Design of RC deep beam based on SNI 2847:2019 and analysed using STM and CAST

Muhammad Aswin*, Tonny, and Sonny

Civil Engineering Department, Faculty of Engineering, Universitas Sumatera Utara, Medan, Indonesia

*Email: muhammad.aswin@usu.ac.id

Abstract. Up to present, many studies and researches on reinforced concrete (RC) deep beams had been carried out in order to obtain an effective design approach. The strut-and-tie model is the most widely known and has even been included in various design codes. SNI 2847:2013 lately introduced new code provisions in designing on RC deep beam which is improved in SNI 2847:2019. Design which using the manual calculations takes quite a lot of time, accordingly, for saving time of design and analysis, the modelling program such as CAST (Computer Aided Strut and Tie) can be used. CAST is Strut-and-Tie (STM)-based, easy to be used, and presents a complete package of both design and analytical tools. This study is aim to introduce Indonesian code (namely SNI 2847:2019) in design and analysis of RC deep beam based on STM, which analysed by using CAST. The results have shown that design and analysis based on SNI 2847:2019 quite effective. The force ratio of analysis results either STM and CAST is less than 1 (one), meaning that the design result can be applied.

1. Introduction

In general, foundations, pile caps, bridges, and shear walls, etc. have utilized RC deep beams. This is because the deep beam is able to carry large shear loads on its elements. Deep beam can be designed in such a way both single and continuous [1]. The design of the beam generally uses the Bernoulli hypothesis where the stress distribution is considered linear over the cross section and the shear is considered to have a non-significant effect. In contrast to ordinary beam, deep beam is a type of beam which dimensions of the net stretch ln are implied to be no more than four times the beam height (h) [2]. Deep beam has undergone various developments in its design methods. Many researches and studies have been carried out to make the most effective deep beam design. One of the best known and most widely used methods is the strut-and-tie method, which was the forerunner of the strut-and-tie was adopted through the concept of the Truss Analogy concept which was first introduced by Ritter [3] and Mörsch [4]. The strut-and-tie method was then developed by Schlaich [5] for D-region analysis. This method is basically the development of the truss analogy method originally proposed by Ritter.

Because of its superiority and simplicity for analyzing disturbed areas, this method has been adopted by many design regulations in various countries [6]. Several code provisions for designing the strut-and-tie method approach have undergone various updates and developments such as Eurocode [7], Canadian Standard for the Design of Concrete Structures since 1984 [8] and ACI 318 Building Code the 2002 edition [9]. SNI 2847: 2013 also recently added the strut-and-tie method for deep beam...
design in its code and get some improvements in SNI 2847: 2019. The safety of the design approach using strut-and-tie method is determined by the stress limit requirements as specified by the codes and plasticity assumptions that apply to the D-region in accordance with the strut-and-tie model that has been made. Even though various researches have been carried out with regard to strut-and-tie method, there is still no definitive modeling for each design. Therefore, the assumption of the truss modeling is very varied and needs to be checked for the feasibility of its use [10].

Although the strut-and-tie has been widely used, the design itself takes quite a lot of time in determining the struts and ties dimensions. Tjhin, et al [11] developed a software-based solution incorporating strut-and-tie which helps reduce the time in designing structures with strut-and-tie. Al-Bayati, et al [10] also then did the RC deep beam design with STM based software where the design he made showed very effective way in time.

The main objective of this paper is presenting a guide for designing RC deep beams by using SNI 2847:2019. Then, the design results were analyzed using STM and CAST. The final aim of this analysis is to obtain the force ratio (FR).

2. Design of Deep Beams

2.1. Design Specification
In a deep beam design, the required net span length \( l_n \) is equal to or less than 4 times the height of the overall structural component. Deep beam must also have the condition that the beam region with a load is centered within \( 2h \) of the supports which is loaded on one side and supported on the opposite side in such a way that a compressed path can be formed between the load and the supports. SNI 2847:2019 provides a condition that a deep beam must be designed taking into account the nonlinear longitudinal strain distribution. Clause 23 of SNI 2847:2019 contains steps for the deep beam design using the strut-and-tie method. Besides, the deep beam must be proportioned so that \( V_u \) is less than or equal to \( 0.83\sqrt{f'_c b_d}d \).

