Proceedings of International Conference : Problem, Solution and Development of Coastal and Delta Areas
Semarang, Indonesia – September 26th, 2017
Paper No.C-44

The Flexural Behavior of the Full Height Rectangular Opening Castellated Steel Beam with Diagonal Stiffener

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Abstract-The full height rectangular opening of castellated steel beam is failed in Vierendeel mechanism. The Vierendeel failure mechanism made the load capacity of castellated steel beam is lower than its original section. In this research, the 16 mm diameter of steel bar as the diagonal stiffener is used as a reinforcement on the full height rectangular opening of castellated steel beam has a purposes to prevent Vierendeel failure mechanism so the load capacity of castellated steel beam can reach its maximum capacity. This research used a specimen of 3059 mm long span of castellated steel beam to study the flexural behavior. The specimen will be given the static load until it reached its maximum capacity. The test result show that the load capacity of the castellated steel beam is increase 157% compare to its original section. From the theoretical calculation it has 6.15% difference from the laboratory test result.

Keywords: castellated, Vierendeel, flexural behavior

1. Introduction

The castellated steel beam is a name commonly used for a type of expanded beam. It is made by expanding a standard rolled shape in a manner which creates a regular pattern of holes in the web [1]. The castellated steel beam generally has advantages in structural strength, economic value, and architectural design. The castellated steel beam is stronger compare to the original steel section because it has higher section's height so it gains more inertia. The economic value became one of the reason why castellated beam is chose as an alternative beam structure. the economic value of castellated steel beam depends on some factors like beam's span, load capacity, and beam's height [Boyer, J.P., 1964, *Castellated Beams – New Developments*, AISC National Engineering Conference, Omaha, Nebr., May 1964]. The web holes can also be seen as an architectural design that made the structure more beautiful.

There is many type of cutting pattern on the web section. Each type of this pattern created difference holes in the web like hexagonal, circular and rectangular opening shape. The castellated steel beam theory has the basic concept that the higher the castellated section, the higher the inertia would be increased and the load capacity would be increased as well. The Previous study show that the full height rectangular opening castellated steel beam is failed in Vierendeel mechanism [2] see Figure 1. The Vierendeel mechanism is caused by the appearance of plastic hinges on each of the corner of rectangular opening. This make the load capacity is lower than the original IWF section.

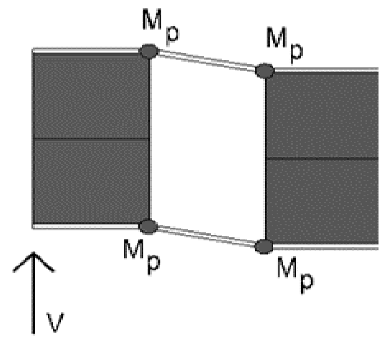

Figure 1. Plastic hinges appeared on each corner of the full height rectangular opening castellated steel beam

This study has a purpose to prevent Vierendeel failure mechanism so it can be optimized its yield moment capacity beam by welding the diagonal stiffener on the web opening as a reinforcement, see Figure 2.

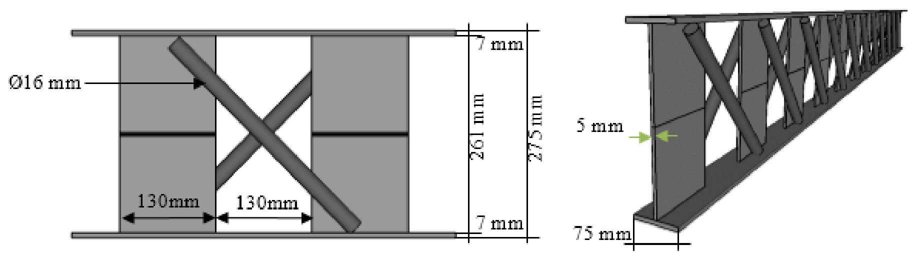

Figure 2. Full height rectangular opening castellated steel beam with diagonal stiffener

2. Research Method

One specimen of the full height rectangular opening castellated steel beam was made from the original section IWF 150x75x5x7 and analyzed using manual calculation and SAP2000 program during this research. The original IWF section has height of section, H = 150 mm, width of section, B = 75 mm, thickness of web, t_w = 5 mm, and thickness of flange, t_f = 7 mm. it has yield strength, f_y = 336 MPa. From this original IWF section, the castellated was made into the new section height, H = 275 mm that is about 1,8 times of the original one. The span of the specimen is 3059 mm. The rectangular pattern was made by the size of hole width, b = 130 mm and hole height, h = 261 mm.

