

The Effect of Hole Width on Full Height Rectangular Opening Castellated Steel Beam with Diagonal Stiffener Concerning Its Flexural Capacity

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Abstract: The use of a diagonal stiffener in a full height rectangular opening castellated steel beam can prevent the failure mechanism of vierendeel. This results in the flexural capacity of the castellated beam higher than the original IWF section. The flexural capacity of a castellated steel beam can be optimized by designing the hole width on the web section. This research aims to find out the effect of several values of castellated steel beam hole width on the flexural capacity. In this research, there are 4 castellated steel beam models whose flexural capacity values are calculated using the truss analysis and pushover analysis methods. Based on the calculation results, it can be concluded that the smaller the value of the hole width, the greater the flexural capacity of the castellated steel beam will be. The largest increase in flexural capacity from the original IWF to the castellated beam is 140.93%.

Keyword: *castellated; pushover; rectangular opening; steel*

1. Introduction

Castellated steel beams are the development of the form of the IWF section along which the web is cut with a certain pattern and then reconnected by welding, thus forming a new section with openings on its web. Castellated steel beams has several advantages, namely increased stiffness and flexural strength of beams due to greater inertia of the cross section. The increase in the magnitude of the cross-section inertia is obtained from the change in height of the castellated section which is higher than the previous IWF section without any change in its own weight. In addition, the holes in the web also add the artistic value and facilitate pipe installation. However, the disadvantage of castellated steel beams is the occurrence of the vierendeel mechanism caused by the formation of plastic joints at the angles of the web openings.

The vierendeel mechanism that occurs in castellated beams in the form of a full-height rectangular hole results in a decrease in the capacity of the castellated beam to be smaller than in the previous IWF section due to the appearance of plastic joints at the opening angles of the web [1] [5]. The use of steel bar as diagonal stiffener in the full-height rectangular opening castellated steel beams can prevent vierendeel failure thereby increasing the flexural capacity of the beams [2] [8]. Increased flexural capacity in the steel beam shows that the structure has great strength in resisting external forces. Figure 1 shows the failure of vierendeel in the full-height rectangular opening castellated beam and Figure 2 shows the existence of a diagonal stiffener in the full-height rectangular opening castellated steel beam.

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The purpose of this research is to find out the relationship between the hole width in the web section to increase the flexural capacity of the full-height rectangular opening castellated steel beams with diagonal stiffeners.



Fig. 1. Vierendeel failure in the full height rectangular opening castellated steel beam [1]

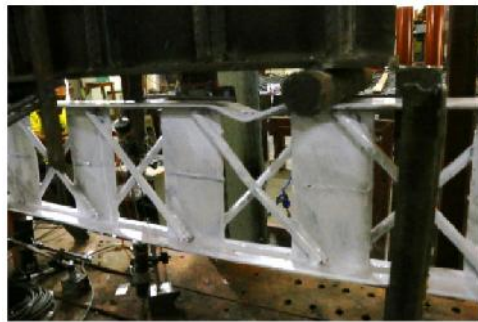


Fig. 2. Diagonal stiffener on the full height rectangular opening castellated steel beam [2] [8]

2. Research Method

The castellated steel beam specimen was designed from the IWF 200x100x8x5.5 with a cross section height of $h = 200$ mm, cross section width of $b = 100$ mm, flange thickness of $t_f = 8$ mm, and web thickness of $t_w = 5.5$ mm. The yield strength of IWF steel section and steel bar is using standard BJ37 code that is $f_y = 240$ MPa. Based on the original IWF section data, a cross-section of castellated steel beams can be made with a cross-sectional height of $H = 362$ mm and the hole height of the cross-section of $d = 324$ mm. The span of the beam of $L = 3$ m is determined according to the limit so that no lateral torsional buckling occurs. Diagonal stiffener is steel bar with diameter of $\varnothing = 19$ mm, which is attached to each hole. One point loading is placed in the center of the beam span. The discussion in this research focuses only on the flexural buckling of castellated steel beams so that the stiffness in the restrain is ignored. This research used 4 models were variations in the hole widths of 110 mm, 120 mm, 130 mm, and 140 mm. The detail specification of the castellated steel beam model can be seen in Table 1 and Figure 3. The plastic moment capacity of the IWF beam, M_p , can be calculated using the following equation:

$$M_p = f_y \times Z_x \tag{1}$$

Table 1. Detail specification of Full-Height Rectangular Opening Castellated Steel Beam Model with Diagonal Stiffener

