Optimization Analysis of The Strength Capacity and The Economic Value Comparison of Castellated Steel Beam and Its Equivalent IWF Beam

Listiyono Budi 1, a), Aris Widodo 1, b), Bambang Haryadi 1, c), Bambang Endroyo 1, d), Dimas Wicaksono 1, e), Triono Subagio 1, f)

1 Department of Civil Engineering, Faculty of Engineering, Universitas Negeri Semarang
E3-E4 Building, Sekaran Campus, Gunungpati, Semarang, Central Java, Indonesia

a) Corresponding author: listiyono.budi@mail.unnes.ac.id
b) ariswidodo71@mail.unnes.ac.id
c) bambang.haryadi@mail.unnes.ac.id
d) bbenndroyo@yahoo.com
e) dimaz_arch@mail.unnes.ac.id
f) bagio.beck@mail.unnes.ac.id

Abstract. The research is aimed to figure out the comparison of the strength capacity and economic value comparison of castellated steel beam to its equivalent IWF beam. The profile of the castellated steel beam in this study included all profiles of castellated steel beam on the market based on the products catalog of the castellated steel beam from PT. Gunung Garuda. The finite element method was used in this study with the aid from Abaqus program to get a comparison of the strength capacity of castellated steel beam to its equivalent IWF beam. The next stage involved the calculation of a comparison of the economic value of the castellated steel beam with hexagonal holes with to its equivalent IWF beam. The results of the study showed that the castellated steel beam experienced an increase in the strength capacity of 1,189 up to 2,330 times compared to its equivalent IWF beam. The comparison of the strength capacity between the castellated steel beam and its equivalent IWF beam is at 1,010 up to 1,539. Based on the combination between the comparison of strength capacity and the economic value, there are 14 (58.33%) profiles of the castellated steel beam which is categorized as efficient in terms of the design of the structure and cost, there are four (16.67%) profiles of the castellated steel beam which is categorized as efficient in terms of the design of the structure but not efficient in terms of cost, and there are 6 (25.00%) profiles of the castellated steel beam which is categorized as inefficient in terms of the structure and cost. The results of this study indicate that the castellated steel beam can replace its equivalent IWF beam. Selection of profile of the castellated steel beam is appropriate to provide efficiency in terms of weight of the structure between 58.5% to 15.1% and can provide efficiency in terms of cost of between 48.4% to 0.9%.

Keywords: Castellated Steel Beam, Hexagonal Hole, Strength Capacity, Economic Value

INTRODUCTION

The structural system of the building has experienced rapid development. The main purpose of the development is to look for a structural system that is still safe but has a more lightweight structure.
and have a method of construction that is more easily and more quickly. It is aimed at obtaining more efficient cost of construction while still concerning about security of the post-construction building structural system.

The castellated steel beam with hexagonal holes is a IWF steel beam which is cut on the part of its web post with a pattern of zigzag, circle, square or modification of those forms, then connected by welding. The results of welding will produce IWF steel beam with a hole in its body and has a height of beam that is higher than a height of the original IWF steel beam.

The castellated steel beam with hexagonal holes has been widely used on the construction of the building in Indonesia. Therefore, it requires experimental research or a theoretical study to investigate the behavior of the structure (the distribution of forces, deflection, and model of structural failure) and the difference of the IWF steel beam profile, as well as the comparison of economic value of the castellated steel beam with hexagonal holes to its equivalent IWF steel beam. Therefore, it is expected that the results of this study could be a reference to the practitioner or the owners of the building regarding how the structural behavior of the the castellated steel beam with hexagonal holes with its comparison on its economic values to its equivalent IWF beam profile.

The use of FEM software to analyze the structural behavior of castellated steel beam gives results that are close to the results of experimental tests, one of the FEM software that can be used is Abaqus. The output of using the Abaqus program in the analysis of castellated steel beams can give the results of structural failure behavior and deflection values that are almost the same as experimental test results [1][2][3][7]. The FEM program that can be used besides Abaqus is Ansys, the Ansys program can also be used to analyze castellated steel beams and can give almost the same results as experimental tests [4][8]. In addition to analyzing the structural behavior of castellated steel beams, the use of the Abaqus program can also be performed to perform an optimization analysis of the shape and distance between the hexagonal holes of castellated steel beams [5][6]. In applications of the building construction, castellated steel beam are also often used to replace its equivalent IWF beam profile because they have advantages such as being able to provide the same or greater strength capacity than its equivalent profile IWF beam profile at a lower price [9].