The 16 mm diameter of steel bar as the diagonal stiffener is used as a reinforcement on the full height rectangular opening of castellated steel beam has a purposes to prevent Vierendeel failure mechanism so the load capacity of castellated steel beam can reach its maximum capacity. The steel bar has yield strength, f_y = 312 MPa. The specimen will be given the two point static load until it reached its maximum capacity during test on laboratory, see Figure 3.

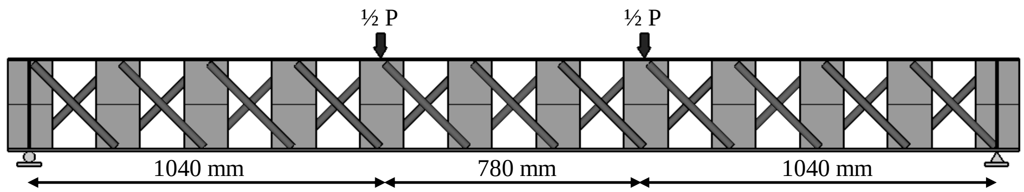

Figure 3. The Specimen of full height rectangular opening castellated steel beam with diagonal stiffener

The load capacity of the original IWF section can be calculated by multiply the moment capacity of IWF section (M_y) with the distance between the joint load and the joint restraint (d). Where the moment capacity of section can be calculated by multiply the section modulus (S) with its yield strength (f_y), as shown in equation 1 and equation 2. Using that equation, the load capacity of IWF 150x75x5x7 can be found to be 57 kN.

$$M_y = S.\, f_y \quad (1)$$

$$Py = 2 \times \frac{M_y}{d} \quad (2)$$

Where,
M_y = Moment capacity of section
S = Section modulus
P_y = Load capacity of section
d = distance between point load and restrain

The load capacity of capacity of the full height rectangular opening castellated steel beam with diagonal stiffener is designed following the assumption of truss analysis method, see Figure 4 [3]. Each element of the castellated steel beam that are flange, web, and diagonal stiffener are calculated separately as a compression or a tension element. The yield flexural capacity is determined by the nominal strength of flange section.

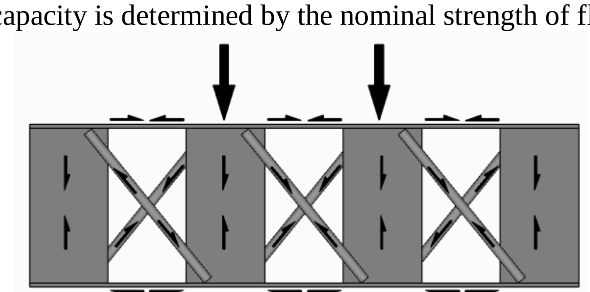
Figure 4. Truss analysis method

Load capacity of the full height rectangular opening castellated steel beam with diagonal stiffener can be calculated based on the nominal strength of compression and tension elements of flange and diagonal stiffener. The nominal strength of tension element can be calculated as follow

$$P_y = f_y A_s \tag{3}$$

$$M_y = \tfrac{1}{2} P_y d \tag{4}$$

where
P_y = nominal yield strength of tension elements (N)
f_y = yield stress of section (MPa)
A_s = area of section (mm^2)
M_y = flexural capacity (Nmm)
d = distance between joint restrain to joint load (mm)

the nominal strength of compression element is calculated based on critical force due to buckling failure. The calculation limit of compression element is determined based on the section's shape. Flange, web, and diagonal stiffener have a circular and a rectangular shape of section, so SNI-1729 2015 mentioned in Table E.1.1. that the nominal compressive strength of this type of shape is calculated based on limit states of flexural buckling [4]. Flexural buckling can be calculated as follow

$$P_n = f_{cr} A_g \tag{5}$$

where f_{cr} = critical stress (MPa), A_g = area (mm^2). The effective slenderness ratio is determine by

$$\lambda = \frac{KL}{r} \tag{6}$$

where λ = effective slenderness ratio, K = effective length factor, L = laterally unbraced length of member (mm), r = radius of gyration (mm). The critical stress, f_{cr} is determined as follow

$$\text{When } \lambda \le 4.71\sqrt{\frac{E}{f_y}} \text{ or } \frac{f_y}{f_e} \le 2.25, \tag{7}$$

$$\text{Then } f_{cr} = \left[0.658^{\frac{f_y}{f_e}}\right] f_y \tag{8}$$

$$\text{When } \lambda > 4.71\sqrt{\frac{E}{f_y}} \text{ or } \frac{f_y}{f_e} > 2.25, \tag{9}$$

$$\text{Then } f_{cr} = 0.877 f_y \tag{10}$$

where f_y = yield stress (MPa), E = elastic modulus (MPa), f_e = elastic buckling stress (MPa). Elastic buckling stress can be calculated as

$$f_e = \frac{\pi^2 E}{\lambda^2} \tag{11}$$

The nominal strength of compressive and tension elements of the full height rectangular opening castellated steel beam can be calculated as shown in Table 1.

