



## Numerical Modeling of the Collapse Behavior of Tall Reinforced Concrete Beams

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### ABSTRACT

The strut-and-tie model method is a structural design approach based on identifying D-regions and B-regions in reinforced concrete members. This study aims to investigate numerical simulation of a deep beam model using the finite element method in SAP2000 v14 to obtain parameters required for strut-and-tie design. The simulation results illustrate stress and deflection trajectories within the model. The findings indicate that the maximum deflection at the ultimate load is 2.0041 mm. In terms of stress distribution, the maximum compressive stress (S11) at the ultimate load reaches 36 MPa, while the maximum tensile stress (S22) at the support region is 100 MPa

## INTRODUCTION

The collapse behavior of tall beam structures is essential to study in order to understand the performance of such structures. This behavior can be determined through laboratory simulations, specifically by conducting experimental tests on structural beam specimens with a loading history applied to the structure until collapse, or through finite element method numerical simulations using software. In laboratory simulations, a proper understanding is required regarding the idealization of the actual beam structure into a model to be tested in the laboratory; strain gauge installation techniques, load models and types, and support model details significantly influence the analysis results obtained. Modeling and simulation using software require a basic understanding of theory and concepts.

The objectives of the research in this study are to examine the strut-and-tie model method for the design of high-rise reinforced concrete beams, to study the numerical simulation of the finite element method on a test specimen model to obtain the parameters required for the design of the strut-and-tie model, to investigate the failure behavior of high-rise reinforced concrete beams, and to conduct a comparative study of the results of the finite element method on the high-rise beam test model with the results of Harjasaputra's experimental research (Harjasaputra, 2006).

This study adopts the test specimen model parameters derived from the experimental research on high-rise reinforced concrete beams conducted by (Harjasaputra, 2006) and employs the strut-and-tie model calculations in accordance with ACI 318-14. In 2010, (Pranata & Suryoatmono, 2019) simulated this test specimen model using ADINA software. In this study, we will resimulate the model using SAP v.14 software to examine the stress and deflection trajectories. The parameters studied are deformation, diagonal strut strength, and ultimate beam strength. 2D test specimen modeling (plane stress).

## LITERATURE REVIEW

### *Tall Beam*

A tall beam is a beam characterized by shear failure behavior. A beam is classified as a tall beam if its clear span length ( $l_n$ ) is equal to or less than four times its height (American Concrete Institute, 2008).

According to (SNI, 2019), a high beam is defined as a structural member that is loaded on one side and supported at the opposite end such that a compression zone, such as a strut, can form between the load and the support. It is further specified that the ratio of the beam's clear span to its height must meet the requirement  $(l/h) < 4$ . A high beam is also defined as a beam with a clear span  $l_n$  not exceeding four times the beam's height ( $h$ ) for uniformly distributed loads, or twice the effective beam height ( $2d$ ) from the bearing surface for beams with concentrated loads.



Figure 1. High Beam

High-rise beam structures are generally found in elements with a relatively small span-to-height ratio, so that shear behavior is more dominant than bending. Examples can be found in short-span beams that support large loads, where the stress distribution is no longer linear as in slender beams. Additionally, shear transfer beams fall into this category because they function to significantly transfer loads from the elements above them to the structural system below through a complex compression-tension mechanism. A similar phenomenon is observed in vertical walls bearing gravitational loads, which act as compression members with a significant shear contribution. Furthermore, shear walls designed to resist lateral forces caused by wind or earthquakes also exhibit the characteristics of tall beams, particularly regarding stress distribution and cracking patterns. In fact, floor slabs subjected to horizontal loads under certain conditions can behave as tall beams, especially when diaphragm action occurs, leading to uneven force distribution. In the design process, beams classified as tall beams must account for the nonlinear distribution of longitudinal strain along the beam height as well as lateral bending.

**Main Stress Trajectory**

(Hardjasaputra & Tumilar, 2002) explains that an elastic body subjected to a load prior to cracking will generate a compression field and a tension field. Principal stress lines are lines along which points with the same principal stress value lie, consisting of compression lines and tension lines. The trajectory lines indicate the direction of the principal stress at each point under consideration. Thus, stress trajectories are a set of lines representing the positions of points that have a principal stress of a specific value.