Model	Beam Span Length (mm)	Hole Width (mm)	Diagonal Stiffener Length (mm)
C-1	3000	110	237
C-2	3000	120	247
C-3	3000	130	257
C-4	3000	140	267

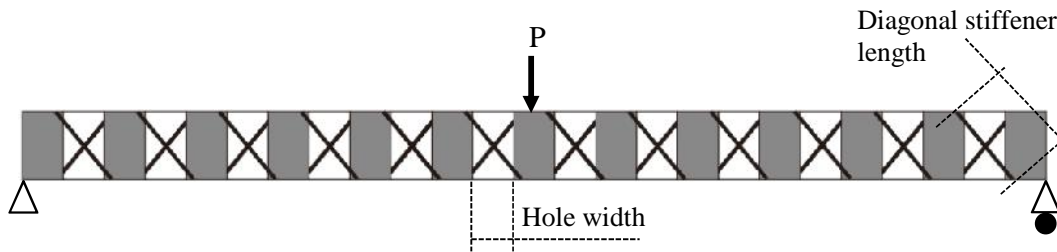


Fig. 3. The full-height rectangular opening castellated steel beams

2.1. Truss Analysis

Diagonally positioned stiffener makes the transfer of load on the castellated beam to be similar to the formation of the truss structure system [2]. The analysis of the truss system makes it relatively simple design castellated beams. The truss analysis, only the compression and tension elements are calculated to determine the value of the load capacity. The equation used to calculate the tension element according to SNI-1729-2015 [3] is as follows:

$$P_n = f_y \times A_g \quad (2)$$

Where

P_n = tensile strength (N)

f_y = yield strength (MPa)

A_g = gross area (mm²)

The calculation of compression element according to SNI-1729-2015 is determined based on the type of cross-sectional geometric shapes [7]. In castellated steel beams, the compression elements have a solid rectangular shape and a solid circle. Therefore, the compression element capacity is determined only by flexural buckling, which is calculated by the following equation:

$$P_n = f_c \times A_g \quad (3)$$

Where A_g is the gross area and f_c is the critical stress (MPa) determined based on the value of member slenderness calculated using the following equation:

$$\lambda = \frac{K}{r} \quad (4)$$

Where

= member slenderness

K = effective length factor

L = laterally unbraced length of the member

r = radius of gyration

from the calculation of the value of the member slenderness of the cross section, we can find the value of the critical stress

$$\text{When } \lambda \leq 4.71 \sqrt{\frac{E}{f_y}} \text{ or } \frac{f_y}{f_e} \leq 2.25, \quad (5)$$

$$\text{Then } f_c = \left[0.658 \frac{f_y}{f_e} \right] f_y \quad (6)$$

$$\text{When } \lambda > 4.71 \sqrt{\frac{E}{f_y}} \text{ or } \frac{f_y}{f_e} > 2.25 \quad (7)$$

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$$\text{Then } f_c = 0.877 f_y \quad (8)$$

Where

E = modulus of elasticity (MPa)

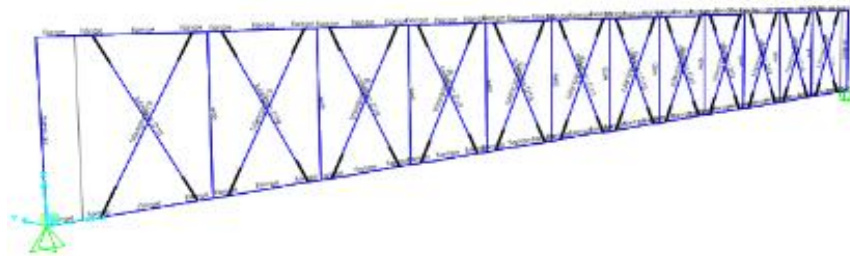
f_e = elastic buckling stress (MPa)