Table 1. Nominal strength of compressive and tension elements for the long span specimen

Element	P_{cr} (kN)	P_y (kN)
Flange	164	176
Diagonal Stiffener	60	63

Using truss model calculation, the load capacity of specimen is iteratively calculated until one of the two elements, which is flange and diagonal stiffener, reached its nominal strength. Using this method, it can be found that the specimen have maximum load capacity 84 kN, the axial strength of flange is 164 kN, and the axial strength of diagonal stiffener is 27 kN. These value show that the flange section flange is the one that will reach its nominal strength.

3. Test Result and Discussion

This section compare between analysis result above and the laboratory test of the full height rectangular opening castellated steel beam with diagonal stiffener. Figure 5 show the load-displacement curve of the specimen. As mentioned above the theoretical load capacity of specimen is 84 kN. The test result show that the load capacity of specimen is 89.5 kN. The difference of the theoretical analysis and laboratory test of the specimen is 6.15%. This means that the theoretical model used in the research method can be used to predict the real load capacity of the full height rectangular opening castellated steel beam with diagonal stiffener. The maximum displacement of the specimen is 22.66 mm.

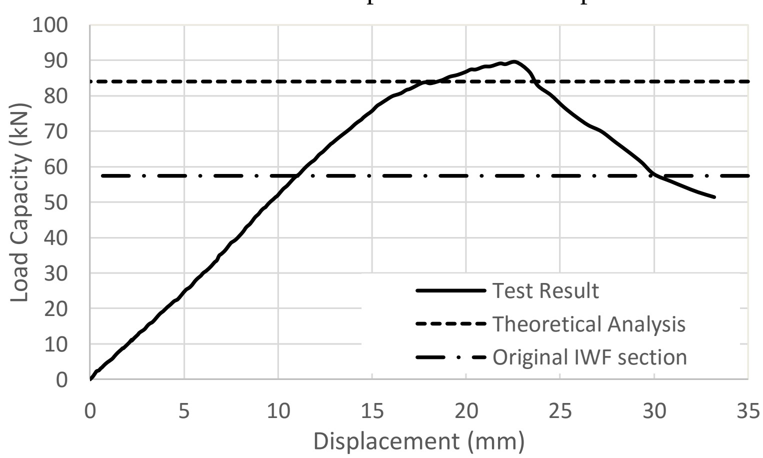

Figure 5. Load-displacement relation of the full height rectangular opening castellated steel beam with diagonal stiffener

The load-displacement curve shows that the specimen failed in a rather flexible condition. After it reached the maximum load capacity, the load started to drop and the diagonal stiffener started to fail in buckling, see Figure 6. The flange failure is already predicted from the theoretical analysis. The failure of flange section means that the specimen failed in flexural condition. The load capacity of the original IWF section and the specimen can be seen on Table 2. The test result show that the load capacity of the full height rectangular opening castellated steel beam with diagonal stiffener is increase 157% compare to the original IWF section.

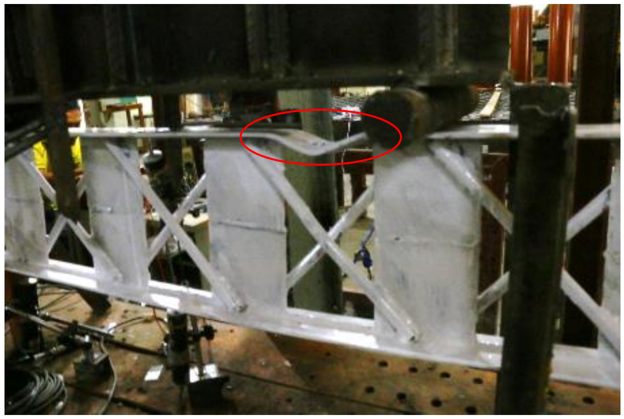

Figure 6. Flexural failure of the long span specimen

Table 2. The Load Capacity Of Full Height Rectangular Opening Castellated Steel Beam With Diagonal Stiffener

Structure	Theoretical Load Capacity (kN)	Testing Result (kN)	Comparison to Original IWF Section (%)
- Original IWF section	57	-	
- Castellated beam	84	89.5	157

4. Summary

Based on the result of this study, the following conclusions can be drawn:

1. Diagonal stiffener on a full height rectangular opening castellated steel beam can be used to prevent Vierendeel mechanism. The load capacity of the specimen is increase 157% compare to the original IWF section.
2. Truss analysis method can be used to calculate the load capacity of full height rectangular opening castellated steel beam with diagonal stiffener. Load capacity theoretical calculation is 57 kN that has 6.15% difference from the real load capacity.
3. The failure of the specimen is buckling failure on the flange section, which is a flexural failure.

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