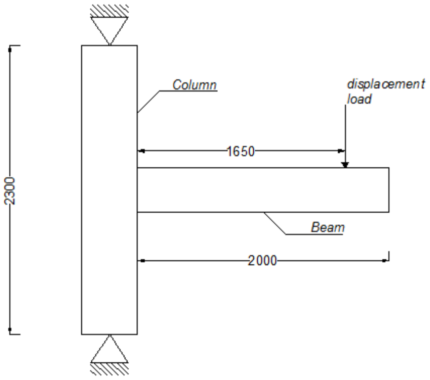
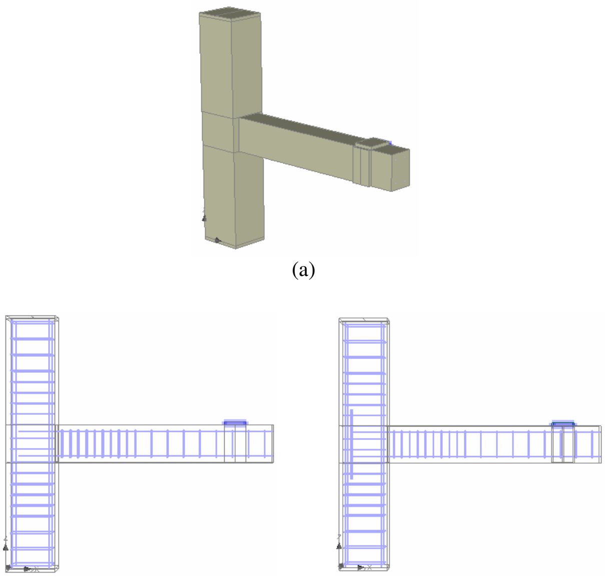


Figure 17. Specimen model

VII. RESULT AND DISCUSSIONS

In pre-processing window the model is built and the processing steps are performed by create the geometry of FE model as shown in Figure 18. Then the material properties are assigned to the various elements of each beam and column specimens. After that, the structural element boundaries are come, various supports, loadings and monitoring points are defined in Figure 19. Also, the finite element meshing parameters are given and meshing of the model is generated accordingly. Various analysis steps are defined. The FE non-linear analysis is done in Run window.

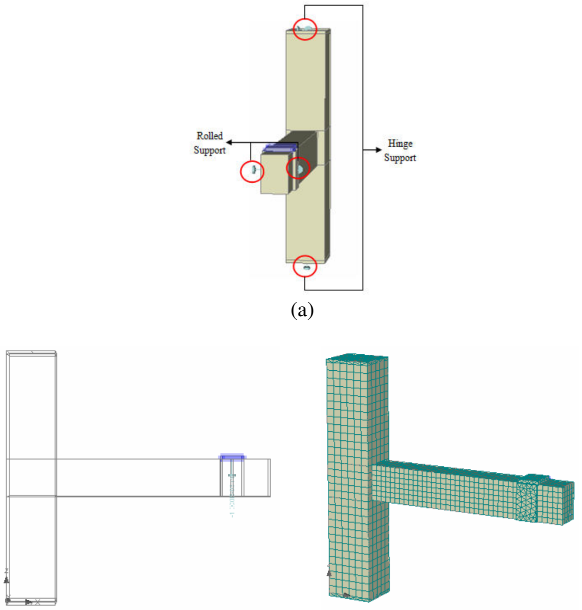
The FE non-linear static analysis calculates the effects of steady loading conditions on a structure. A static analysis can, however, include steady inertia loads (such as gravity and rotational velocity), and time-varying loads that can be approximated as static equivalent. The static analysis refferd to in the modelling is to provide a monotonic load, this load is used to determine the displacements, stresses, strains, and forces in structures or components by loads.


(a)

(b) (c)

Figure 18. (a) specimen model; (b) headed bar configuration of reinforcement; (c) hooked bar configuration of reinforcement

When the FE nonlinear static analysis is completed the, the results are shown in third part of the ATENA i.e. Post processing. The stress- strain values at every step, crack pattern and cracks propagation at every step shown help in to analyse the behavior of the elements at every step of load deflection.



