Comparative analysis of the flexural capacity of conventional steel beams with Castellated beams

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Abstract. South Kalimantan, especially Banjarmasin City, has a thick layer of soft soil. Low bearing capacity is a major issue in planning the structure. Castellated beam is an innovation to create high structural capability with low weight. This research aims to gain the effect of the hexagonal opening angle on the bending capacity of the castellated beam. The research was conducted by numerical testing using ANSYS. This research compares the flexural capacity of conventional steel beams to the geometric effect of castellated beam with hexagonal opening angle variations. This research concluded that the geometric effect of a castellated beam can provide an increase in flexural capacity of about 8 to 19% compared to conventional steel beams. The optimum bending capacity is at the hexagonal opening angle of 45° to 50°. At the 60° opening angle, the castellated beam has decreased its flexural capacity.

1. Introduction

South Kalimantan, especially in the city of Banjarmasin, has soft soil types. Soft soil behavior is that it has a very low bearing capacity and high soil compression. The low bearing capacity will result in the inability of the soil to carry the working load and high soil compression will cause a difference in consolidation decline which can damage the structure. This is a challenge for civil engineering academics, especially academics at Lambung Mangkurat University, so that they can produce innovations in a structure that is stronger but also has a lighter weight than conventional structural components. One of these innovations is the use of castellated beam steel.

Castellated beam is a development of conventional hot rolled steel beam, by making a cut pattern on the web of the WF steel beam profile into 2 pieces, which will later be shifted and welded into one unit, so that it can increase almost 50% of the original profile height [1]. By making a higher profile it will increase the flexural strength, moment of inertia (Ix) and section modulus (Sx) [2].

In this research, a zigzag cut pattern will be made on the web along the span, which will then be shifted and welded together to form hexagonal web openings. Several variations of the opening angle will be made which will later be compared the bending capacity with conventional WF steel beams. Broadly speaking, the purpose of this study is to obtain an increase in the bending capacity of the effect of the opening angle on conventional beams.

The results of this study are expected to provide information about the flexural strength behavior of the castellated beam with variations in the angle of the hexagonal opening. So that it can be a source of literature and a reference in the world of construction in order to produce a recommendation for a structure that is stronger and also has a lighter weight than some of the models that have been studied.
It also aims to minimize the use of excessive steel material to maintain environmental resistance. So that we get an efficient structural design in using these materials. Such a structure is especially needed for construction in soft soil areas, for example the Banjarmasin area. Because the city of Banjarmasin has a thick soft soil layer, it is in need of a strong and lightweight structural innovation.

2. Literature review
Castellation is the process of cutting a web profile with a zigzag-shaped pattern on a hot rolled WF, I or H profile. Half of the cutting of the profile body is joined by sliding or reversing and then welded to the web to form a new profile with a polygonal hole. This can increase the profile height (h) from the previous profile. In castellated beam planning, an opening angle is generally used in the range of $45^\circ$ to $60^\circ$ [3].

2.1. Inertia of castellated beam
Calculation of inertia in the cross section of the opening can use equation 1:

$$ I_{x\text{nett}} = 2.I_{x\text{tee}} + 2.A_{\text{tee}} \left( \frac{\text{defect}}{2} \right)^2 $$

(1)

Calculation of full inertia (in areas with no openings) used equation 2:

$$ I_{x\text{gross}} = I_{x\text{nett}} + tw . Do^3 \frac{12}{1} $$

(2)

2.2. Flexural capacity of castellated beam
According to ASCE journal page 3327 [4], the nominal bending moment of a castellated beam:

$$ M_n = M_p - f_y \cdot \Delta A_s \left( \frac{h_o}{4} + e \right) $$

(3)

![Figure 1. Cross section of a castellated beam.](image)

3. Research methodology
This study aims to obtain the behavior of the castellated beam, especially at a given bending capacity. In this study, two types of beams will be compared, namely conventional WF steel beam and castellated beam. It will be seen the difference in flexural capacity that can be provided from conventional WF steel beams with castellated beams.

