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

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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 next 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 design 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 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.

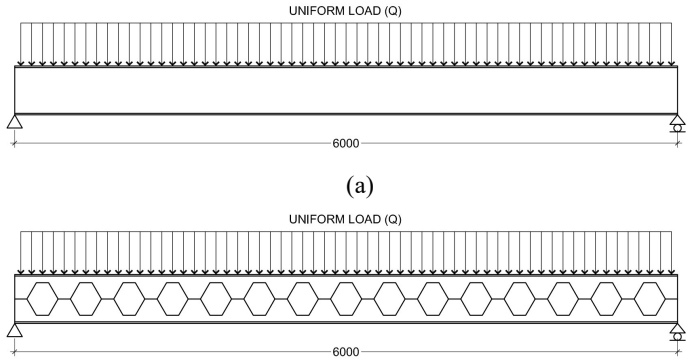
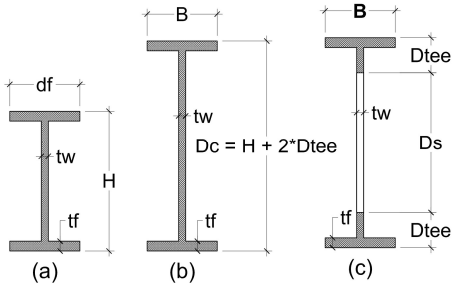


FIGURE 1. Type of Load and Support that will be Used to, (a) IWF Beam, (b) Castellated Steel Beam

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).



H = Web Height of IWF Beam (mm)
Ds = Height of Hexagonal Hole of Castellated Steel Beam (mm)
Dc = Web Height of Castellated Steel Beam (mm)
B = Flange Wide of Castellated Steel Beam (mm)
Dtee = Web Height above Hexagonal Hole of Castellated Steel Beam (mm)
tf = Flange Thickness (mm)
tw = Web Thickness (mm)

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.

TABLE 1 . List of IWF Beam Model and Castellated Steel Beam Model

No	IWF Beam Model		Castellated Steel Beam Model		No	IWF Beam Model		Castellated Steel Beam Model	
	Code	Profile Dimension (mm)	Code	Profile Dimension (mm)		Code	Profile Dimension (mm)	Code	Profile Dimension (mm)
1	IWF-01	100 x 100	CB-01	150 x 100	13	IWF-13	346 x 174	CB-13	519 x 174
2	IWF-02	150 x 75	CB-02	225 x 75	14	IWF-14	350 x 175	CB-14	525 x 175
3	IWF-03	150 x 150	CB-03	225 x 150	15	IWF-15	350 x 350	CB-15	525 x 350
4	IWF-04	198 x 99	CB-04	297 x 99	16	IWF-16	396 x 199	CB-16	594 x 199
5	IWF-05	200 x 100	CB-05	300 x 100	17	IWF-17	400 x 200	CB-17	600 x 200
6	IWF-06	200 x 200	CB-06	300 x 200	18	IWF-18	400 x 400	CB-18	600 x 400
7	IWF-07	248 x 124	CB-07	372 x 124	19	IWF-19	450 x 200	CB-19	675 x 200
8	IWF-08	250 x 125	CB-08	375 x 125	20	IWF-20	500 x 200	CB-20	750 x 200
9	IWF-09	250 x 250	CB-09	375 x 250	21	IWF-21	588 x 300	CB-21	882 x 300
10	IWF-10	298 x 149	CB-10	447 x 149	22	IWF-22	600 x 200	CB-22	900 x 200
11	IWF-11	300 x 150	CB-11	450 x 150	23	IWF-23	700 x 300	CB-23	1050 x 300
12	IWF-12	300 x 300	CB-12	450 x 300	24	IWF-24	800 x 300	CB-24	1200 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.