elastic buckling stress (f_e) can be calculated by the following equation

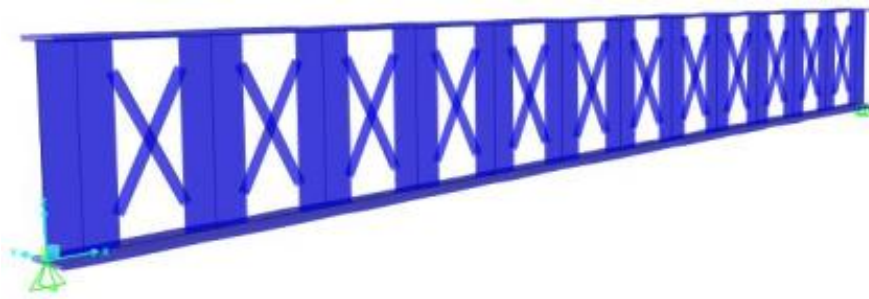
$$f_e = \frac{\pi^2 E}{\lambda^2} \quad (9)$$

2.2. Pushover Analysis

In general, the pushover analysis stage can be performed with a two dimensional frame model on SAP2000. The loading pattern, steel hinge properties and pushover load case must be defined on the model [4]. After the analysis process, the output can be read on the pushover analysis curve. The castellated steel beam model in SAP2000 is shown in Figure 4.



(a) Frame view of castellated steel beam model



(b) Extrude view of castellated steel beam model

Fig. 4. The full-height rectangular opening castellated beam model with diagonal stiffener

The steel hinge properties is determined based on the material stress and deformation that occurs in the castellated steel beam element. Compressive structural member will experience critical stress and tensile structural member will experience yield stress. Meanwhile, the deformation value of an element can be calculated using the following equation

$$\delta = L \times \varepsilon \quad (10)$$

where δ is the axial deformation of member (mm), L is the calculated member span length (mm), and ε is the material strain value (mm/mm).

3. Result and Discussion

3.1. Flexural Capacity of IWF 200x100x8x5.5

The IWF plastic moment capacity value is used as a basic reference for the increase that occurs after the IWF section is changed to a castellated beam. IWF 200x100x8x5.5 has a plastic cross sectional modulus of $Z_x = 200125 \text{ mm}^3$. From the equation (1), we get the value of the plastic moment capacity of the IWF 200x100x8x5.5, $M_n = 48.04 \text{ kNm}$.

3.2. Truss Analysis

The calculation of the flexural capacity of castellated steel beams starts with the calculation of compressive or tensile strength of each element. The length of the diagonal stiffener element increases with the increment of the hole width as shown in Table 1 above. For the flange section, each variation has the same tensile stress value of 240 MPa while the compressive stress values for each variation can be seen in Table 2.

Table 2. Critical Stress Value on flange and diagonal stiffener

Model	Hole Width (mm)	Critical Stress Flange member (MPa)	Critical Stress Diagonal stiffener (MPa)
C-1	110	216.08	211.50
C-2	120	214.03	209.12
C-3	130	212.00	206.78
C-4	140	209.98	204.47

The data in Table 2 shows that the greater the hole width in the castellated steel beam is, the smaller the critical stress value in the flange member will be. The increase in the hole width also affects the length of the reinforcing steel used as a diagonal stiffener that has an impact on decreasing the critical stress value. Table 3 below shows the capacity values for the flange and diagonal stiffener elements calculated based on equations 2 to 9.

Table 3. Axial Strength of Flange and Diagonal Stiffener

Model	Flange		Diagonal Stiffener	
	Compressive Strength (kN)	Tensile Strength (kN)	Compressive Strength (kN)	Tensile Strength (kN)
C-1	59.97	68.05	187.03	192.00
C-2	59.29		186.58	
C-3	58.63		186.14	
C-4	57.97		185.69	

The load on the castellated steel beam produces axial forces that appear on each element, especially on the flange and diagonal stiffener elements. The greater the load applied to the castellated beam, the axial force will also become greater depending on the magnitude of the member angle.

The truss analysis is carried out with iteration of increasing the load value on the castellated steel beam, so the axial force with the equal value to the axial capacity of the flange or diagonal stiffener elements appears. The results of the truss analysis calculation can be seen in Table 4. From these data, the castellated beam has failed in the compressive flange because the axial force

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caused by the load has the same value as the compressive strength of the flange in each castellated steel beam model.