The method used in this research is numerical testing using ANSYS software. The numerical test method using ANSYS is to look for the influence of certain variables on other variables in a controlled manner and is carried out systematically in obtaining data, so that the data can be used in making decisions and conclusions.
3.1. Research material data

Steel material in this study is used in the process of manual calculation and numerical testing. The material data used is steel sheets that have been tested for strength by Arya in 2017 with the title Research on Corrugated Plate Girder Behavior [5]. In his research, steel sheets sold in the market of Malang City showed the yield tensile strength (fy) above 240 Mpa, with the ultimate strength (fu) exceeding 370 Mpa. So that in this study determined the quality data of the steel material used is BJ 37, with a yield strength fy = 240 Mpa and breaking strength fu = 370 Mpa.

3.2. Model of the test object geometry

The model tested in this study was taken a sample of the WF 150x75x5x7 steel profile with a length of 2000mm. Then the WF steel profile is processed into a castellated beam with several variations of the hexagonal opening angle. The list of model variations is presented in Table 1 as follows.

| Model | L (mm) | tw (mm) | tf (mm) | hw (mm) | bf (mm) | 9° |
|-------|--------|--------|--------|--------|--------|----|
| AO    | 2000   | 5      | 7      | 136    | 75     | -  |
| Al    | 2000   | 5      | 7      | 154.19 | 75     | 20 |
| A2    | 2000   | 5      | 7      | 164.87 | 78     | 30 |
| A3    | 2000   | 5      | 7      | 186    | 75     | 45 |
| Ad    | 2000   | 5      | 7      | 195.59 | 75     | 50 |
| AS    | 2000   | 5      | 7      | 222.6  | 78     | 60 |

Figure 2. Stress-strain relationship curve of steel material.
3.3. Test setup

The test object is a beam with a span of 2000mm, placed on two simple support, namely hinge support and rollers. The load is given in the form of two points load in the middle of the span with a distance between load points as far as 200mm.

Giving two points load is intended so that the internal force that occurs in the middle of the beam span is pure bending, without any shear forces. Because the shear between the two points of the load is zero. So that the results read are purely due to the force in the moment. This test is designed to obtain the bending capacity of the beam specimen.

![Test setup diagram](image)

**Figure 4.** Illustration of test setup.

![Moment and shear diagram](image)

**Figure 5.** Illustration of moment and shear diagram on a beam.
The load is applied gradually to the beam, until it collapses. The collapse given by numerical testing is an error sign while running. This error indicates that the load applied has exceeded the ultimate limit of the beam. The number of stages of giving a load is 20 load steps. For deflection readings, a nodal deformation direction is given on the lower side of the beam right in the middle of the span. As well as for the reading of the flexural strain value, given the nodal strain on the upper side of the wing, the middle side of the body and the underside of the wing in the middle of the span. The strain value read is 5 points. The numerical test setup is as follows.

4. Results and Discussion

4.1. Result of manual calculation
In calculating the bending capacity of conventional hot rolled WF beam, using beam theory. Beawal calculates the slenderness of the body and wings, resulting in that the WF hot rolled section is classified into the compact section classification. So the calculation uses the plastic moment theory. The results of the plastic moment in the hot rolled beam are 235.200 kgcm. The risk of lateral torsional buckling is negligible. With the value of the plastic moment, the value of Pu which causes the block to undergo a plastic phase is 52.260 N.