Deep beam requires shear reinforcement which must be installed along the span and distributed on the two sides of the deep beam. The total distributed distance along the two sides of the deep beam must not be less than the following requirements:

- The area of the shear reinforcement which is perpendicular to the longitudinal axis of the beam, \( A_v \), must not be less than \( 0.0025b_w s \), and \( s \) must not exceed smaller than \( d/5 \) and 300 mm.
- The area of shear reinforcement which is parallel to the longitudinal axis of the beam, \( A_{vh} \), must not be less than \( 0.0025b_w s_2 \), and \( s_2 \) must not exceed smaller than \( d/5 \) and 300 mm.

2.2. Details of Specimen
Concrete deep beam is designed with height \( h \) is equal to 1500 mm, and loading and support plate width \( l_b \) is 150 mm. 2 point-loads are applied to beam which each is located on 1/3 and 2/3 of total span. Each applied load is 1000 kN. According to code, Net span \( l_n \) will be designed not more than 4h, then we take the total span of \( L \) equal to 6150 mm. Details of the specimens are presented in Figure 1. The actual cylindrical compressive strength of concrete was assumed to be 30 MPa. Both longitudinal steel and transverse steel of specified yield strength of 400 MPa was used.
2.3. Design of Reinforcement in Deep Beams Using Strut-and-Tie Model

Applied loads at the beam in two equal loads are symmetrical. Many possible truss models can be used for the given loading and geometry of the deep beams. To attain the most appropriate model, it can refer to the stress flows that occur in the deep beam. Figure 2 shows the stress flows in the deep beam modelled by using LUSAS14 Software.

Based on the stress flows as shown in Figure 2, it can be assumed the truss model which is presented in Figure 3(a) which has trapezoidal shape. Meantime, the truss model as exhibited in Figure 3(b) was proposed by Gaetano Russo, et al. [12]. The procedures for designing the RC deep beams which adopted from SNI 2847: 2019 can be explained as follows:

1. Define the geometry of truss model
   To obtain effective height $d_e$, the height of the nodal zones must first be assumed based on the stress flow. Then determine the $\theta$. The angle $\theta$ must not be taken at less than 25° [2].
2. Resolving the assumed truss model to define member forces
The member forces for the truss model are determined from equilibrium conditions. Member forces were analyzed by using SAP2000. The truss forces are shown in Figure 4. The tensile forces are carried by the tensile reinforcement and the compressive forces shall be carried by the concrete.

![Figure 4. Member forces by applied loads in the truss model](image)

3. Checking the bearing capacity
   The applied stress on both bearing plates at loading and support locations must not exceed the node strength given by SNI 2847:2019.

4. Designing and Verifying Struts and Ties Capacities
   The diagonal struts and the horizontal strut are both assumed as prismatic. The strut capacities then were checked against the forces in specified member. Computed width both struts and ties are given in Figure 5.

5. Designing the reinforcement for tension area and body reinforcement.

6. Checking the strength of nodal zone and anchorage
   The nodal capacity of struts and tie is checked for all nodes. the designed nodal capacity must meet the permissible limit. The details of the beam finally designed is shown in Figure 6.
3. Analysis

3.1. Analysis by Using Strut-and-Tie Method
Analysis was carried out on both truss models. The deep beam which had been designed by SNI 2847:2019 steps analysed to obtain the force ratio. Force ratio is the quotient of the force acting with the section capacity. If the force ratio obtained is less than 1, it means that the STM model can be applied to the deep beam which was designed by using SNI provisions before. The analysis results of each model are presented in Table 1 and 2.

| Member | Type  | $\Phi F_{ns}$ (kN) | $F_u$ (kN) | Force Ratio |
|--------|-------|--------------------|------------|-------------|
| 1-2    | Strut | 2237.625           | 1834.9     | 0.820       |
| 2-3    | Strut | 1549.125           | 1538.46    | 0.993       |
| 3-4    | Strut | 1549.125           | 1538.46    | 0.820       |
| 1-4    | Tie   | 1596.56            | 1538.46    | 0.964       |