Table 4. Load Strength for Each of Castellated Steel Beam Model

Model	Load Strength (kN)	Flexural Capacity (kNm)	Axial Force	
			Flange (kN)	Stiffener (kN)
C-1	90.27	67.70	187.03	25.49
C-2	90.05	67.54	186.58	25.75
C-3	89.84	67.38	186.14	26.04
C-4	89.63	67.25	185.69	26.33

3.3. Pushover Analysis

The pushover analysis of the castellated steel beam model is performed using the SAP2000 program. Material properties and steel cross section data used are the theoretical data with non-linear defined stress-strain relationship.

In the pushover analysis, steel hinge properties are only defined on the flange and diagonal stiffener because plastic joints only occur in these two elements. Steel hinge properties are modeled using axial hinge options, where critical load values are used. This is because the critical load on the element has a smaller value than the yield load. The steel hinge curves on the flange and diagonal stiffener can be seen in Figure 5. Critical load and displacement values are calculated using the equations (3) and (10).

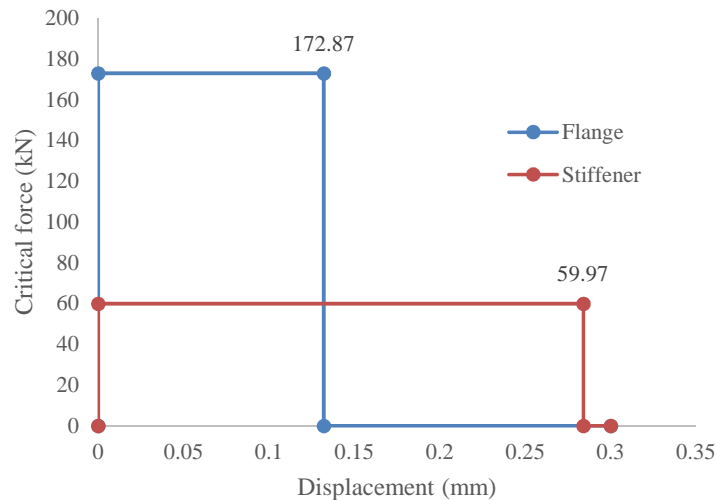


Fig. 5. Axial steel hinges curve for flange and stiffener element

The output of the SAP2000 pushover analysis is a load-displacement curve. Table 5 and Figure 6 shows that the castellated steel beam model with a hole width of 100 mm has a load capacity of 89.27 kN and a displacement of 4.06 mm. Based on the pushover analysis, all castellated steel beam models share the same types of failure. All castellated steel beam models experience a type of flexural buckling failure in the compressive flange in the center of the beam span. The load capacity and displacement values for all castellated beam models can be seen in Table 6.

Based on the pushover analysis output data, the value of flexural capacity for all castellated steel beam models show a similar trend. This is due to differences in the hole width which tend not to differ greatly for each castellated steel beam model.

Table 5. Pushover analysis output of C-1 castellated steel beam model

Step	Displacement (mm)	Force (kN)
0	0.00	0.00
1	0.80	20.14
2	1.60	40.27
3	2.40	60.41
4	3.20	80.55
5	3.51	88.30
6	4.06	89.27
7	4.97	41.57

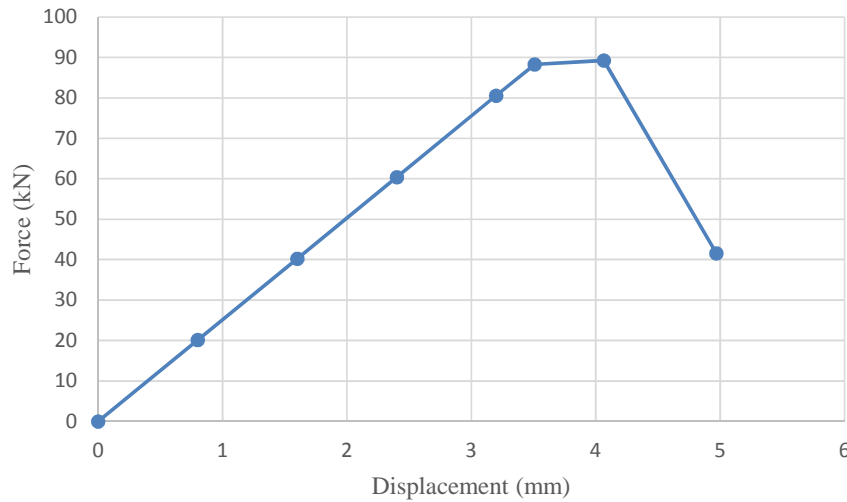


Fig. 6. Load-displacement curve pushover analysis of C-1 castellated steel beam model

