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Experimental Study on Castellated Beams with Hexagonal Variation Using Monotonic Loading

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ABSTRACT

One method that can be used to economically reduce the weight of steel beam used in the construction is the utilization of castellated beam. The beam is made by using steel material profile split in the middle of the plate web, and the resulting pieces are then welded together in certain method to form a hexagonal shaped hole. This study aims to determine optimal dimension of castellated steel beam that can meet technical requirement such as flexural strength, deflection, and web buckling from the point of web openings and determine load capacity that is able to be borne by castellated steel beam as well as formulizing damaged/failed model that occur on castellated steel beam. In the test of castellated steel beam, 1 normal profile test material of IWF 200.100.5,5.8 and 6 normal profile test materials of IWF 200.100.5,5.8 modified into castellated steel beam with different cutting angle variation ∅ 50°, ∅ 60°, and spaced web openings ∅70° fixed at (e) 90 mm and the variation of different web openings distance of 60 mm, 90 mm, and 120 cm with a fixed angle of the cutting body ∅ 60°. Test of castellated steel beams was carried out using Static Loading Frame - two-point load in monotonic loading. From the test results it is known that the castellated steel beams with ∅ 60°, e = 90 mm is able to withstand the maximum load compared to test material variation of another angle and distance, while the maximum load deflection value is greater than the variations in the value of the angle cut and bend the smaller web. Bending stress and bending moment are higher than the other test materials. In this test, the test specimens still exhibit elastic behavior and has not reached the yielding stress. This is because when the load increases, the beam has been damaged. All test specimens were damaged by buckling and lateral torsion buckling on flange and web profile.

Key word :castellated steel,web opening angle,maximum capacity, failure models

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INTRODUCTION

Steel construction is a favorable alternative in the construction of buildings and other structures in both small and large scale [1]. This is because the steel material has several advantages over other construction materials. One alternative of the use of steel as a construction material is the so-called castellated steel. Castellated steel beam is a beam that has a hollow web plate elements, which are formed by splitting the middle of the plate web, then the lower part of hemispheres is reversed and put back together between the top and bottom by sliding a little later on the body plate that has been put together and then welded, which weighs the same as the previous but with higher [2]. In such a way, the beam of the same size would produce higher modulus and bigger moment of inertia. On the other hand with the high beams then its slenderness increased, and thereby decreasing the critical stress or it will result in a smaller critical stress of the yielding stress [3]. The shape of the castellated beam parts is shown in Figure 1 and Figure 2.

Figure 1and Figure 2, equations are acquired as follow:

$$\tan\varnothing = \frac{h}{t} \quad \text{or} \quad b = \frac{h}{\tan \sim} \qquad (1)$$

$$d_g = d_b + h$$

$$rd_T = \frac{d_b - h}{2} \qquad (2)$$

$$s = 2(b + e) \qquad (3)$$

Castellated steel beams bending stress, in elastic condition, the bending stress at any point on the cross section along the element can be determined by equations:

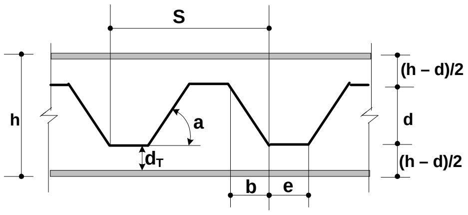

Figure 1. Profile of I-beam is halved along its body

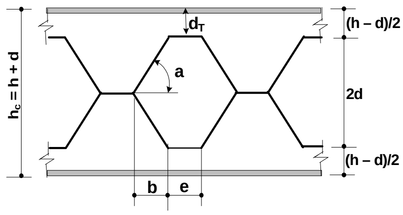

Figure 2. Geometry of castellated beam cut point

$$f_y = E \times \varepsilon \qquad (4)$$

where: f_y= Stress (Mpa)
E= Elastic Modulus (Mpa)
ε= Strain

where; d_g = height of castellated profile, d_b = height of normal profile, h = height of body cut