| Average results | 0.899 |

Figure 6. Final design of RC deep beam
| Member | Type | $\Phi F_m$ (kN) | $F_u$ (kN) | Force Ratio |
|--------|------|-----------------|-----------|-------------|
| 1-2    | Tie  | 1596.557        | 769.22    | 0.482       |
| 2-3    | Tie  | 1020.703        | 999.96    | 0.980       |
| 2-6    | Tie  | 1596.557        | 1538.45   | 0.964       |
| 6-8    | Tie  | 1596.557        | 769.22    | 0.482       |
| 6-7    | Tie  | 1020.703        | 999.96    | 0.980       |
| 1-3    | Strut| 1583.55         | 1261.61   | 0.797       |
| 2-4    | Strut| 1836            | 1261.61   | 0.687       |
| 3-4    | Strut| 963.9           | 769.23    | 0.798       |
| 4-5    | Strut| 1549.125        | 1538.45   | 0.993       |
| 5-6    | Strut| 1836            | 1261.61   | 0.687       |
| 5-7    | Strut| 963.9           | 769.23    | 0.798       |
| 7-8    | Strut| 1583.55         | 1261.61   | 0.797       |

Average value 0.787

3.2. *Analysis by Using CAST*

Analysis was also performed using the CAST program. CAST is a program developed by University of Illinois to facilitate design on the basis of the strut-and-tie model. Creation or modification of strut-and-tie models, truss analysis, selection of reinforcing steel, and capacity checks of the struts and nodes were utilized by CAST. The use of CAST is also not difficult and quite user friendly. By using CAST, it can easily measure the efficiency of the design results. In brief, analysis of deep beam using CAST can be summarized into five steps below:

1. **Setting Up the Workspace**
   In the beginning, user will be asked to fill in the project description. After filling in the project description, fill in the d-region thickness and material strength to be used. D-region thickness is the transverse structure thickness to be analyzed. Before drawing the model correctly, first determine the guidelines and grid points. These guidelines and grid points will be very helpful in drawing the whole structure. Grid points are important coordinate points which can then be used to draw lines later.

2. **Constructing the Model**
   After the guideline is created, now construct the model according to our design. Specify the outer line, the pre-made strut-and-tie models, bearing plates, and loading and supports.

3. **Obtaining Strut-and-Tie Model Forces**
   To determine whether the strut-and-tie model that we created is correct, we must run the truss analysis. If an error occurs, then the model we use is invalid so we need to change the strut-and-tie model first. But if the analysis of the program is successful, the results will show compression and tension members and their values.

4. **Defining and Assigning Properties**
   After the compression and tension values appear, now determine the dimensions of the struts and tie that will be used. All the properties used in this design are in accordance with previous deep beam design calculations. In this CAST analysis program, we cannot define two dimensions of width on one strut. Both faces are defined with the same width of 240 mm in accordance with the results of the previous design calculations based on SNI 2847: 2013 Code.

5. **Checking Stresses**
Struts and tie characteristics that have been defined in the program are then analyzed again with “Run Truss Analysis” command. The results will show the efficiency of the stresses in the strut and tie sections. It is also possible to check stresses on each nodal face. Efficiency that is stated to be safe is not more than 1. If the efficiency value shows more than 1, it means that the width of the strut or tie is not suitable for use. Then, modify the strut or tie width and run the analysis again. Figure 7 shows the result of analysis with CAST program based on calculated design properties before. Figure 7(a) shows the results of Model-1 analysis and Figure 7(b) shows the results of Model-2.

Figure 7. Analysis results by using CAST for each model

4. Result and Discussion
Analysis results based on STM and CAST can be seen in Table 3. This table shows the comparison of average force ratio according to the STM and CAST analysis. The results show that the force ratio of all strut and tie member meets the safety requirements (less than 1). It means that these truss models are applicable to design the RC deep beam using SNI 2847-2019 provisions. The analysis results between STM and CAST has no significant difference, which indicates that CAST is quite effective to be utilized to analyze the RC deep beam.

| Model | Average Force Ratio |
|-------|---------------------|
|       | STM     | CAST     |
| 1     | 0.899   | 0.895   |
| 2     | 0.787   | 0.784   |

5. Conclusions
The results of the analysis can be concluded below:
1. The strut-and-tie model according to SNI 2847:2019 provision is an ideal method to design and analyze the RC deep beams.
2. The truss model of RC deep beam can be approached based on the stress trajectory or stress flows that simulated using FEM.
3. The design results of both truss model provided no significant different.
4. The results STM and CAST analysis shows the efficiency meets the permitted requirements which are less than 1. CAST is effective way to analyze the RC deep beam.


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