(a)

(b) (c)

Figure 19. (a) support modeling at specimens; (b) displacement load modeling; (c) fe mesh of specimen

To ensure the accuracy of analytical result, the result of ATENA 3D analysis should be compared with the result of experimental analysis (Irvan Simamora et al., 2013). The comparative result is the backbone curves of cyclic loading test on exterior beam-column joint using headed bar. The results are shown in Figure 20 and Figure 21, the comparative result show that the backbone curves of cyclic loading result at ATENA 3D analysis approach the result of experimental test, then the specimens model in ATENA 3D can be used for monotonic loading.

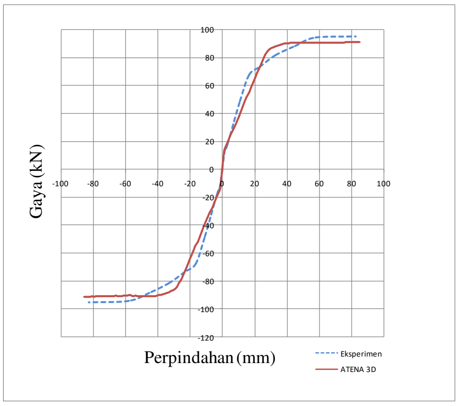


Figure 20. Backbone curve result specimen HD-22

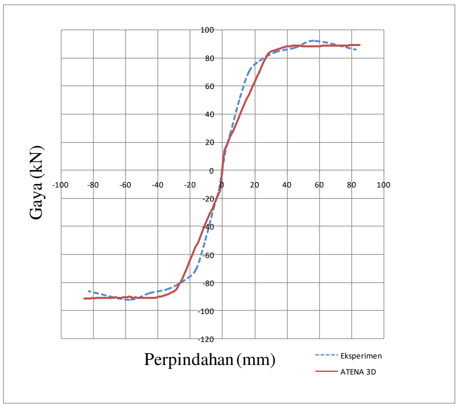


Figure 21. Backbone Curve Result Specimen HK-22

The monotonic loading result of ATENA 3D analysis for each specimen are shown in Table 5. The result of the ATENA 3D analysis show that each specimen which loaded with monotonic load give more or less the same result.

Table 5. Result of modeling

Analysis in ATENA 3D	Maximum Load
Monotonic Load – Headed Bar	91.44 kN
Monotonic Load – Hooked Bar	89.58 kN

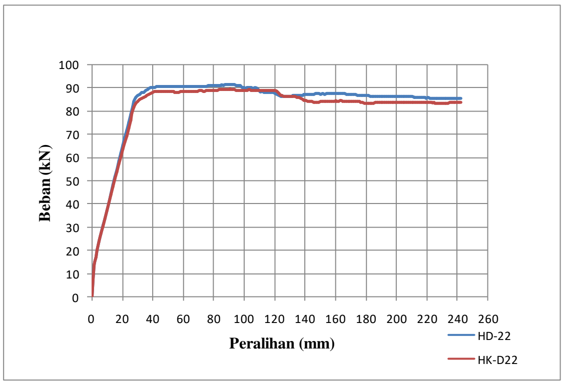
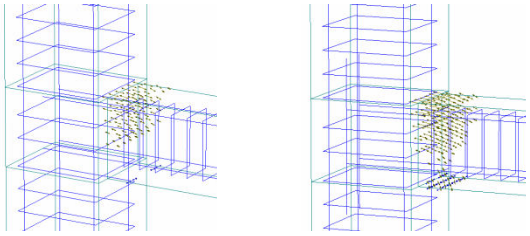


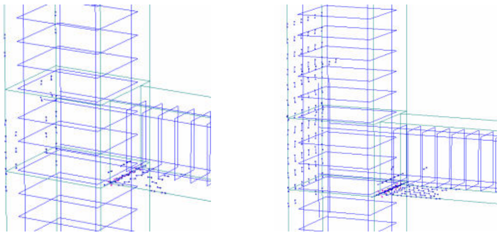
Figure 22. Monotonic curve result of exterior beam-column joint

From the result of ATENA 3D analysis, the description of principal stress and strain which occur at beam-column joint explains that the mechanism of force transfer in beam-column joint have a different styles between hooked bar dan headed bar.



