Design and analysis of RC corbel based on SNI 2847:2019 and analysed using computer aided strut-and-tie model

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Abstract. In this study, the corbel has been reviewed by considering its design and analysis based on Strut-and-Tie Model (STM). Many studies on corbels had been carried out in order to obtain an effective design approach. SNI 2847-2019 is one code that regulate to design and analyse corbel using STM. For initial stage, dimensions and steel reinforcements of corbel are designed using SNI 2847-2019 based on the empirical formulas. Afterward, design and analysis corbel were conducted using two different truss models. Aside from that, the Computer Aided Strut and Tie (CAST) software was applied on last analysis stage. Each analysis was required to generate the force ratio (FR), so it can be determined reliability of the used truss models. The design results based on the used models exhibited that the steel reinforcements of corbel are quite similar. In addition, the average force ratio for Model-1 and Model-2 are gained of 0.6204 and 0.6147, respectively. Meanwhile, the CAST analysis results also provided similar force ratio, namely 0.5805 and 0.5985 for each Model-1 and Model-2. Accordingly, STM and CAST can be used to design and analyse corbels.

1. Introduction

Corbel is a structural element that functions to transfer the loads of beam and slab to the columns or walls [1]. In addition, Mattock et al [2] explained that corbel is usually made and placed on the front side of the column, and is often used in precast concrete construction to carry the main beam. Meantime, El-Maaddawy and El-Sayed [3] stated that corbel is widely used in the construction of precast buildings such as parking buildings, factories (workshops), warehouses, houses, offices, bridges, etc.

Due to the shape and its function, corbels always fail in the shear failure mode. This condition is quite dangerous. Accordingly, needs to provide the corbel design formula. Then, the shear capacity of the corbel can be generated [4]. Russo, et al. [4] also explained that failure modes that might occur in consoles without stirrups can cause shear failure or flexural failure, as well the strut concrete cracking or diagonal concrete separation. In addition, Dipohusodo [5] states that the shear strength of a corbel cannot be completely equated with a deep beam.

Corbels can be categorized as the structural element that having discontinuous or disturbance area. This is because the actual strain distribution that occurs in the corbel was already non-linear. The strut-and-tie model (STM) method that was first introduced by Ritter (1899) and Morsch (1902) can be applied. This method is very useful in describing the strength in the discontinuity or disturbed region.

Al-Bayati [6] explains that currently the use of the strut-and-tie model method is quite extensive in its use, however in analytical applications, it takes a lot of time in the design and analysis process. Therefore, various software is needed to overcome this problem. In addition, Johnson [7] asserts that the simulation and modeling of structural elements, both in terms of design and analysis, is greatly helped by the existence of finite element modeling (FEM) software. Thus, main objective of this study is presenting a guide for designing corbel by using SNI 2847:2019 [8] approach. The design and analysis stage were also done by using other Truss Models based STM, and then analyzed completely using the CAST software.
2. Design of Corbel

2.1 Design Specification

In order to design a corbel, shear span-to-depth ratio \((a/d)\) has to be less than 1. The section 16.5.1.1 of SNI 2847:2019 [8] provides the design steps for corbel using empirical method. As well, the corbel must be proportioned, so that \(V_u\) is less than or equal to \((0.2 \times f'_c \times b_w \times d); ((3.3 + 0.08 \times f'_c) \times b_w \times d); (11 \times b_w \times d)\). Aside from that, if the corbel was designed using STM, the shear span-to-depth ratio \((a/d)\) has to be less than 2. This provision is included in the section 23.2.9 of SNI 2847-2019.