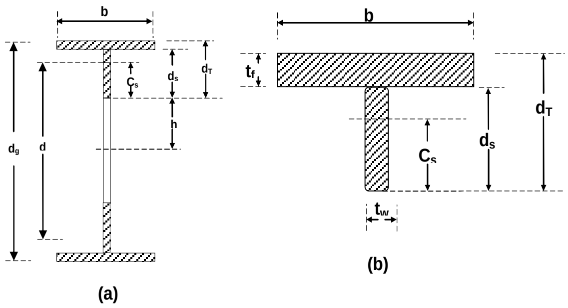

Figure 3. Profile I-section of castellated steel beam Material

For profile width and resistance moment, the acquired equations are:

$$A_T = a_f + a_s = b \cdot t_f + d_s \cdot t_w \qquad (5)$$

$$M_y = A_f \left(d_s + \frac{t_f}{2}\right) + A_s \frac{d_S}{2} \qquad (6)$$

$$I_y = A_f \left(d_s^2 + d_s t_f + \frac{t_f^2}{3}\right) + A_s \frac{d_S^2}{3} \qquad (7)$$

$$C_S = \frac{M_y}{A_T} \qquad (8)$$

$$S_s = \frac{I_T}{C_S} \quad (9)$$

$$d = 2\,(h + C_S)$$

Thus, Inertia Moment (I_g) of castellated profile is :

$$I_g = 2\, I_T + \frac{A_T \mathbf{d^2}}{2} \qquad (10)$$

In castellated beam, part of the wing profile restrains most of the bending moment due to vertical loads, hence the loss of area due to openings in the cabinet will not cause stability problem caused by the the moment, but the shear force (V) which is retained by the body must be considered [4]. In the middle of span, shear force (V) is a minimum and does not pose a problem of stability in many areas due to the sliding openings in the cabinet, but the ends (near the pedestal), stress due to shear force in the area of openings, particularly thin section (upper edge of the opening) become the problem that need to be taken into account.

Analysis and design by [5], formulated the basics of castellated steel beam stress analysis are as follows:

1. The edges of the top and bottom of the beam experiencing bending stress and tensile urged, by σb = Sb / M, must be continuous along the beam, with the ratio between the width and thickness is minimum and with allowable stress.
2. The axial shear stress (V) on the beam is held by the webfor the whole beam section (solid), and is held by the body parts outside the opening (stem) for beam section that is open and hollow.
3. At the openings in the body profile, the axial shear stress is equallydistributed in both the top and bottom edge of the beam, which produces a secondary stress, namely:

$$\pm_{c} = \frac{M}{S_b} \quad (11)$$

4. The axial shear stress working on the solid body along the neutral line. This stress is caused buckling in the castellated beam.
5. The solid body transfers axial forces vertically by half the difference of the axial shear on the end panels.
6. Section of castellated beam on the pedestal should be an integral part. Because of the moment, the beam section has bending stress. And because of shear force, shear beam section has a friction stress. The maximum stress (f_{max}), which occurs caused by the bending moment on the beam can be expressed by the following equation [6]:

$$f_{max} = \frac{M \cdot c}{I_g} \quad (12)$$

Where:

M : bending moment (kNm)

I_g : Gross inertia of castellated profile (mm^4)

c : Distance of weight point (mm)

Failures in the castellated beam can be caused by dimensional pieces which are actually holes in the web, the distance of a web post, and high web openings. Thus, there are five models of failures in the castellated beam [7]:

a. Vierendeel mechanism
b. Flexural mechanism
c. Lateral – Torsion – Buckling
d. Rupture on the welded jointa web post
e. Shear bucklingof a web post

The specimens were tested using Static Loading Frame with a capacity of 150 tons, and the application of the monotonic loading is shown in Figure 5.

Figure 4. Testing Specimens

Figure 5. Testing of flexural strength by means of Static Loading Frame

2. RESEARCH METHODOLOGY

Steel beams used in this study is a steel beam with a beam length of 200.100.8.5,5 IWF 1500 mm, which is simply supported (joint-roller). In this study, 1 piece of steel beams IWF 200.100.8.5,5 and 3 pieces of steel beam with cutting angle (∅) 50°, 60°, 70°, the web openings fixed distance (e) 90 mm and 3 pieces variation of different web openings distance of 60 mm, 90 mm, and 120 mm with a fixed angle of the cutting web∅ 60°are used. This can be seen in Figure 4 and Research Flowchart is shown in Figure 6.