To calculate the bending capacity of a castellated beam, an equation based on the ASCE journal page 3327 is used. The recapitulation of the inertia value of the cross section (Ix), the plastic modulus (Zx) and the bending capacity (Mn) of each test object is shown in Table 2.

| No | Model | Hexagonal Opening Angle | Cross section inertia, Ix (cm\(^4\)) | Plastic Modulus, Zx (cm\(^3\)) | Flexural capacity (Moment Nominal, kgcm) |
|----|-------|-------------------------|--------------------------------------|-------------------------------|--------------------------------------|
| 1  | A0    | 0                       | 668                                  | 114.17                        | 235200                              |
| 2  | A1    | 20                      | 833.03                               | 112.55                        | 248520                              |
| 3  | A2    | 30                      | 964.18                               | 120.13                        | 253503                              |
| 4  | A3    | 45                      | 1246.33                              | 132.07                        | 256968                              |
| 5  | A4    | 50                      | 1395.90                              | 136.89                        | 257145                              |
| 6  | A5    | 60                      | 1851.12                              | 145.50                        | 245400                              |
Figure 10. Relationship of bending capacity (Mn) with hexagonal opening angles based on manual calculations.

Table 2 shows that the inertia value of the cross section (Ix) and plastic modulus (Zx) of each specimen increases with the increase in the angle of the hexagonal opening on the castellated beam. This shows that given a large hexagonal opening angle, it will increase the inertia value and plastic modulus. However, when viewed from the resulting flexural capacity (Mn), it is shown that when given an opening angle between 45° to 50° (A3 and A4 models) it will result in a flexural capacity value that does not increase much compared to the increase in capacity in previous models (model A0 - A3). Meanwhile, if the angle of the hexagonal opening is increased to reach 60° (model A5), it can be seen that the bending capacity has decreased. This shows that the maximum bending capacity value is generated by the opening angle of 50° (A4 model). Figure 10 shows the change in the value of the bending capacity of each specimen.

4.2. Validation of numerical test results with ANSYS

ZModel geometry is created by importing a model that has been created using the Autocad program. The file imported from Autocad is in the .iges format in 3D solid. The definition of the support conditions and load conditions is made the same as the illustration of the test setup in Figure 4, namely simple support (hinge-roller) and two-point loads. For the application of support in the ANSYS program, the nodal displacement facility is used and for the load definition the nodal forces facility is used. The results of the load relationship curve with beam deflection in the middle of the span can be seen in Figure 12.
Figure 1. Shape of deformation in test object.

Figure 2. Load-Deformation Relationship of the beam in the middle span produced by ANSYS.
Table 3. Comparison of yield load between manual analytical and numerical testing.

| Model | Hexagonal opening angle | Manual analitic Py (N) | Numeric by ANSYS | Analisis vs Numerik | Manual analytical formula sketch |
|-------|-------------------------|------------------------|------------------|---------------------|---------------------------------|
| A0    | 0                       | 52260                  | 50700            | 2.99%               |                                 |
| A1    | 20                      | 55226                  | 55250            | -0.04%              |                                 |
| A2    | 30                      | 56334                  | 58500            | -3.84%              |                                 |
| A3    | 45                      | 57104                  | 61750            | -8.14%              |                                 |
| A4    | 50                      | 57143                  | 63050            | -10.34%             |                                 |
| A5    | 60                      | 54533                  | 57000            | -4.52%              |                                 |

From figure 12 it can be seen that giving a hexagonal opening angle to a conventional WF beam will increase the bending capacity. The greater the opening angle made, the bending capacity will also increase. However, when viewed for the hexagonal opening angles of 45° and 50° (A3 and A4 models), it shows insignificant improvement results when compared to the previous models (A0 - A3). Meanwhile, if the opening angle is enlarged to 60° (A5 model) it will cause a decrease in capacity. This shows that the ANSYS numeric test results with manual calculations show the same conclusion, namely the optimum hexagonal opening angle, namely the 50° opening angle (A4 model). Table 3 shows the comparison of the load values that cause steel beam to yield (elastic limit) from the results of manual calculations and numerical testing. The difference in yield difference between analytical manual calculations and the maximum numerical test is not more than 11%.

5. Conclusion
The effect of castellated geometry can increase the bending capacity of the beam by about 8 - 19% from conventional WF beams. The most effective hexagonal opening angles on the castellated beam in increasing the flexural capacity, ranging from 45° to 50°.

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