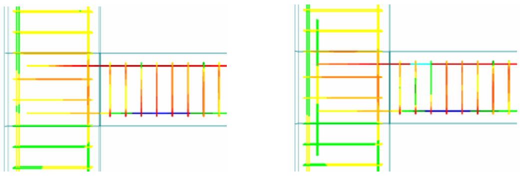
(a) (b)

Figure 23. Principal strain (a) headed bar and (b) hooked bar



(a) (b)

Figure 24. Principal stress (a) headed bar and (b) hooked bar



(a) (b)

Figure 25. Tensile strength σ_{xx} (a) headed bar and (b) hooked bar

The principal stress that occur at beam-column joint with using hooked bar have a different pattern compared to those using headed bar. The mechanism of stress transfer in hooked bar shown in Figure 26. The concrete in front of the hook, where it just begins to bend away from the straight portion of bar, is typically crushed at full development of the bar, 90-degree hooks tend to be pulled straight around the bend of the bar as load is applied. The bond stress occur because of tensile force which is resulted by monotonic load. This is clearly described in Figure 24(b), which the principal stress that occur in front of the hook in specimen HK-22.

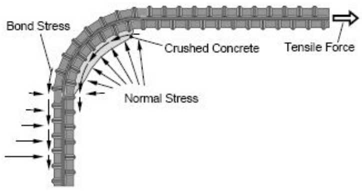


Figure 26. Stress transfer in hooked bar

Headed bar anchorage is provided by a combination of head bearing and bond. Initial anchorage is carried primarily by bond. As additional stress is applied to the bar, bond achieves peak capacity and begins to decline. As the process of bond deterioration occurs, bar anchorage is transferred to the head, causing a rise in head bearing.