The purpose of the present study this is to investigate the comparison of strength capacity between all the profiles of the castellated steel beam with hexagonal holes on the market to its original and equivalent IWF beam profiles, as well as to determine the comparison of economic value of all profiles of castellated steel beam with hexagonal holes on the market to its equivalent IWF beam profile.

**METHODOLOGY**

The finite element analysis method was used in this present study with the Abaqus program to model hexagonal holes on the castellated steel beams and IWF beams (with a beam span of 6000mm) with the uniform load along the beam span and the roller support as shown in the following figure.

![FIGURE 1. Type of Load and Support that will be Used to, (a) IWF Beam, (b) Castellated Steel Beam](image)

**The Design of IWF Beam Model and Castellated Steel Beam Model**

The size of the test object consisting of the dimensions of the castellated steel beam and IWF beam profiles, the number of holes and the distance between the holes in the castellated steel beam are determined as follows:
1) The castellated steel beams used in this study are made of IWF steel beam profile. The height ratio of castellated steel beams with hexagonal holes is 150% higher than its original IWF steel beam profile (see Figure 2).

![Figure 2](image)

**FIGURE 2.** (a) Cross Section of Original IWF Beam; (b) Cross Section of Castellated Steel Beam at Whole Section; (c) Cross Section of Castellated Steel Beam at Hole Section

2) The original IWF beam and castellated steel beam are steel profiles on the list of steel beam products produced by PT. Gunung Garuda [10]. With the total number of profiles for IWF beams and castellated steel beams, each of which is 24 profiles. The total profiles to be analyzed are 48 profiles. Detailed data on IWF beam profiles and castellated steel beams can be seen in table 1 below.

| No | IWF Beam Model | Profile Dimension (mm) | Castellated Steel Beam Model | Profile Dimension (mm) |
|----|----------------|------------------------|-----------------------------|------------------------|
| 1  | IWF-01         | 100 x 100              | CB-01                       | 150 x 100              |
| 2  | IWF-02         | 150 x 75               | CB-02                       | 225 x 75               |
| 3  | IWF-03         | 150 x 150              | CB-03                       | 225 x 150              |
| 4  | IWF-04         | 198 x 99               | CB-04                       | 297 x 99               |
| 5  | IWF-05         | 200 x 100              | CB-05                       | 300 x 100              |
| 6  | IWF-06         | 200 x 200              | CB-06                       | 300 x 200              |
| 7  | IWF-07         | 248 x 124              | CB-07                       | 372 x 124              |
| 8  | IWF-08         | 250 x 125              | CB-08                       | 375 x 125              |
| 9  | IWF-09         | 250 x 250              | CB-09                       | 375 x 250              |
| 10 | IWF-10         | 298 x 149              | CB-10                       | 447 x 149              |
| 11 | IWF-11         | 300 x 150              | CB-11                       | 450 x 150              |
| 12 | IWF-12         | 300 x 300              | CB-12                       | 450 x 300              |

3) All size parameters of the hexagonal hole are based on the hole height (Ds) according to the product data of the castellated steel beam with hexagonal holes from PT. Gunung Garuda [10]. The distance of the first/last hexagonal hole from the edge of the beam is expressed in the notation “x1”. The size parameters of the hexagonal holes can be seen in Figure 3.

![Figure 3](image)

**FIGURE 3.** The Parameters of Hexagonal Hole in Castellated Steel Beam

4) The number of hexagonal holes (n) is calculated based on equation 1 below:

\[
n = \left(\frac{L - (2 + s1)}{s2}\right) + 2
\]
where,

\( n \) : the number of hexagonal holes, if the result is not round then the number of holes is rounded down

\( L \) : total length of castellated steel beam measured from support to support (mm)

\( s_1 = 0.995 \times D_s \) (mm)

\( s_2 = 1.080 \times D_s \) (mm)

5) The distance of the hexagonal hole from the edge of the beam \((x_1)\) is calculated based on equation 2 below:

\[
x_1 = \left( \frac{L - (2 \cdot s_1) - (n - 2) \cdot s_2}{2} \right) \geq s
\]

(2)

where,

\( x_1 \) : distance of the first / last hole from the edge of the beam (mm), with the following conditions:

- if \( x_1 \geq s_2 \) then it meets the requirements
- if \( x_1 \leq s_2 \) then it does not meet the requirements, the number of holes must be reduced by 1

6) Based on equation 1 & 2, the design of the test object to be used in this study can be seen in table 2 below.