Table 6. Results of Load Strength and Flexural Capacity of All Castellated Steel Beam Models

Model	Load Strength (kN)	Deformation (mm)	Distance between Joint Restrain and Load (m)	Flexural Capacity (kNm)
	P_n		a	$M_n = \frac{1}{2} P_n \times a$
C-1	89.27	4.06	1.5	66.95
C-2	89.23	4.16	1.5	66.92
C-3	89.22	4.05	1.5	66.92
C-4	89.22	4.14	1.5	66.92

3.4. Flexural Capacity Comparison of Truss Analysis and Pushover Analysis

Figure 7 shows the flexural capacity comparison curve between the truss analysis and the pushover analysis methods. In the C-1 model, there is an increase in the flexural capacity from the original IWF by 140.93%. Then, the flexural capacities of C-2, C-3, and C-4 models increase by 140.60%, 140.27% and 140.00%, respectively.

The difference in the values of flexural capacity using the truss analysis and pushover analysis methods for the C-1, C-2, C-3, and C-4 models are 1.11%, 0.92%, 0.68%, and 0.49%, respectively. Although the values of flexural capacity of castellated beam models are relatively not too different, from the calculation data, especially on the results of the truss analysis, it can be concluded that the smaller the hole width on the full-height rectangular opening castellated steel beams with diagonal stiffeners is, the greater the value of flexural capacity will be. This can happen because based on the bending beam theory, most of the flexural force is held by the flange element in the IWF section. The stronger the flange element is, the greater the flexural force that can be held will be. In this case, the strength of the flange element in the castellated steel beam is determined by the size of the hole width.

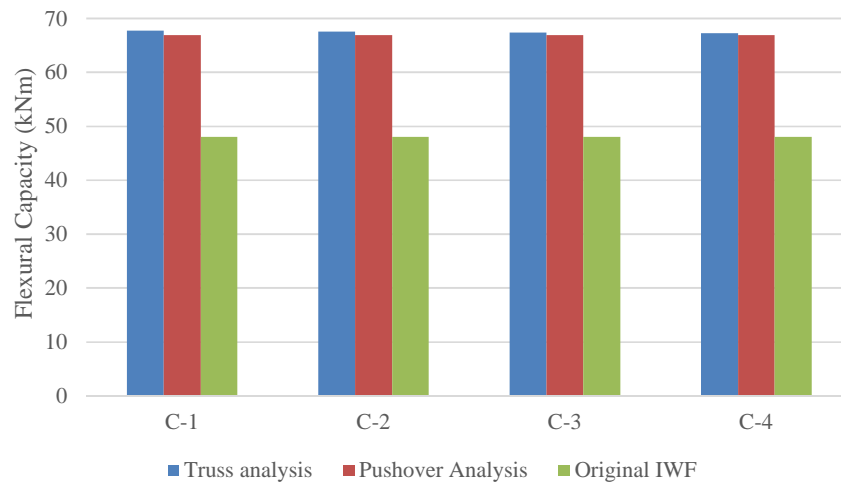


Fig. 7. Flexural Capacity comparison between truss analysis and pushover analysis

4. Summary

Based on the result of this research, the conclusions can be drawn as follows:

1. The analysis shows that the castellated steel beam with the hole width of 110 mm has a load capacity and flexural capacity of 90.27 kN and 67.70 kN. The castellated steel beam with the hole width of 120 mm has a load capacity and flexural capacity of 90.06 kN and 67.54 kN. The castellated steel beam with the hole width of 130 mm has a load capacity and flexural capacity of 89.84 kN and 67.38 kN. The castellated steel beam with the hole width of 140 mm has a load capacity and flexural capacity of 89.67 kN and 67.25 kN.
2. By using the same diameter of the reinforcing steel for the stiffener, the smaller the hole width in the full-height rectangular opening castellated steel beams with a diagonal stiffener is, the greater the value of the load capacity and flexural capacity will be.
3. The largest increase in flexural capacity from the original IWF to the castellated beam occurs in the C-1 model with a hole width of 110 mm, which is equal to 140.93%. Then, the C-2 (120 mm), C-3 (130 mm), and C-4 (140 mm) models have increased flexural capacities by 140.60%, 140.27% and 140.00%, respectively.

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