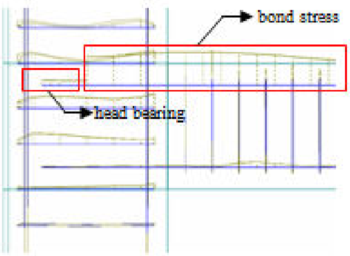


Figure 27. Stress sigma xx of headed anchorage bar

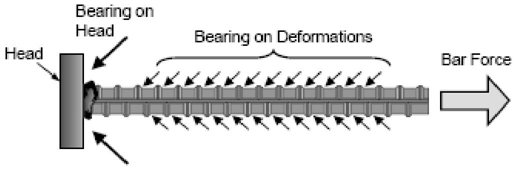


Figure 28. Stress transfer in headed bar

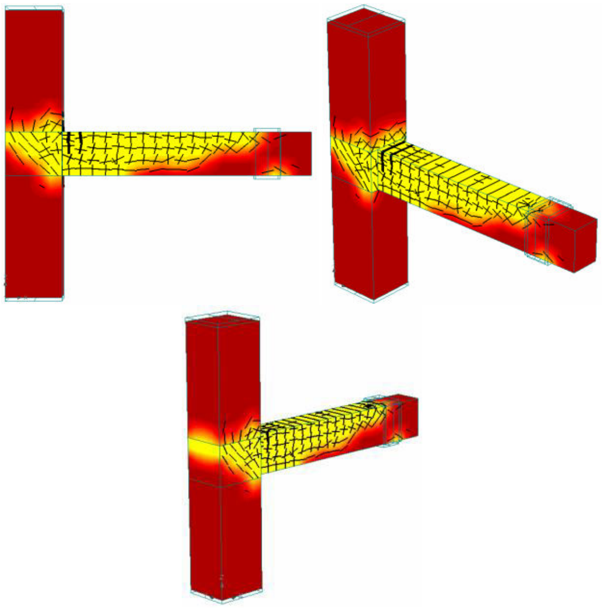


Figure 29. Area of tensile stress and crack pattern HD-22

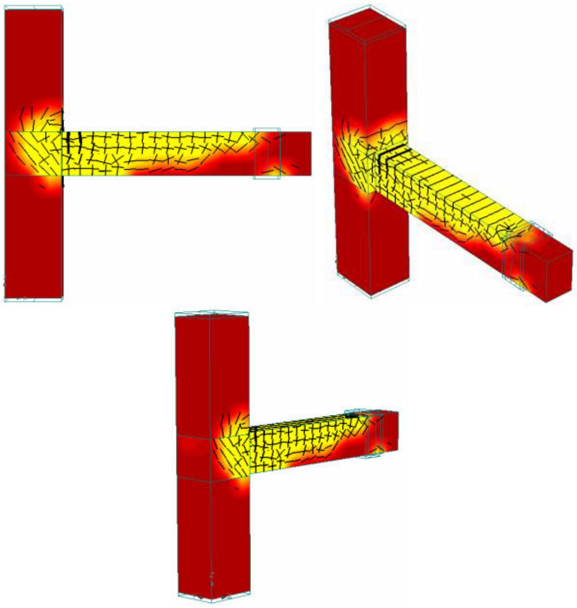


Figure 30. Area of tensile stress and crack pattern HK-22

Headed bar anchorage is provided by a combination of head bearing and bond. Initial anchorage is carried primarily by bond. As additional stress is applied to the bar, bond achieves peak capacity and begins to decline. As the process of bond deterioration occurs, bar anchorage is transferred to the head, causing a rise in head bearing. The anchorage capacity at failure is provided by a combination of peak head bearing and reduced bond. This pattern of behavior was observed in CCT nodes (Figure 31). Using this understanding of headed bar anchorage, a model for anchorage capacity was developed based on separate models for the head bearing and bond components.

The anchorage mechanism of headed bars is typically modeled according to strut-and-tie concepts with the bar head region classified as a compression-compression-tension (CCT) nodes. These nodes are further classified as either surface CCT nodes or interior CCT nodes, depending on the location of headed bars. The interior CCT node is formed inside a member such as an exterior beam-column joint. the dimension of the interior CCT node is determined from internal stress fields. Fan shaped stresses is shown in Figure 32, it is formed from bond stresses along anchorage length of headed bar.

The crack that occurs in beam-column joint is diagonal crack pattern. From STM the crack patterns due to tensile and compressive stress can be clearly described. Failure mode regarding headed bar anchorage in an exterior beam-column joint is joint shear faiure, this failure mode governs the response of an exterior beam-column joint.

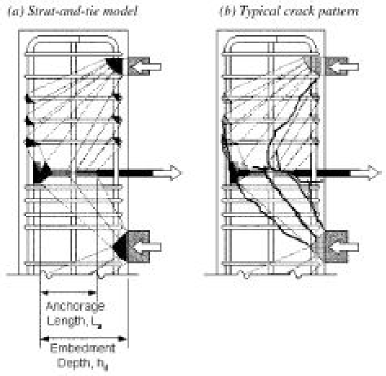


Figure 31. Strut-Tie Model and Crack Pattern (M. K. Thompson)

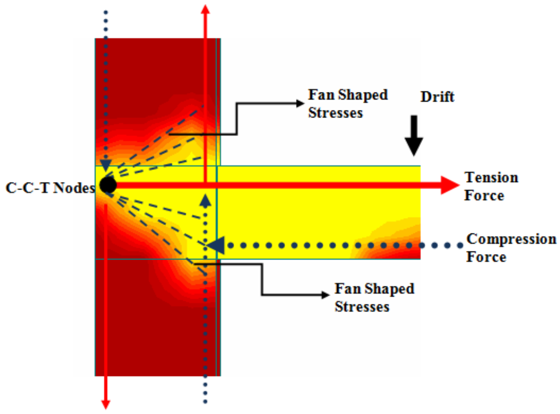


Figure 32. Load path of C-C-T nodes

The behavior on the discontinuity region of the column beam joints can be obtained with the STM approach. Nodal generated by the headed bars has been studied and classified. According to the two loading conditions experienced by the headed bar, strut (compression field) and tie (tensile stress), there are generally two types of nodes in the beam joints of the column, namely Compression-Compression-Tension (C-C-T nodes) and Tension-Tension-Compression (T-T-C nodes).