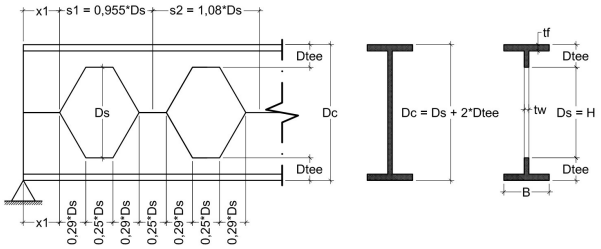


FIGURE 3. The Parameters of Hexagonal Hole in Castellated Steel Beam

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

$$n = \left(\frac{L - (2 \cdot s1)}{s2}\right) + 2$$

(1)

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)

s1 : 0.995 x Ds (mm)

s2 : 1,080 x Ds (mm)

5) The distance of the hexagonal hole from the edge of the beam (x1) is calculated based on equation 2 below:

$$x1 = \left(\frac{L - (2 \cdot s1) - \{(n - 2) \cdot s2\}}{2} \right) \geq s \quad (2)$$

where,

x1 : distance of the first / last hole from the edge of the beam (mm), with the following conditions:

if x1 ≥ s2 then it meets the requirements

if x1 ≤ s2 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 (x1) for each Castellated Steel Beam Model

Code	Ds	0.125* Ds	0.25* Ds	0.29* Ds	s1 = 0.955* Ds	s2 = 1.08* Ds	L	n	x1
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)		(mm)
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:

$$K = P/\delta \quad (3)$$

where ,

K : Strength Capacity (N/cm)

P : Load (N)

δ : 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.

TABLE 3. Abaqus Output Results of Castellated Steel Beam Model and IWF Beam Model in First Yield Condition

No	IWF Beam Model				Castellated Steel Beam Model			
	Code	Deflection (δ), mm	Load (P), N	Strength Capacity (K_{IWF}), N/cm	Code	Deflection (δ), mm	Load (P), N	Strength Capacity (K_{IWF}), N/cm
1	**IWF-01**	12,4980	12885.43	1,031.00	**CB-01**	8.2866	19,909.18	2,402.58
2	**IWF-02**	8.3372	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	21450.62
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	9554.65	**CB-08**	1.9625	39,009.15	19,876.96
9	**IWF-09**	2.6896	57.991.12	21,561.02	**CB-09**	1.4357	59,414.00	41,383.45
10	**IWF-10**	2.3228	35,083.38	15103.68	**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	32232.15
12	**IWF-12**	1.6692	65,642.05	39,326.60	**CB-12**	0.9604	67,176.78	69,945.84

13	**IWF-13**	1.5562	37,641.83	24,188.23	**CB-13**	0.8291	37,941.54	45,760,30
14	**IWF-14**	1.6184	45,183.87	27,918,37	**CB-14**	0.8735	45,590.87	52,192.91
15	**IWF-15**	1.1645	79,842.99	68,561.75	**CB-15**	0.7123	81.169.15	113.947.47
16	**IWF-16**	1.1326	45,577.19	40,242.08	**CB-16**	0.6404	46,035.60	71,886.09
17	**IWF-17**	1.2032	54,068.04	44,938.35	**CB-17**	0.6693	53,855.81	80,463.72
18	**IWF-18**	0.8331	88,488,94	106.212.33	**CB-18**	0.5485	89,670.46	163.489.50
19	**IWF-19**	0.9728	60,393.51	62,084.21	**CB-19**	0.5850	60,921.90	104.140.41
20	**IWF-20**	0.8047	67,519.96	83.909.15	**CB-20**	0.4801	67,775,17	141.156.74
21	**IWF-21**	0.4675	82,015,89	175,447.92	**CB-21**	0.3492	83,512.45	239,166.69
22	**IWF-22**	0.5728	74,268.00	129,659.61	**CB-22**	0.3919	75,289.89	192.128.56
23	**IWF-23**	0.3424	90,360,31	263.876.93	**CB-23**	0.2628	91,375.74	347,649.61
24	**IWF-24**	0.2972	110,633.71	372240,48	**CB-24**	0.2218	98.158.41	442,495.71

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 was to the original IWF beams. The comparison of the castellated steel beams to the original IWF beams can be seen in table 4 below.

TABLE 4. The Comparison of Strength Capacity of Castellated Steel Beam to Its Original IWF Beam