**TABLE 2. Number of Hexagonal Holes \((n)\) and Hexagonal Hole Distance from Beam Edge \((x_1)\) for each Castellated Steel Beam Model**

| Code | \( D_s \) | \( 0.125 \times D_s \) | \( 0.25 \times D_s \) | \( 0.29 \times D_s \) | \( x_1 = 0.955 \times D_s \) | \( s_2 = 1.08 \times D_s \) | \( L \) | \( n \) | \( x_1 \) |
|------|----------|-----------------|-----------------|-----------------|-----------------|-----------------|-------|-------|-------|
| CB-01 | 100      | 12.50           | 25.00           | 29.00           | 95.50           | 108.00          | 6000   | 55    | 42.50 |
| CB-02 | 150      | 18.75           | 37.50           | 43.50           | 143.25          | 162.00          | 6000   | 36    | 102.75|
| CB-03 | 150      | 18.75           | 37.50           | 43.50           | 143.25          | 162.00          | 6000   | 36    | 102.75|
| CB-04 | 198      | 24.75           | 49.50           | 57.42           | 189.09          | 213.84          | 6000   | 27    | 137.91|
| CB-05 | 200      | 25.00           | 50.00           | 58.00           | 191.00          | 216.00          | 6000   | 27    | 109.00|
| CB-06 | 200      | 25.00           | 50.00           | 58.00           | 191.00          | 216.00          | 6000   | 27    | 109.00|
| CB-07 | 248      | 31.00           | 62.00           | 71.92           | 236.84          | 267.84          | 6000   | 22    | 84.76  |
| CB-08 | 250      | 31.25           | 62.50           | 72.50           | 238.75          | 270.00          | 6000   | 21    | 196.25|
| CB-09 | 250      | 31.25           | 62.50           | 72.50           | 238.75          | 270.00          | 6000   | 21    | 196.25|
| CB-10 | 298      | 37.25           | 74.50           | 86.42           | 284.59          | 321.84          | 6000   | 18    | 140.69 |
| CB-11 | 300      | 37.50           | 75.00           | 87.00           | 286.50          | 324.00          | 6000   | 18    | 121.50 |
| CB-12 | 300      | 37.50           | 75.00           | 87.00           | 286.50          | 324.00          | 6000   | 18    | 121.50 |
| CB-13 | 346      | 43.25           | 86.50           | 100.34          | 330.43          | 373.68          | 6000   | 15    | 240.65 |
| CB-14 | 350      | 43.75           | 87.50           | 101.50          | 334.25          | 378.00          | 6000   | 15    | 208.75|
| CB-15 | 350      | 43.75           | 87.50           | 101.50          | 334.25          | 378.00          | 6000   | 15    | 208.75|
| CB-16 | 396      | 49.50           | 99.00           | 114.84          | 378.18          | 427.68          | 6000   | 13    | 269.58 |
| CB-17 | 400      | 50.00           | 100.00          | 116.00          | 382.00          | 432.00          | 6000   | 13    | 242.00|
| CB-18 | 400      | 50.00           | 100.00          | 116.00          | 382.00          | 432.00          | 6000   | 13    | 242.00|
| CB-19 | 450      | 56.25           | 112.50          | 130.50          | 429.75          | 486.00          | 6000   | 12    | 140.25 |
| CB-20 | 500      | 62.50           | 125.00          | 145.00          | 477.50          | 540.00          | 6000   | 10    | 362.50 |
| CB-21 | 588      | 73.50           | 147.00          | 170.52          | 561.54          | 635.04          | 6000   | 9     | 215.82 |
| CB-22 | 600      | 75.00           | 150.00          | 174.00          | 573.00          | 648.00          | 6000   | 9     | 159.00 |
| CB-23 | 700      | 87.50           | 175.00          | 203.00          | 668.50          | 756.00          | 6000   | 7     | 441.50 |
| CB-24 | 800      | 100.00          | 200.00          | 232.00          | 764.00          | 864.00          | 6000   | 6     | 508.00 |

**Strength Capacity of Beam Structure**

The strength capacity / stiffness is a comparison between a load received by the structure of the beam to the deflection in the structure of the beam caused by the load [11], or it is mathematically written in the form of the equation as follows:

\[
K = \frac{P}{\delta}
\]

(3)
where,
\[ K : \text{Strength Capacity (N/cm)} \]
\[ P : \text{Load (N)} \]
\[ \delta : \text{Deflection (cm)} \]

**Comparative Analysis of Economic Value**

The next analysis was to compare the economic value between castellated steel beam with hexagonal holes and its equivalent IWF beam profile. The economic value of IWF beam profile is calculated by multiplying its total weight to its price per kg. The economic value for castellated steel beam with hexagonal holes can be obtained by calculating the parameters as follows:

1) The total weight of the castellated steel beam with hexagonal holes is multiplied by its price per kg. The price which will be used as a reference is Rp. 15,000,- per kg.