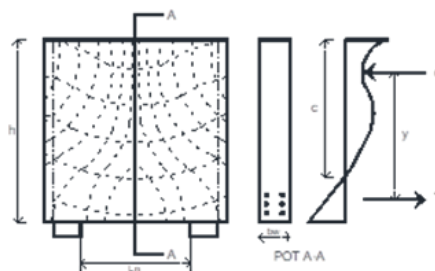


Figure 2. Stress Trajectory

Several key characteristics of stress trajectories reveal a systematic pattern of principal stress distribution within a structural element. At every point in the material, there are always two principal trajectories – the compression trajectory and the tension trajectory – whose directions are perpendicular to each other, representing the principal stresses. In a structural component subjected to loading, these trajectories do not exist in isolation but form two major groups: the compressive trajectory group and the tensile trajectory group, which describe the flow of forces within the element. As they approach the boundary or edge of the element, compressive and tensile trajectories tend to terminate at a right angle (90°), conforming to the existing boundary conditions. Meanwhile, in the neutral line region, the direction of the trajectories typically forms an angle of approximately 45°, indicating a transition condition between tensile and compressive dominance. The density of the trajectories also holds significant physical meaning; the closer the spacing between trajectories, the greater the value of the principal stress occurring in that region. Furthermore, the stress trajectory pattern is not always uniform throughout the structure; in certain regions such as region B, the trajectory pattern tends to be more regular and smooth, whereas in other regions such as region D, the pattern becomes more irregular (turbulent) due to the complexity of the stress distribution and the influence of loading conditions as well as element geometry.

#### ***Strut and Tie***

A uniform and consistent design approach for all types of structures and all structural components is essential; this approach must be based on realistic physical models. To this end, the strut-and-tie model method was pioneered by research conducted by (Schlaich et al., 1987) at the University of Stuttgart, Germany. It subsequently developed rapidly (Aldebar et al., 1990); (Reineck, 2002). Experimental research in Indonesia has been conducted, among others, by (Harjasaputra, 2006), specifically an experimental study on the loading of reinforced concrete beams until failure. The reinforced concrete beams tested had a span-to-height ratio of  $2.28/0.8 = 2.8125$ , which is greater than 2.5; therefore, according to the ACI 318R-08 criteria (ACI, 2008), they do not actually fall into the category of deep beams. Nevertheless, based on the failure behavior exhibited – specifically shear failure (diagonal splitting) – it can be categorized as a deep beam, whose behavior differs significantly from that of a conventional beam because it does not fail due to bending. The deep beam in question has the shape of a conventional rectangular beam; prior to testing, several strain gauges were installed, and subsequently, a loading test was conducted until failure occurred. During loading, strain and deflection were automatically recorded by electronic measuring instruments, while the crack patterns on the beam were sketched manually. Thus, information regarding the failure behavior of the deep-beam can be obtained.

#### ***Areas D and B***

Areas B and D of several beam types subjected to concentrated and uniformly distributed loads are shown in Figure 3. Area D or Area B is formed due to the influence of the height-to-span ratio, significant changes in structural geometry, the type of load, and the location of the supports. The geometric and load configurations determine both Area D and Area B.

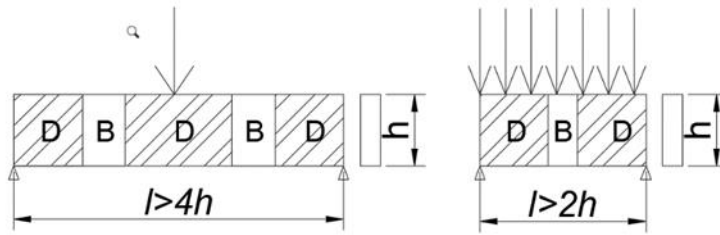


Figure 3. Areas D and B

(Schlaich et al., 1987) established a consistent design philosophy for structures composed of Zone D and Zone B, namely the Strut and Tie Model. Thus, while the entire structure can be designed using the Strut and Tie Model – which is more commonly applied in Zone D – Zone B is specifically focused on designing for shear and torsional effects. The application of the Strut and Tie Model in structural design begins with the determination of Zones D and B. In actual structures, Zones D and B may occur simultaneously; therefore, it is necessary to identify the division of these zones within the structure so that appropriate design procedures can be applied. For design in Zone B, Bernoulli's principle is used, and in Zone D, the Strut and Tie method is used. To clearly define Zone D, the boundary line between Zone D and Zone B must first be determined.