2.2. Design of Corbel Based on the Empirical Method

Reinforced concrete corbel is designed with height \(H\) of 500 mm, loading and support plate width is \(l_b\) of 150 mm. Concrete cover, \(C_c\) of 50 mm. Corbel width, \(b_w\) of 350 mm. Vertical load \((V_u)\) of 300 kN and Horizontal load \((N_u)\) of 60 kN were applied at shear span \((a = 200\) mm). According to the code, effective depth is equal to \(H-C_c\) or 450 mm. The compressive strength of concrete was assumed to be 30 MPa. The yield stress of both longitudinal steel and stirrup steel of 400 MPa was specified. The corbel and the steel reinforcements are presented in Figure 1.

2.3. Design of Corbel Based on STM

To attain the most appropriate model, we have to see the stress flows in the corbel. Figure 2 shows the stress flow in the corbel analyzed by using finite element modeling called LUSAS14. Based on these stress flows, the Truss Model-1 can be illustrated as shown in Figure 3 (a). Meantime, Figure 3(b) shows Truss Model-2 which adopted from the previous research [9].
The procedure of corbel design based on SNI 2847: 2019 [8] as per guidelines are as follows:

1. Define the geometry of truss model
   To obtain effective height \(d\), the height of the node zones must first be assumed. Then determine the \(\theta\). The angle \(\theta\) must not be taken at less than 25\(^\circ\).

2. Resolving the assumed truss model to define member forces
   The truss model that has been designed is analyzed using SAP2000 program to find the member forces. Figure 4 shows the Truss Model-1 with member forces and width of struts-ties. Meanwhile, Figure 5 exhibits member forces, as well width of struts and ties of the Truss Model-2.

3. Checking the Bearing Capacity
   The applied stress on bearing plates at loading locations must not exceed the node strength.

4. Designing and Verifying Struts and Ties Capacities
   The diagonal strut, vertical and horizontal strut was assumed as prismatic shape. The strut capacities then were checked against the forces in specified member.

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**Figure 2.** The Stress Flows in Corbel analyzed using LUSAS14

**Figure 3.** (a) Truss Model-1; (b) Truss Model-2 [9]
5. Checking the strength of nodal zone and anchorage
The nodal capacity of struts and tie is checked for all nodal. the designed nodal capacity must meet
the permissible limit. To check the anchorage of the tie, Section 25.4.2.3 SNI 2847:2019 [8] provides
an equation to calculate the length of anchorage is
\[ l_d = \left( \frac{f_y}{1.1 \lambda} \right) \left( \frac{\psi_c \psi_t \psi_y}{\psi_{c_t}} \right) d_b \]
and must be at least 300 mm. Section 23 specifically for design with strut-and-tie method, it is stipulated also that the
minimum reinforcement installed must also meet the requirements equation
\[ \sum \frac{A_{s_i}}{b_w s_i} \sin (\alpha_i) \geq 0.003 \]
The final details of corbel were shown in Figure 6 and Figure 7.

![Figure 4. Truss Model-1 with Member Forces and Struts-ties](image1)

![Figure 5. Truss Model-2 with Member Forces and Tuts-ties](image2)
3. Analysis

3.1 Analysis by Using STM

Analysis was carried out on both truss model. The corbel 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 corbel which was designed by using SNI provisions previously. The analysis results of each model are presented in Table 1 and 2.

Figure 6. Detail of corbel for Model-1

Figure 7. Detail of Corbel for Model-2
Table 1. STM Analysis Result for Model-1

| Member | Type | $F_{ns}$ (kN) | $\Phi F_{ns}$ (kN) | $F_u$ (kN) | Force Ratio |
|--------|------|--------------|-------------------|-----------|------------|
| 2-1    | Tie  | 680.469      | 510.352           | 433.330   | 0.849      |
| 5-7    | Tie  | 226.823      | 170.117           | 146.215   | 0.659      |
| 2-3    | Tie  | 680.469      | 510.352           | 433.330   | 0.849      |
| 3-4    | Tie  | 453.646      | 340.234           | 259.970   | 0.764      |
| 4-5    | Strut| 669.375      | 502.031           | 360.550   | 0.718      |
| 5-4    | Strut| 1294.125     | 970.594           | 360.550   | 0.371      |
| 3-5    | Strut| 1160.250     | 870.188           | 505.220   | 0.581      |
| 5-3    | Strut| 1338.750     | 1004.063          | 505.220   | 0.503      |
| 5-6    | Strut| 1472.625     | 1104.469          | 866.668   | 0.785      |
| 6-5    | Strut| 1963.500     | 1472.625          | 360.550   | 0.305      |
| 4-8    | Strut| 535.500      | 401.625           | 305.940   | 0.762      |
| 8-4    | Strut| 1338.750     | 1004.063          | 305.940   | 0.305      |
|        | Average result |              |                  |           | 0.661      |