2) The total length of cutting the body plate (web) of the IWF beam during the process of making castellated steel beam with hexagonal hole is multiplied by the price of cut steel per meter. The price which will be used as a reference is Rp. 50,000,- per meter of cutting length.

3) The total length of the welded joint when joining pieces of the IWF beam body plate to become a castellated steel beam is multiplied by the welding price per meter. The price which will be used as a reference is Rp. 460,000,- per meter of welding length.

**The Making of IWF Beam Model and Castellated Steel Beam Model with Abaqus**

In this study, the finite element analysis was performed by using Abaqus program. The use of the Abaqus program in the analysis of castellated steel beams can provide the results of the analysis in line with the results of experimental testing and the results of theoretical calculations \([1][2][7]\). Abaqus program that was used in this study is the Abaqus version 2017 issued by Dassault Systems SIMULIA Corp in 2016. Element used in the generation of models of castellated steel beam with hexagonal holes consisted of shell elements with the type of element S4R. Element S4R has 6 (six) degrees of freedom for each node and can provide a solution that is accurate for various types of problems that occur on the shell element of thin plates \([1][2][7]\).

**RESULT AND DISCUSSION**

**The Analysis Results of IWF Beam Model and Castellated Steel Beam Model**

The results of the analysis using Abaqus for a IWF beam and castellated steel beam model consist of the data on the maximum load and the value of maximum deflection on the first yield. The first yield occurs when the stress value reaches a value of 350.011 MPa. The results of the analysis of the Abaqus for the IWF beam model and castellated steel beam can be seen in Table 3 below.

| No | Code | Deflection (\(\delta\)), mm | Load (P), N | Strength Capacity \((K_{IWF})\), N/cm | Code | Deflection (\(\delta\)), mm | Load (P), N | Strength Capacity \((K_{IWF})\), N/cm |
|----|------|-----------------------------|-------------|---------------------------------|------|-----------------------------|-------------|---------------------------------|
| 1  | IWF-01 | 12,4980                     | 12,885.43   | 1,031.00                        | CB-01 | 8.2866                     | 19,909.18   | 2,402.58                        |
| 2  | IWF-02 | 8.3732                      | 14,660.18   | 1,758.40                        | CB-02 | 5.5024                     | 21,799.63   | 3,961.82                        |
| 3  | IWF-03 | 8.0476                      | 31,066.92   | 3,860.40                        | CB-03 | 4.5986                     | 39,106.05   | 8,503.95                        |
| 4  | IWF-04 | 6.3096                      | 24,770.02   | 3,925.75                        | CB-04 | 3.2857                     | 27,885.40   | 8,486.86                        |
| 5  | IWF-05 | 6.2098                      | 28,202.43   | 4,541.58                        | CB-05 | 3.5148                     | 34,705.52   | 9,874.08                        |
| 6  | IWF-06 | 4.9323                      | 51,264.87   | 10,393.80                       | CB-06 | 2.3992                     | 51,465.05   | 21,540.62                       |
| 7  | IWF-07 | 3.7939                      | 31,880.19   | 8,402.95                        | CB-07 | 1.9044                     | 32,415.09   | 17,020.97                       |
| 8  | IWF-08 | 4.0369                      | 38,570.71   | 9,554.65                        | CB-08 | 1.9625                     | 39,009.15   | 19,876.96                       |
| 9  | IWF-09 | 2.6896                      | 57,991.12   | 21,561.04                       | CB-09 | 1.4357                     | 59,414.00   | 41,383.45                       |
| 10 | IWF-10 | 2.3228                      | 35,083.38   | 15,103.68                       | CB-10 | 1.1863                     | 35,400.11   | 29,839.90                       |
| 11 | IWF-11 | 2.4565                      | 39,955.91   | 16,265.58                       | CB-11 | 1.2495                     | 40,273.48   | 32,232.15                       |
| 12 | IWF-12 | 1.6692                      | 65,642.05   | 39,326.60                       | CB-12 | 0.9604                     | 67,176.78   | 69,945.84                       |
The Comparative Analysis of Strength Capacity of Castellated Steel Beam to Its Original IWF Beam