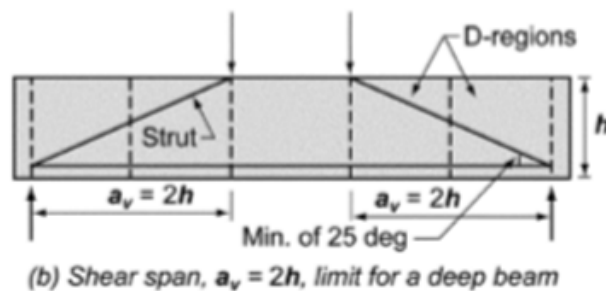


Figure 4. High Beam (ACI, 2008)

The design provisions for the components of strut-and-tie models are set forth in Appendix A, "Strut-and-Tie Models," of ACI 318R-14 (ACI 2014), and must in all respects meet the following strength requirements:

$$\phi F_n \geq F_u \quad (1)$$

The strut force is calculated using Equation 2

$$F_{ns} = f_{ce} \cdot A_{cs} \quad (2)$$

$$f_{ce} = 0.85 \cdot \beta_s \cdot f'_c \quad (3)$$

The tie force is calculated using Equation 4.

$$F_{nt} = f_{ce} \cdot A_{nt} \quad (5)$$

$$f_{ce} = 0.85 \cdot \beta_n \cdot f'_c \quad (6)$$

The objective of this study is to investigate the numerical simulation of a test specimen model using the SAP v.14 finite element method. This study employs a test specimen model based on the results of experimental research on high-rise reinforced concrete beams conducted by (Harjasaputra, 2006) and calculations using the strut-and-tie model in accordance with ACI 318-14. In 2010, (Pranata & Suryoatmono, 2019) simulated this test specimen model using ADINA software. In this study, we will resimulate the model using SAP v.14 software to examine the stress and deflection trajectories. The parameters studied are deformation, diagonal strut strength, and ultimate beam strength. 2D test specimen modeling (plane stress).

The implementation of a numerical simulation of the test specimen using the finite element method with nonlinear modeling in SAP v.14 software was performed separately for material behavior and element behavior. To study material behavior, a specific material feature available in SAP v.14 software – concrete – was used. Meanwhile, the element model utilized a 2D solid model, so the analysis employed the plane stress approach. The modeling of reinforcing steel in this study was performed using the 2D solid element feature combined with the bilinear material behavior of steel.

## METHODOLOGY

The case study in this research uses a reinforced concrete high-rise beam model derived from experimental research on high-rise beams (Hardjasaputra, 2006). The materials used are reinforcing steel with a yield strength ( $f_y$ ) of 435 MPa and concrete with a compressive strength ( $f'_c$ ) of 37 MPa. The experimental testing process involved testing the high-rise beam with a gradual loading history until failure. The loading history was divided into three stages: 300 kN, 600 kN, and 1100 kN. A sketch of the test specimen model can be seen in the figure below.

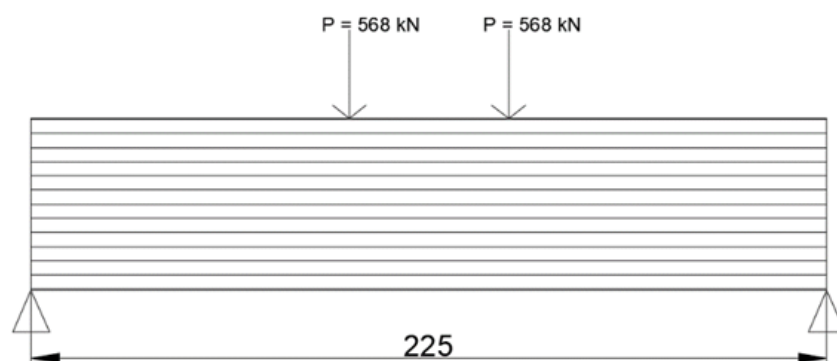


Figure 5. Sketch of the test specimen model

The collected primary data was analyzed using SAP v.14. When modeling the material properties of steel, the input parameters were the elastic modulus of steel ( $E$ ) at 200,000 MPa and the yield strength of steel ( $f_y$ ) at 435 MPa. The input data parameters for modeling concrete material properties using SAP2000 v14 software were determined based on the mechanical characteristics of concrete