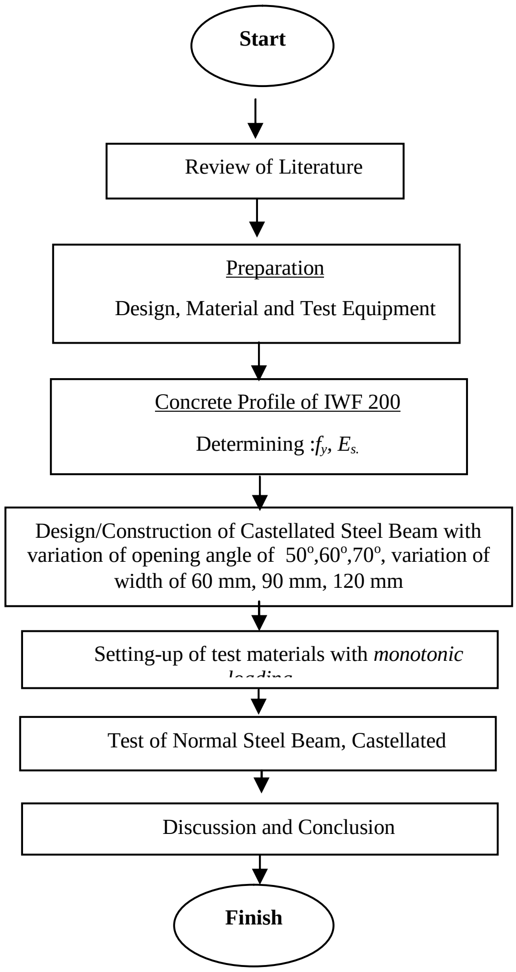

Figure 6. Research Flowchart

In this study, the use of each test material of castellated steel beams using 3 pieces of LVDT mounted on the test material midspan where the two pieces were put on the web and 1 test material were placed on the bottom flange of the test material. Four strain gauges for steel that were positioned in the top flange, web top, middle and bottom web. The test object was then loaded incrementally by hydraulic jacks. The results of the LVDT and Strain Gauge were automatically recorded in the load cell in a computer that has been designed to automatically connect with a Static Loading Frame.

3. RESULTS

The test results show that the flexural stress of castella steel beam with web opening angle ∅50^o (BC-50^o) is equal to 70.7 N / mm² and strain of 0.00035; for a castella steel beam with web opening angle ∅60o (BC-60^o) obtained the stress of 100.1 N/mm² and strain of 0.0005. For a castella steel beam with web opening angle ∅70^o (BC-70^o), the stress obtained 73.7 N /mm² and strain of 0.00036. The test results obtained for normal steel beam stress of 149.9 N / mm² and strain of 0.000749. The test results can be seen in Figure 7.

As for the test results to variations in web opening distance, the maximum stress for the BC-60 is 68.38 N / mm² with strain value of 0.00034; while for BC-90 has a maximum stress of 100.05 N / mm² with strain value of 0.00050.The BC-120 has a maximum stress of 82.23 N / mm² with strain value of 0.00041. The test results can be seen in Figure 8.

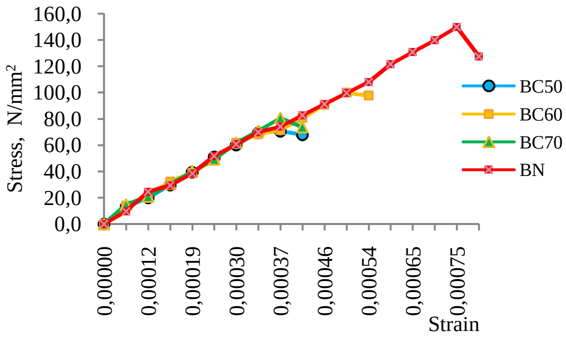

Figure 7. The relationship between stress and strain

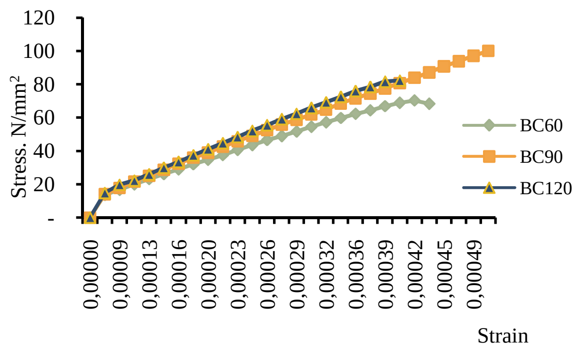

Figure 8. The relationship between stress and strain with beam openings distance variation

For normal steel beam, the moment capacity (Mn) of 32.85 kNm with a maximum load is 146 kN. For castella steel beams with the BC-50^o, the obtained moment capacity is 22.16 kNm and the maximum load is 104 kN. For castella steel beams BC-60^o, the moment capacity is 31.37 kNm and the maximum load is 134 kN. For the castella steel beam BC-70^o, the moment capacity obtained was 25.32 kNm and the maximum load capacity is 114 kN. Relationship with a load moment capacity can be seen in the Table 1.