Table 2. STM Analysis Result for Model-2

| Member | Type | $F_{nt}$ (kN) | $\Phi F_{nt}$ (kN) | $F_u$ (kN) | Force Ratio |
|--------|------|--------------|-------------------|-----------|------------|
| 2-1    | Tie  | 453.646      | 340.234           | 279.500   | 0.821      |
| 3-4    | Tie  | 226.823      | 170.117           | 106.030   | 0.623      |
| 2-3    | Strut| 133.875      | 100.406           | 72.530    | 0.722      |
| 3-2    | Strut| 133.875      | 100.406           | 72.530    | 0.722      |
| 2-8    | Strut| 580.125      | 435.094           | 305.940   | 0.703      |
| 8-2    | Strut| 1338.750     | 1004.063          | 305.940   | 0.305      |
| 2-4    | Strut| 714.000      | 535.500           | 128.460   | 0.240      |
| 4-2    | Strut| 223.125      | 167.344           | 128.460   | 0.768      |
| 2-5    | Strut| 714.000      | 535.500           | 192.030   | 0.359      |
| 5-2    | Strut| 535.500      | 401.625           | 192.030   | 0.478      |
| 4-5    | Strut| 133.875      | 100.406           | 72.510    | 0.722      |
| 5-4    | Strut| 133.875      | 100.406           | 72.510    | 0.722      |
| 3-5    | Strut| 223.125      | 167.344           | 128.500   | 0.768      |
| 5-3    | Strut| 535.500      | 401.625           | 128.500   | 0.320      |
| 5-6    | Strut| 357.000      | 267.750           | 219.490   | 0.820      |
| 6-5    | Strut| 490.875      | 368.156           | 219.490   | 0.596      |
| 5-7    | Strut| 490.875      | 368.156           | 300.000   | 0.815      |
| 7-5    | Strut| 714.000      | 535.500           | 300.000   | 0.560      |
|        | Average Result |              |                  |           | 0.615      |

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, we can easily measure the efficiency of our design results. In brief, analysis of deep beam using CAST can be summarized into five steps as 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 corbel design calculations. In the CAST analysis program, we cannot define two dimensions of width on one strut.

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 8](image)

**Figure 8.** (a). Analysis Result of Model-1; (b). Analysis Result of Model-2 using CAST

4. Results and Discussion
   Table 3 shows the force ratio of each Truss Model by using STM and CAST. The results show that the average force ratio less than 1 (one), meaning that all truss models are applicable to design and analyse the corbel based on the SNI 2847-2019 provisions. The analysis results between STM and CAST has no significant difference. It indicates that CAST is quite effective to be used to assist in analysing the RC deep beam.
Table 3. Comparison Result between STM and CAST

| Type Model | Force Ratio rata-rata STM | Force Ratio rata-rata CAST |
|------------|--------------------------|---------------------------|
| Model-1    | 0.661                    | 0.688                     |
| Model-2    | 0.615                    | 0.708                     |

5. Conclusions
1. The truss model can be constructed by using FEM approach.
2. SNI 2847-2019 is one code STM based which can be used to design and analyse the RC corbel.
3. CAST is quite effective to be used to assist in analysing the RC deep beam.

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