relevant to structural behavior, particularly under nonlinear loading conditions. The Poisson's ratio of concrete in this study was assumed to be 0.2, representing the relationship between lateral strain and axial strain under elastic conditions. For the uniaxial compressive parameters of concrete, the maximum compressive strength is set at  $f'_c = 37 \text{ MPa}$ , while the ultimate compressive strength is determined as  $f'_{cu} = 0,85 f'_c = 31,45 \text{ MPa}$ . The ultimate compressive strain of concrete used  $\epsilon_{cu} = 0,0025$ , which represents the deformation limit of concrete before failure under compression. Meanwhile, uniaxial tensile parameters for concrete are particularly important in the analysis of reinforced concrete beams with potential shear failure. In this study, the post-cracking tensile stress ( $f_{ctp}$ ) is assumed to be equal to the uniaxial cut-off tensile stress ( $f_{ct}$ ). This value is calculated using the empirical equation by Bresler et al., 1963.

$$f_{ct} = 0,33\sqrt{f'_c} \quad (7)$$

The analytical steps in this study began with modeling the high-rise beam structure using SAP2000 v14 software, which is designed to represent the behavior of structural elements in a manner that closely approximates actual conditions. Next, loads were applied to the high-rise beam structural model in accordance with the loading scenarios examined in the study. The applied loads were then distributed across all shell elements in the high-rise beam using the Finite Element Method (FEM), enabling a more detailed and continuous stress analysis of each element section. This FEM-based modeling via SAP2000 v14 aimed to visualize the stress distribution patterns and determine the maximum stress intensities occurring within the structure. Stress evaluation is performed by referring to the element stress output, where component S11 represents normal stress along the main axis associated with the presence of tensile reinforcement, while component S12 represents shear stress associated with the mechanism of compression reinforcement in the high-rise beam system. With this approach, the stress distribution and concentration in high beams can be comprehensively analyzed as a basis for interpreting structural behavior.

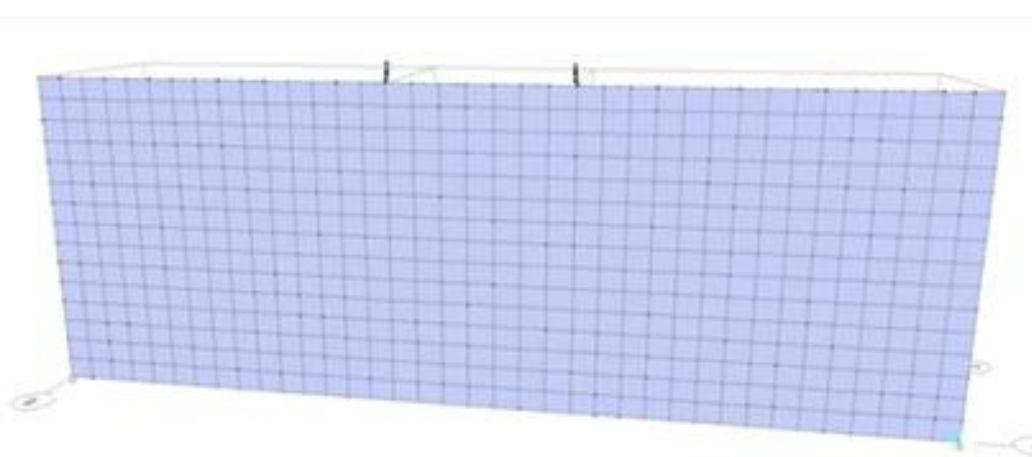


Figure 6. High Beam Model

## RESULT

### Calculations using the Strut and Tie Model

Calculations using the strut-and-tie model are performed manually based on analytical equations. The calculation steps include checking the support capacity (area of node 0 in the loading and support regions), selecting the strut-and-tie model for design, isolating the disturbed region, selecting reinforcement, calculating diagonal compression struts, and checking the capacity and reinforcement.

The predicted ultimate load  $P_u$  is 568 kN (Harjasaputra, 2006). Analytical calculations were performed without considering the  $\phi$  factor; the results obtained were compared with experimental test results.