Table 1. Moment capacity of the normal and castellated steel beam

No	Sample	P_n kN	I_x mm^4	M_n kNm
1	BN	146	18400000	27,57
2	BC-50°	104	42110560	22,16
3	BC-60°	134	42110560	31,37
4	BC-70°	114	42110560	25,32

From the test results, it is shown that the BC-60 value of the nominal moment (Mn) of 18.88 kNm with a load of 114.66 kN. For BC-90 with a load of 134.15 kN nominal moment obtained 27.63 kNm. And for the BC-120 with loading values of 103.44 kN, obtained nominal moment is 22.71 kNm. Correlation between moment capacity and load can be seen in Table 2.

Table 2. Moment capacity and the load of the beam with web distance variation

No	Sample	P_n kN	I_x mm^4	M_n kNm
1	BN	146	18400000	27,57
2	BC-60	114	42110560	18,88
3	BC-90	134	42110560	27,63
4	BC-120	103	42110560	22,71

The amount of deflection of the test results for normal steel beam is equal to 4.68 mm with a load of 146 kN, while the castellated steel beam of BC-50° with load of 104 kN deflection value is obtained as 1.67 mm, for castellated steel beam ofBC-60° with a load of 134 kN deflection value is obtained as 7.125 mm, for castellated steel beam-70° BC, deflection value is obtained as 3.52 mm. For the correlation between load and deflection, the results are presented in Figure 9.

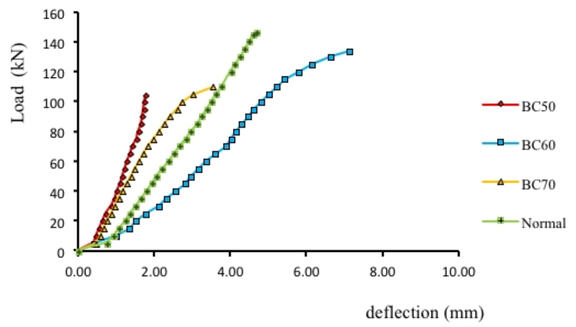

Figure 9. The relationship between stress and strain with beam openings angle variation

BC-60 reached maximum load of 114.66 kN with deflection of 3.315 mm, while the BC-90 reached maximum load of 134.145 kN with deflection of 6.125 mm; BC-120 reached maximum load of 103.44 kN with a maximum deflection of 4.035 mm. Correlation of test results and the load deflection can be seen in Figure 10.

Test results also show that the upper web buckling value is 4.38 for normal steel beam and lower web buckling is 4.97 mm. For the castellated steel beam of BC-50°, upper web buckling values is 6.91 and lower web buckling is13.07 mm;castellated steel beams of BC-60° has upper web buckling values of 3.85 mm and lower web buckling is10.63 mm, and for castellated steel of BC-70° , the upper web buckling value is 10.73 mm and 6.45 mm for lower web buckling.

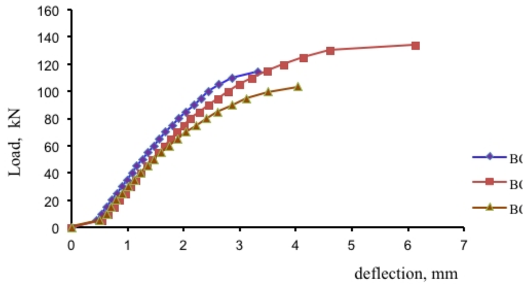

Figure 10. Relation between load and deflection of beams with distance openings variation.

The web buckling for castellated steel beams of BC-60 is 9.05for the upper web buckling value and for the lower web is 6.2 mm. For castellated steel beam of BC-90, the upper web buckling value is 3.85 mm and the lower web bucklingis 10.63 mm.For castellated steel beam of BC-120, the upper web buckling is 14.72 mm and the lower web buckling is 4.58 mm.

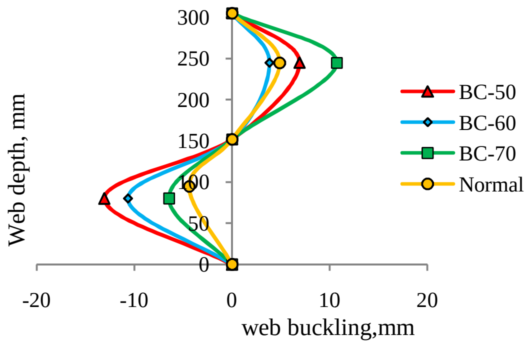

Figure 11. The relationship between web buckling and web depth.