The comparison of the strength capacity of the castellated steel beams to the original IWF beam was carried out to obtain the amount of increase in the strength capacity of each castellated steel beam profile compared to the original IWF beams. The comparison of the castellated steel beams to the original IWF beams can be seen in table 4 below.

| No | IWF Beam Model | Weight per Meter ($W_{IWF}$), kg | Strength Capacity ($K_{IWF}$), N/cm | Castellated Steel Beam Model | Weight per Meter ($W_{CB}$), kg | Strength Capacity ($K_{CB}$), N/cm | Strength Comparison ($K_{CB}/K_{IWF}$) |
|----|----------------|---------------------------------|----------------------------------|----------------------------|-----------------------------|---------------------------------|-----------------------------------|
| 1  | IWF-01         | 17.19                           | 1,031.00                         | CB-01                      | 17.20                       | 2,402.58                        | 2.330                             |
| 2  | IWF-02         | 14.01                           | 1,758.40                         | CB-02                      | 14.00                       | 3,961.82                        | 2.253                             |
| 3  | IWF-03         | 31.51                           | 3,860.40                         | CB-03                      | 31.50                       | 8,503.95                        | 2.203                             |
| 4  | IWF-04         | 18.20                           | 3,925.75                         | CB-04                      | 18.20                       | 8,486.86                        | 2.162                             |
| 5  | IWF-05         | 21.32                           | 4,541.58                         | CB-05                      | 21.30                       | 9,874.08                        | 2.174                             |
| 6  | IWF-06         | 49.87                           | 10,393.80                        | CB-06                      | 49.90                       | 21,450.62                       | 2.064                             |
| 7  | IWF-07         | 25.65                           | 8,402.95                         | CB-07                      | 25.70                       | 17,020.97                       | 2.026                             |
| 8  | IWF-08         | 29.56                           | 9,554.65                         | CB-08                      | 29.60                       | 19,876.96                       | 2.080                             |
| 9  | IWF-09         | 72.36                           | 21,561.02                        | CB-09                      | 72.40                       | 41,383.45                       | 1.919                             |
| 10 | IWF-10         | 32.03                           | 15,103.68                        | CB-10                      | 32.00                       | 29,839.90                       | 1.976                             |
| 11 | IWF-11         | 36.72                           | 16,265.58                        | CB-11                      | 36.70                       | 32,323.15                       | 1.982                             |
| 12 | IWF-12         | 94.04                           | 39,326.60                        | CB-12                      | 94.00                       | 69,945.84                       | 1.779                             |
| 13 | IWF-13         | 41.35                           | 24,188.23                        | CB-13                      | 41.40                       | 45,760.30                       | 1.892                             |
| 14 | IWF-14         | 49.56                           | 27,918.37                        | CB-14                      | 49.60                       | 52,192.91                       | 1.869                             |
| 15 | IWF-15         | 136.51                          | 68,561.75                        | CB-15                      | 137.00                      | 113,947.47                      | 1.662                             |
| 16 | IWF-16         | 56.65                           | 40,242.08                        | CB-16                      | 56.60                       | 71,886.09                       | 1.786                             |
| 17 | IWF-17         | 66.03                           | 44,938.35                        | CB-17                      | 66.00                       | 80,463.72                       | 1.791                             |
| 18 | IWF-18         | 171.68                          | 106,212.33                       | CB-18                      | 172.00                      | 163,485.90                      | 1.539                             |
| 19 | IWF-19         | 75.96                           | 60,824.21                        | CB-19                      | 76.00                       | 104,140.41                      | 1.677                             |
| 20 | IWF-20         | 89.65                           | 83,909.15                        | CB-20                      | 89.60                       | 141,156.74                      | 1.682                             |
| 21 | IWF-21         | 151.11                          | 175,447.92                       | CB-21                      | 151.00                      | 239,166.69                      | 1.363                             |
| 22 | IWF-22         | 105.50                          | 129,659.61                       | CB-22                      | 106.00                      | 192,128.56                      | 1.482                             |
| 23 | IWF-23         | 184.87                          | 263,876.93                       | CB-23                      | 185.00                      | 347,649.61                      | 1.317                             |
| 24 | IWF-24         | 209.91                          | 372,240.48                       | CB-24                      | 210.00                      | 442,495.71                      | 1.189                             |

Table 4 shows that the castellated steel beam experienced an increase in the strength capacity of 1,189 up to 2,330 times compared to the original IWF beam. The highest increase on the strength capacity of the castellated steel beam with a code CB-0. On the other hand, the smallest increase on the strength capacity of the castellated steel beam with a code CB-24 was indicated.