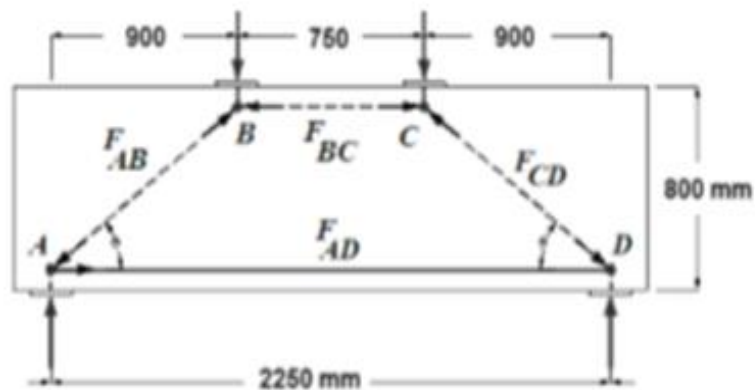


Figure 7. Strut and Tie Model for Design

### Calculations of the Strength of the Nodal Area

Calculation of the nodal area strength at the loading location ( $\beta = 1.0$  for the CCC type) using the following equation:

$$F_{nn} = f_{ce} \cdot A_{ns}$$

$$F_{nn} = 0,85 * 1,0 * 37 * 150 * 250.$$

$$F_{nn} = 1179375 \text{ N} = 1179,375 \text{ kN}$$

Calculation of the nodal area strength at the support location ( $\beta_n = 0.8$  for CCT type) using Equation 5.

$$F_{nn} = f_{ce} \cdot A_{ns}$$

$$F_{nn} = 0,85 * 0,8 * 37 * 150 * 250$$

$$F_{nn} = 943500 \text{ N} = 943,5 \text{ kN}$$

The calculation results show that the stress at the nodal points at the loading and support locations is greater than the predicted ultimate load.

### Strength Calculation for Strut BC and Tie AD

The strut BC is calculated using Equation c, and the tie AD is calculated using Equation 4. The magnitudes of the factored forces  $F_{AD}$  and  $F_{BC}$  can be calculated using the moment equilibrium equation at point A.

$$\sum M_A = 0$$

$$F_{BC} = \frac{511200000}{800 - 1.125w_c}$$

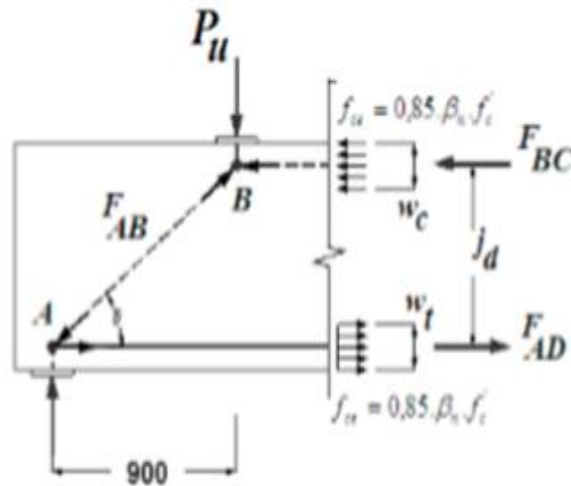


Figure 8. Design of Strut and Tie Strength (Harjasaputra, 2006)

The load factor  $F_{BC}$  is calculated as follows :

$$F_{BC} = \frac{511200000}{800 - 1.125w_c} = 743563,64 \text{ N} = 743,56 \text{ kN}$$

$$F_{AD} = F_{BC} = 743.56 \text{ kN}$$

Next, the strength capacity of the BC strut is calculated using Equation 2.

$$F_{ns} = f_{ce} \cdot A_{cs}$$

$$F_{ns} = 0.85 * 1,0 * 378250 * 100$$

$$F_{ns} = 786250 \text{ N} = 786.25 \text{ kN}$$

The calculation results show that the design strength of the BC strut  $F_{ns}$  is greater than the load factor of the BC strut ( $F_{BC}$ ). Meanwhile, the AD tie calculation is performed using 4.

$$F_{ns} = A_{st} \cdot f_y$$

$$F_{ns} = 1962,5 * 435$$

$$F_{ns} = 853687,5 \text{ N} = 853,69 \text{ kN}$$

The calculation results show that the strength of the AD tie is greater than the factored load on the AD tie.