C-C-T nodes occurs at the headed bar in tensile state, where the T-T-C nodes is in compression. At the C-C-T nodes, the compressive force is produced by concrete and tensile forces by reinforcing steel. Where, on the T-T-C nodes the opposite occurs, the compressive force is produced by the reinforcing steel and the tensile force by the concrete. Thus the T-T-C nodes is weaker than C-C-T.

The type of failure that occurs in specimen HD-D22 which loaded with monotonic load is joint shear crack and flexural crack. The type of failure is affected by the length of the head and the head of the head.

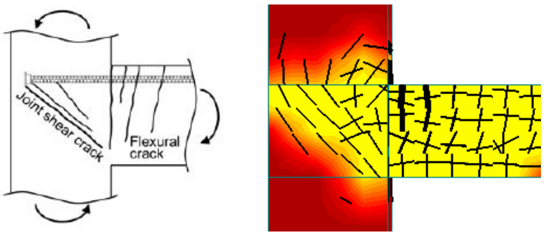


Figure 33. Joint shear and flexural crack

The compression force will be transferred to the concrete behind the bar head, therefore the concrete cover should be designed with sufficient thickness in order to withstand concrete push-out.

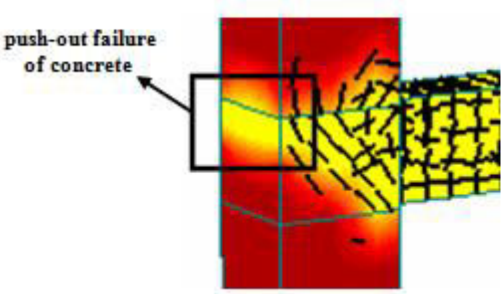


Figure 34. Concrete push-out failure

VIII. CONCLUSIONS

A Strut and Tie Model is proposed to investigate the mechanism of force transfer with using headed achorage bar. The result obtained from numerical analysis by ATENA 3D and previous experimental test (Irvan Simamora, et. al.) have close and far-reaching result, this is described by the backbone curves for each test. Based on this study, the following conclusions are drawn:

1. The maximum load achieved due to the application of monotonic load between the headed bar and hooked bar only has 2.08% difference. It means exterior beam-column joint which using headed bar has same capacity with hooked bar.
2. The presented STM with development of C-C-T nodes clearly explains two different load transfers from the headed bar to the exterior beam-column joint. A strut with uniform stress field from the head to the compressive zone of the beam represents the head bearing resistance, and a fan-shaped compression field along interface of the headed bar/concrete represents the bond resistance.
3. The stress field for bond resistance determines the controlling failure mode of deep beam with a headed bar. If the shear stress at the headed bar/concrete interfaces reaches its bond strength, bond failure occurs. When the principal stress of the stress field reaches an effective compressive strength of concrete, concrete diagonal crushing failure occurs.
4. The proposed models are capable of explaining the failure mode and the ultimate load for a headed bar in C-C-T nodes depending on the head size, material strengths, and the surrounding structural configuration including geometry and reinforcement details. When a headed bar is anchored into an exterior beam-column joint as beam main reinforcement, bond failure is expected considering the practical range of material and geometric characteristics.

IX. REFERENCES

[1] I. Simamora, I. Imran, and F. Yamazaki, "Experimental Study on The Performance of Headed Anchorage Bar in Beam-Column Joints," in *Proceeding the 6th Civil Engineering Conference in Asia Region: Embracing the Future through Sustainability*, 2013.