It can be seen that the failure model of the normal steel beams are lateral torsion buckling and the web bucklingmechanism. For steel beam with web opening angle variation ∅50°, the damageis of lateral torsion buckling, the web bucklingmechanism. For specimens with opening angle variation of ∅60°, failure that occurs is caused by lateral torsion buckling and buckling of web pots. Meanwhile, test materials with opening anglevariation of∅70° also suffered damage or failure due to buckling of web pots and lateral torsion buckling.

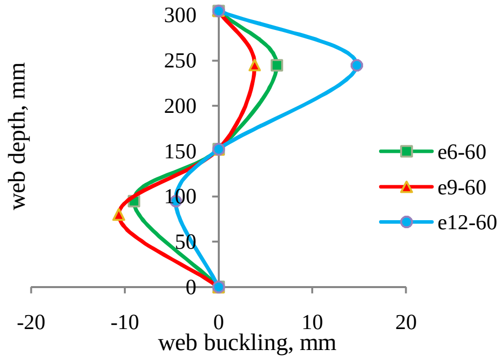

Figure 12. Relationship between web buckling and web depth for castellated steel beams.

Beam failure models for all variations of castellated beams can be seen in Table 3.

Figure 13. Failure/damage model to the steel beams.

4. DISCUSSION

From the test results of varied specimens, it can be seen that castellated steel beam with web opening angle of φ 60° has stress value higher compared to cutting angle of other castellated beams. As for the test material for distance variations web openings, in terms of the value of the maximum stress, the results showed that the BC-90 has a stress value greater than the variation range of other openings, where the results indicate that the higher beams is achieved then its slim size is also increased thus affecting the value of the stress on the castellated steel beams. In the yielding condition, increase in profile cutting angle (Ø) and the distance of the web openings (e) shows the tendency of the smaller moments that happened. Based on the test results, it can be concluded that the deflection is proportional to the load that is being held by the profile or in other words the greater the load incurred the greater deflection. The bigger the hole in the broad field of web weight resulted in reduced beam section that affects the amount of deflection in the beam. Similarly to the web buckling, the larger bend angle of the cutting profile (Ø) and the distance of the web openings (e) show the value of bending is also greater.

Table 3. The damage shape of castellated steel beam

Sample	Position of failures	Failure modes
BC- 50^o	Web and flange	Lateral Torsional Buckling, Buckling of web pots
BC- 60^o	Web and flange	Lateral Torsional Buckling, Buckling of web pots
BC- 70^o	Web and flange	Lateral Torsional Buckling, Buckling of web pots
BC-60	Web and flange	Lateral Torsional Buckling, Buckling of web pots
BC-90	Web and flange	Lateral Torsional Buckling, Buckling of web pots
BC-120	Web and flange	Lateral Torsional Buckling, Buckling of web pots

CONCLUSIONS

From the test results of castellated steel beam with web opening angle variation with fixed web opening distance and distance variation of web opening with fixed web opening angle, following conclusions are obtained. In this test, all test materials still exhibit elastic behavior and has not reached the yielding stress, the nominal moment capacity of castellated steel beam with variation of the angle of BC-60° 31.37 kNm with loading of 134 kN and for the nominal moment capacity of the castellated steel beam with distance variation of web openings of BC-90 at 27.63 kNm with a maximum loading of 134.15 kN. Optimal dimensions of castellated steel beams that can meet the technical requirements such as flexural strength, deflection, and bending of the body, which in terms of the variation of opening angle Ø 60° obtained bending stress of 100.047 N / mm² with a deflection of 7.125 mm and web buckling by 10, 63 mm. The web openings for the variation distance is the distance of (e) 90 mm with bending stress of 100.05 N / mm² and deflection of 6.125 mm and the web buckling by 10.63 mm. Models of damage that occurred during testing for variation opening angle and distance variation is the web openings lateral torsion buckling and damage to the flange and web. Based on the analysis, for the flexural strength of the castellated steel beams, the optimum profile cutting angle (Ø) and the width of the body openings may not exceed the optimal opening angle of 60° and e = 90 mm.

Subsequent tests on castellated beams using cyclic loadings are still being carried out, and it is expected to combine the results of the tests under monotonic loadings and cyclic loadings before any design guideline can be proposed.

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