#### **Strut AB Strength Calculation**

The diagonal compression force ( $F_{BC}$ ) can then be calculated:

$$F_{BC} = \frac{568000}{\sin 40,657^\circ} = 871477,42 \text{ N} = 871,477 \text{ kN}$$

The width of the strut at the top:

$$w_{ct} = 250 * \sin 40,675^\circ + 100 * \cos 40,675^\circ = 238,784 \text{ mm}$$

The width of the strut at the bottom:

$$w_{cb} = 250 * \sin 40,675^\circ + 125 * \cos 40,675^\circ = 257,74 \text{ mm}$$

Next, the capacity of strut AB is calculated (checked) ( $\beta_s = 0,75$ )

$$F_{ns} = f_{ce} \cdot A_{cs}$$

$$F_{ns} = 0,85 * 0,75 * 37 * (250 * 238,784)$$

$$F_{ns} = 1408079,4 \text{ N} = 1408,08 \text{ kN}$$

The calculation results show that the design strength of strut AB is greater than the factored load on strut AB.

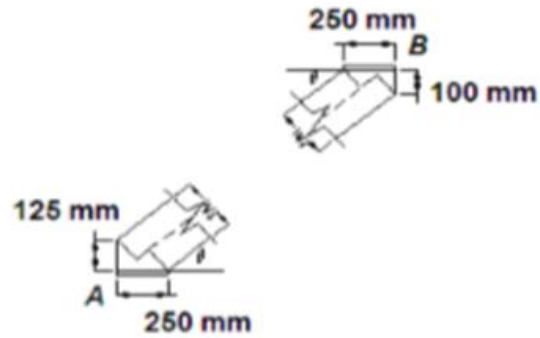


Figure 9. Details of Point A and Point B (Harjasaputra, 2006)

## DISCUSSION

The test specimen has a symmetrical shape, and the two concentrated loads are also placed symmetrically (Figure 10). The beam was modeled as a shell using SAP v.14 software to determine the stress and deflection trajectories under a specified ultimate load.

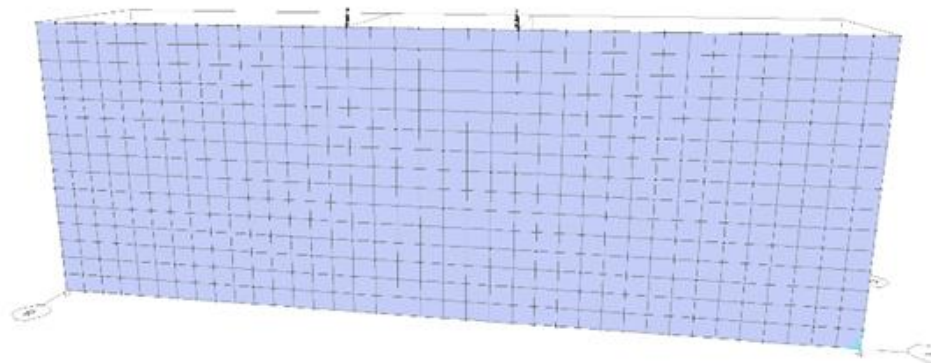


Figure 10. Structural Idealization

The modeling shown in Figure 10 was performed based on the span length and beam height. To represent the truss elements as a simulation of steel reinforcement, the modeling strategy involved placing objects such as nodes and lines, with their spacing adjusted according to the structural drawing details. Meanwhile, the concrete was modeled using surface objects with 2D solid elements.