[2] ATENA Program Documentation Part 1. (2007). Theory. Cervenka Consulting, Prague, Czech Republic.

[3] ATENA Program Documentation Part2-2. (2007). User's Manual for ATENA 3D Version 3.3.2. Cervenka Consulting, Prague, Czech Republic.

[4] ATENA Program Documentation Part4-2. (2007). Tutorial for Program ATENA 3D. Cervenka Consulting, Prague, Czech Republic.

[5] Dewobroto, W. "Simulasi Keruntuhan Balok Beton Bertulang Tanpa Sengkang dengan ADINA", Prosiding Seminar Nasional "Rekayasa Material dan Konstruksi Beton 2005", Bandung, 4 Juni

[6] American Concrete Institute. 2014 . *Building Code Requirements for Structural Concrete* (ACI 318-14). America.

[7] SNI 03-2847-2013. (2013), *Tata Cara Perencanaan Struktur beton untuk Bangunan Gedung.* Badan Standardisasi Nasional. Jakarta, Indonesia.

[8] Imran, I., & Hendrik, F. (2014), "Perencanaan Lanjut Struktur Beton Bertulang", Penerbit ITB, Bandung.

[9] Hardjasaputra, H., & Tumilar, S. (2002), "Model Penunjang dan Pengikat (*Strut-and-Tie Model*) Pada Perancangan Struktur Beton", Universitas Pelita Harapan, Jakarta.

[10] Kotsovos, Michael D. (2015). *Finite Element Modeling of Structural Concrete.* CRC Press, New York.

[11] Kwak, Hyou-Gyoung & Filippou F. C. (1990). *Finite Element Analysis of Reinforced Concrete Structures Under Monotonic Loads.* Department of Civil Engineering. University of California, Barkeley.

[12] MacGregor, J. G., & James K. W. (2006). *Reinforced Concrete Mechanics and Design*. 4th ed. Prentice Hall, Singapore.

[13] Goto, Yukimasa, "Cracks Formed in Concrete Around Deformed Tension Bars," *Journal of the American Concrete Institute, Proceedings Vol. 68*, Detroit, Michigan, April 1971.

[14] Dilger, W.H. and Ghali, A., "Double-Headed Studs as Ties in Concrete," *Concrete International, Vol. 19, No.6, pg. 59-66,* Detroit, Michigan, June 1997.

[15] Mains, R.M., "Measurement of the Distribution of Tensile and Bond Stresses Along Reinforcing Bars," Journal of the American Concrete Institute, Proceedings, Detroit, Michigan, November 1951.

[16] Chun, S.C. & Kim, D.Y. (2004). *Evaluation of Mechanical Anchorage of Reinforcement by Exterior Beam-Column Joint Experiments.* Vancouver.

[17] DeVries, R.A. (1996). *Anchorage of Headed Reinforcement in Concrete.* Texas: The University of Texas at Austin.

[18] R. Park and T. Paulay . 1975 . *Reinforced Concrete Structures . Department of Civil Engineering . University of Canterbury .* Christchurch . New Zealand.

[19] Thompson, M., Jirsa, J.O., Breen, J.E. & Klingner, R.E. (2002). *Anchorage Behavior of Headed Reinforcement: Literature Review.* Texas: Center for Transportation Research Bureau of Engineering Research The University of Texas at Austin.

[20] Thompson, M.K., Jirsa, J.O. & Breen, J E. (2006). Behavior and Capacity of Headed Reinforcement. *ACI Structural Jurnal,* Volume 103.

[21] Wallace, J.W. (1996). *Use of Mechanically Anchored Bars in Exterior Beam-Column Joints Subjected to Seismic Load,* LA: Department of Civil Engineering University of California.

[22] Wallace, J.W. & McConnell, S.W. (1995). *Use of Headed Reinforcement in Beam-Column Joints.*

[23] Chun, S.C. & Hong, S.G. (2009). Strut-and-Tie Models for Headed Bar Development in C-C-T Nodes. *ACI Structural Journal,* Volume 106.