The Comparative Analysis of Strength Capacity of Castellated Steel Beam and Its Equivalent IWF Beam
Based on the strength capacity of each profile of the castellated steel and IWF beam, the comparison of strength capacity of each profile of the castellated steel and IWF beam which has a similar strength capacity can be performed. In addition to comparing the strength capacity, the weight comparison per meter length of the beam between each profile of the castellated steel and its equivalent IWF beam to determine the efficiency of the use of the castellated steel in reducing the weight of the structure of the building. Comparison between the profile of the castellated steel beam and its equivalent IWF beam in terms of the strength capacity and weight per meter length of the beam can be seen in Table 5 below.

### TABLE 5. The Comparison of Strength Capacity of Castellated Steel Beam and Its Equivalent IWF Beam

| No | Castellated Steel Beam Model | Equivalent IWF Beam Model | (W_{CB}, \text{kg}) | (K_{CB}, \text{N/cm}) | (W_{IWF}, \text{kg}) | (K_{IWF}, \text{N/cm}) | \frac{K_{CB}}{K_{IWF}} | \frac{W_{CB}}{W_{IWF}} |
|----|----------------------------|---------------------------|---------------------|----------------------|---------------------|----------------------|-------------------|-------------------|
| 1  | CB-01                      | IWF-02                    | 17.20               | 2,402.58             | 14.01               | 1,758.40             | 1.366             | 1.228             |
| 2  | CB-02                      | IWF-03                    | 14.00               | 3,961.82             | 31.51               | 3,860.40             | 1.026             | 0.444             |
| 3  | CB-03                      | IWF-07                    | 31.50               | 8,503.95             | 25.65               | 8,402.95             | 1.012             | 1.228             |
| 4  | CB-04                      | IWF-07                    | 18.20               | 8,486.86             | 25.65               | 8,402.95             | 1.010             | 0.710             |
| 5  | CB-05                      | IWF-08                    | 21.30               | 9,874.08             | 29.56               | 9,554.65             | 1.033             | 0.721             |
| 6  | CB-06                      | IWF-11                    | 49.90               | 21,740.62            | 36.72               | 16,265.58            | 1.319             | 1.359             |
| 7  | CB-07                      | IWF-11                    | 25.70               | 17,020.97            | 36.72               | 16,265.58            | 1.046             | 0.700             |
| 8  | CB-08                      | IWF-11                    | 29.60               | 19,876.96            | 36.72               | 16,265.58            | 1.222             | 0.806             |
| 9  | CB-09                      | IWF-12                    | 72.40               | 41,383.45            | 94.04               | 39,326.60            | 1.052             | 0.770             |
| 10 | CB-10                      | IWF-14                    | 32.00               | 29,839.90            | 49.56               | 27,918.37            | 1.069             | 0.646             |
| 11 | CB-11                      | IWF-14                    | 36.70               | 32,232.15            | 49.56               | 27,918.37            | 1.155             | 0.741             |
| 12 | CB-12                      | IWF-15                    | 94.00               | 69,495.84            | 136.51              | 68,561.75            | 1.020             | 0.689             |
| 13 | CB-13                      | IWF-17                    | 41.40               | 45,760.30            | 66.03               | 44,938.35            | 1.018             | 0.627             |
| 14 | CB-14                      | IWF-17                    | 49.60               | 52,192.91            | 66.03               | 44,938.35            | 1.161             | 0.751             |
| 15 | CB-15                      | IWF-18                    | 137.00              | 113,947.47           | 171.68              | 106,212.33           | 1.073             | 0.798             |
| 16 | CB-16                      | IWF-15                    | 56.60               | 71,886.09            | 136.51              | 68,561.75            | 1.048             | 0.415             |
| 17 | CB-17                      | IWF-15                    | 66.00               | 80,463.72            | 136.51              | 68,561.75            | 1.174             | 0.483             |
| 18 | CB-18                      | IWF-18                    | 172.00              | 163,489.50           | 171.68              | 106,212.33           | 1.539             | 1.002             |
| 19 | CB-19                      | IWF-20                    | 76.00               | 104,140.41           | 89.65               | 83,909.15            | 1.241             | 0.848             |
| 20 | CB-20                      | IWF-22                    | 89.60               | 141,156.74           | 105.50              | 129,659.61           | 1.089             | 0.849             |
| 21 | CB-21                      | IWF-21                    | 151.00              | 239,166.69           | 151.11              | 175,447.92           | 1.363             | 0.999             |
| 22 | CB-22                      | IWF-21                    | 106.00              | 192,128.56           | 151.11              | 175,447.92           | 1.195             | 0.701             |
| 23 | CB-23                      | IWF-23                    | 185.00              | 347,649.61           | 184.87              | 263,876.93           | 1.317             | 1.001             |
| 24 | CB-24                      | IWF-24                    | 210.00              | 442,495.71           | 209.91              | 372,240.48           | 1.189             | 1.000             |