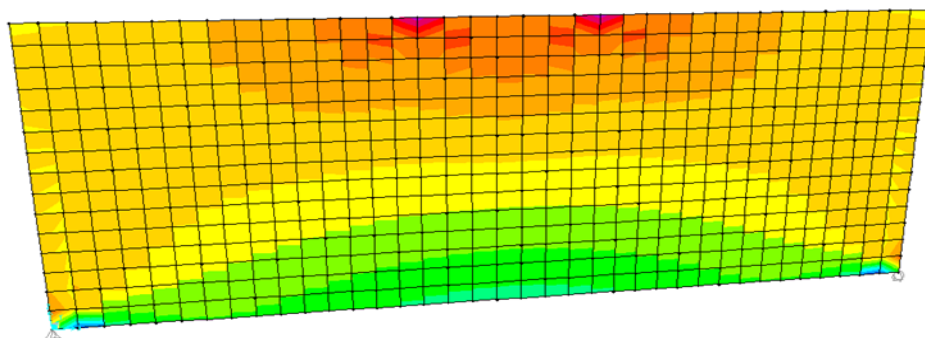


Figure 11. Compressive Stress Trajectory

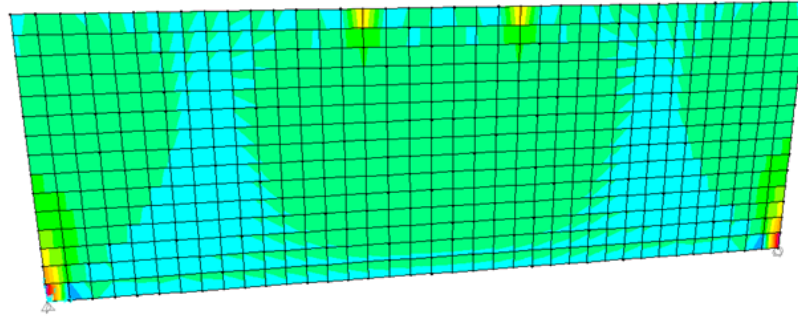


Figure 12. Tensile Strength Trajectori

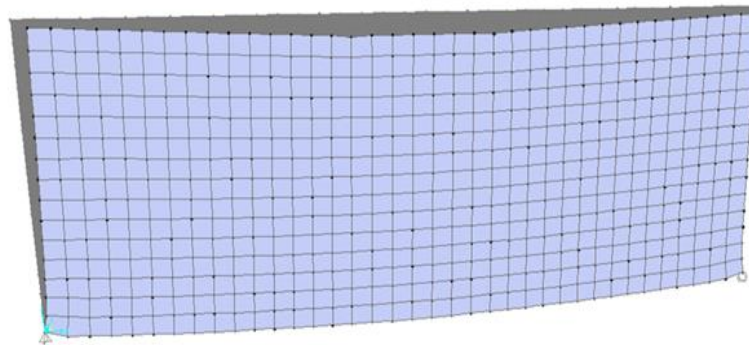


Figure 13 Defleksi Trajectori

From the results of the modeling using SAP v.14 software, we can determine the stress and deflection values. The strain values can be obtained from the stress results. At the ultimate load position, the maximum compressive stress is 36 MPa and the maximum deflection is 2.0041 mm. Meanwhile, at the support position, the maximum tensile stress is 100 MPa, and there is no deflection because it is supported by a fixed support.

## CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, it can be concluded that:

1. SAP v.14 simulation was used to predict the magnitude of compressive and tensile stresses in a tall beam.
2. The magnitude of tensile stress is greater than that of compressive stress at the specified ultimate load.
3. The maximum compressive stress occurs at the ultimate load position, while the maximum tensile stress occurs at the support position, and the maximum deflection occurs at the maximum load position.

## ADVANCED RESEARCH

This study has several limitations that provide opportunities for further development in future research. The numerical modeling conducted using SAP2000 v14 is based on a two-dimensional plane stress approach, which may not fully capture the three-dimensional stress distribution and confinement effects present in actual reinforced concrete deep beam behavior. In addition, the

material modeling of concrete adopts simplified nonlinear parameters, particularly in representing post-cracking tensile behavior, which may influence the accuracy of crack propagation and failure pattern predictions. Future research is recommended to extend the analysis into three-dimensional finite element modeling to better represent the actual structural response, especially for complex loading and boundary conditions. Furthermore, the implementation of more advanced constitutive models for concrete, such as smeared crack or damage plasticity models, is necessary to improve the accuracy of nonlinear behavior simulation. Experimental validation using updated instrumentation techniques, such as digital image correlation (DIC), is also suggested to enhance the reliability of numerical results. In addition, further studies can investigate the influence of reinforcement detailing, such as varying reinforcement ratios and configurations, on the failure mechanism and load-carrying capacity of deep beams. The integration of parametric studies and optimization approaches is also recommended to develop more efficient and economical design guidelines based on the strut-and-tie model, particularly in accordance with updated codes such as ACI 318 and SNI 2847.

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