Table 5 shows the comparison of the strength capacity between each profile of the castellated steel beam with the profile of its equivalent IWF beam is 1,010 up to 1,539. It indicates that all the profiles of the castellated steel beam can replace the profile of the equivalent IWF beam. The strength capacity of the castellated steel beam is more than 100% capacity of its equivalent IWF beam with the weight ratio that varies between 0.444 up to 1.359. Most of the profile of the castellated steel beam steel has weight ratio to its equivalent IWF beam profile in under 1. Therefore, the designs can become more efficient in comparison with the equivalent IWF beam to reduce the weight of its own structural beams that will be used.

### The Comparative Analysis of Economic Value of Castellated Steel Beam to Its Equivalent IWF Beam

Comparison of the economic value between castellated steel beam steel with its equivalent IWF beam was calculated based on the production cost incurred in the production of castellated steel beam and its equivalent IWF beam. The comparison of the economic values for castellated steel beam and its equivalent IWF beam can be seen in table 6 below.

### TABLE 6. The Comparison of Economic Value of Castellated Steel Beam and Its Equivalent IWF Beam

| No | Castellated Steel Beam Model | Equivalent IWF Beam Model |
|----|-----------------------------|--------------------------|

163
Table 6 shows the comparison of the economic value of castellated steel beam and its equivalent IWF beam. 14 profiles or 58.33% of the castellated steel beam have a lower cost of production compared to its equivalent IWF beam with the value of 0.516 up to 0.991 times. Therefore, 14 profiles of the castellated steel beam have a higher economic value compared to its equivalent IWF beam.

The Comparative Analysis of Strength Capacity and Economic Value of Castellated Steel Beam to Its Equivalent IWF Beam

The comparison between castellated steel beam and its equivalent IWF beam in terms of strength capacity and economic value aims to find out whether the castellated steel beam is more efficient in terms of structural design and more cost efficient than its equivalent IWF beam. Regarding these conditions, the results of the comparison on the strength capacity and economic value of castellated steel beams with its equivalent IWF beam can be divided into 3 conditions as follows:

1) Condition A, the comparison of castellated steel beam and its equivalent IWF beam is in efficient conditions in terms of structural design and cost.
2) Condition B, the comparison of castellated steel beam and its equivalent IWF beam is in efficient conditions in terms of structural design but not efficient in terms of cost.
3) Condition C, the comparison of castellated steel beam and its equivalent IWF beam is inefficient in terms of structural design and cost.

The comparison of the strength capacity and economic value of castellated steel beam and its equivalent IWF beam can be seen in table 7 below.

| No | Castellated Steel Beam Code | Equivalent IWF Beam Code | Strength Comparison (K_Cb / K_IWF) | Weight Comparison (W_Cb / W_IWF) | Economic Value Comparison (IDR_Cb / IDR_IWF) | Condition |
|----|---------------------------|-------------------------|----------------------------------|---------------------------------|-------------------------------------------|------------|
| 1  | CB-01                      | IWF-02                  | 1.366                            | 1.228                           | 2,115                                     | C          |
| 2  | CB-02                      | IWF-03                  | 1.026                            | 0.444                           | 0.851                                     | A          |
| 3  | CB-03                      | IWF-07                  | 1.012                            | 1.228                           | 1.728                                     | C          |
| 4  | CB-04                      | IWF-07                  | 1.010                            | 0.710                           | 1.218                                     | B          |
| 5  | CB-05                      | IWF-08                  | 1.033                            | 0.721                           | 1.154                                     | B          |
Table 7 shows 14 profiles or 58.33% of the castellated steel beam fall into category A. The rest, namely 4 profiles (16.67%) of castellated steel beam fall into category B and 6 profiles (25.00%) of castellated steel beam fall into category C.

### CONCLUSION

Based on the results of the comparative analysis between castellated steel beam and original profile of IWF beam in terms of strength and comparative analysis between castellated steel beam and its equivalent IWF beam in terms of strength and economic value, the following conclusions can be drawn:

1) Castellated steel beams experienced an increase in strength capacity of 1,189 to 2,330 times against its original IWF beam profile. The largest increase in strength capacity is indicated by castellated steel beam with code CB-01 and the smallest increase in strength capacity is indicated by castellated steel beam with code CB-24.

2) The comparison of strength capacity between castellated steel beam profile and its equivalent IWF beam profile is 1.010 to 1.539. This shows that all castellated steel beam profiles can replace the equivalent IWF beam profile with a strength capacity of more than 100% of the equivalent IWF beam profile strength capacity.

3) Based on the results of the comparison of the economic value of castellated steel beam and its equivalent IWF beam profile, 14 profiles or 58.33% of castellated steel beam have lower production costs compared to equivalent IWF beam profiles are to a value of 0.516 to 0.991 times. Therefore, the 14 profiles of castellated steel beam have a higher economic value than the equivalent IWF beam profile.

4) Based on the combination of strength capacity comparison and economic value, there are 14 (58.33%) castell steel beam profiles that fall into the efficient category in terms of structural design and cost, there are 4 (16.67%) castell steel beam profiles that fall into the efficient category in terms of structural design but inefficient in terms of cost, and there are 6 (25.00%) castell steel beam profiles that fall into the inefficient category in terms of structural design and cost.

5) In general, castellated steel beam with hexagonal holes can replace its equivalent IWF beam profiles. The right selection of castellated steel beams can provide efficiency in terms of structural weight between 58.5% to 15.1% and provide efficiency in terms of beam production costs between 48.4% to 0.9% or equivalent.

### REFERENCES

[1] Ellobody E., 2011, Interaction of Buckling Modes in Castellated Steel Beams, Journal Construction Steel Research 67, Pages 814-825.
[2] Ellobody E., 2012, Nonlinier Analysis of Cellular Steel Beams under Combined Buckling Modes, Thin-Walled Structures 52, 66-79.
[3] Jamadar A. M. and Kumbhar P. D., 2014, Finite Element Analysis of Castellated Beam: A Review, International Journal of Innovative Research in Advanced Engineering (IJIRAE), Vol. 1, Issue 9, Pages 125-129.
[4] Jichkar R. R., Arukia N. S., and Pachpor P. D., 2014, Analysis of Steel Veam with Web Openings Subjected to Buckling Load, International Journal of Engineering Research and Applications (IJERA), Vol. 4, Issue 5, 185-188.
[5] Budi L., Sukamta, and Partono W., 2017, Optimization Analysis of Size and Distance of Hexagonal Hole in Castellated Steel Beams, Procedia Engineering 171 (2017), Pages 1092-1099.
[6] Partono W., Sukamta, Hardiyati S., and Budi L., 2018, Optimasi Distribusi Lubang pada Balok Baja Kastela, Teknik, 39 (1), 2018, 1-8.
[7] Wang P., Ma N., and Wang X., 2014, Numerical Studies on Large Deflection Behaviors of Restrained Castellated Steel Beams in Fire, Journal Construction Steel Research 100, 136-145.
[8] Wakchaure M. R., and Sagade A. V., 2012, Finite Element Analysis of Castellated Steel Beam, International Journal of Engineering and Innovative Technology (IJET), Vol. 2, Issue 1, Pages 356-370.
[9] Lukmansa I., 2015, Studi Perbandingan Perencanaan Struktur Baja Menggunakan Profil Biasa Dan Profil Kastela pada Proyek Gedung PGN di Surabaya, Ekstrapolasi Jurnal Teknik Sipil Untag Surabaya, Vol. 8 No. 2, Hal. 207-216.
[10] Daftar Produk Balok Baja Kastela Lubang Heksagonal dari PT. Gunung Garuda, 2021, Diakses pada 10 Maret 2021, dari (https://download.katalogmaterial.com/download/katalog-baja-gunung-garuda/)
[11] Pratama R. F., Budio S. P., and Wijaya M. N., 2016, Analisis Kekakuan Struktur Balok Beton Bertulang dengan Lubang Hollow Core pada Tengah Balok, Jurnal Mahasiswa Teknik Sipil, Vol. 1, No. 2, pp.551-561