No	IWF Beam Model			Castellated Steel Beam Model			Strength Comparison (K_{CB} / K_{IWF})
	Code	Weight per Meter (W_{IWF}), kg	Strength Capacity (K_{IWF}), N/cm	Code	Weight per Meter (W_{IWF}), kg	Strength Cap acity (K_{IWF}), N/cm	
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	21450.62	2.064
7	IWF-07	25.65	8,402.95	CB-07	25,70	17,020.97	2.026
8	IWF-08	29.56	9554.65	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	15103.68	CB-10	32.00	29,839,90	1,976
11	IWF-11	36.72	16,265.58	CB-11	36,70	32232.15	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	163.489.50	1.539
19	IWF-19	75.96	62,084.21	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	372240,48	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 was experienced by castellated steel 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			(K_{CB}/ K_{IWF})	(W_{CB}/ W_{IWF})
	Code	(W_{CB}), kg	(K_{CB}), N/cm	Code	(W_{IWF}), kg	(K_{IWF}), N/cm		
1	CB-01	17,20	2,402.58	IWF-02	14.01	1,758,40	1.366	1,228
2	CB-02	14.00	3,961.82	IWF-03	31.51	3,860,40	1.026	0.444
3	CB-03	31.50	8,503.95	IWF-07	25.65	8,402.95	1.012	1,228
4	CB-04	18,20	8,486.86	IWF-07	25.65	8,402.95	1.010	0.710
5	CB-05	21.30	9,874.08	IWF-08	29.56	9554.65	1.033	0.721
6	CB-06	49.90	21450.62	IWF-11	36.72	16,265.58	1.319	1,359
7	CB-07	25,70	17,020.97	IWF-11	36.72	16,265.58	1.046	0.700
8	CB-08	29.60	19,876.96	IWF-11	36.72	16,265.58	1.222	0.806
9	CB-09	72.40	41,383.45	IWF-12	94.04	39,326.60	1.052	0.770
10	CB-10	32.00	29,839,90	IWF-14	49.56	27,918,37	1.069	0.646
11	CB-11	36,70	32232.15	IWF-14	49.56	27,918,37	1,155	0.741
12	CB-12	94.00	69,945.84	IWF-15	136.51	68,561.75	1.020	0.689
13	CB-13	41.40	45,760,30	IWF-17	66.03	44,938.35	1.018	0.627
14	CB-14	49.60	52,192.91	IWF-17	66.03	44,938.35	1,161	0.751
15	CB-15	137,00	113.947.47	IWF-18	171.68	106.212.33	1.073	0.798
16	CB-16	56,60	71,886.09	IWF-15	136.51	68,561.75	1.048	0.415
17	CB-17	66.00	80,463.72	IWF-15	136.51	68,561.75	1.174	0.483
18	CB-18	172.00	163.489.50	IWF-18	171.68	106.212.33	1.539	1.002
19	CB-19	76.00	104.140.41	IWF-20	89.65	83.909.15	1,241	0.848
20	CB-20	89.60	141.156.74	IWF-22	105.50	129,659.61	1.089	0.849
21	CB-21	151.00	239,166.69	IWF-21	151.11	175,447.92	1.363	0.999
22	CB-22	106.00	192.128.56	IWF-21	151.11	175,447.92	1.095	0.701
23	CB-23	185.00	347,649.61	IWF-23	184.87	263.876.93	1.317	1,001
24	CB-24	210.00	442,495.71	IWF-24	209.91	372240,48	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 ration 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

	Code	Economic Value (IDR_{CB}), Rp	Code	Economic Value (IDR_{CB}), Rp	Economic Value Comparison (IDR_{CB} / IDR_{IWF})
1	CB-01	2,666,507.60	IWF-02	1,260,900,000	2,115
2	CB-02	2,413,807.45	IWF-03	2,835,900,000	0.851
3	CB-03	3,988.807.45	IWF-07	2,308,500, 00	1,728
4	CB-04	2,810,869,40	IWF-07	2,308,500, 00	1.218
5	CB-05	3,070,807.45	IWF-08	2,660,400,000	1.154
6	CB-06	5,644,807.45	IWF-11	3,304,800,000	1,708
7	CB-07	3,172,565,70	IWF-11	3,304,800,000	0.960
8	CB-08	3,596,737.50	IWF-11	3,304,800,000	1.088
9	CB-09	7,409,675.00	IWF-12	8,463,600,000	0.875
10	CB-10	3,807,818,30	IWF-14	4,460,400,000	0.854
11	CB-11	4,219,980.00	IWF-14	4,460,400,000	0.946
12	CB-12	9,376,980.00	IWF-15	12,285,900,000	0.763
13	CB-13	4,953,937.20	IWF-17	5,942,700,000	0.834
14	CB-14	5,670,757.25	IWF-17	5,942,700,000	0.954
15	CB-15	13,519,737.25	IWF-18	15,451,200.00	0.875
16	CB-16	6,336,763.15	IWF-15	12,285,900,000	0.516
17	CB-17	7,164,407.20	IWF-15	12,285,900,000	0.583
18	CB-18	16,704,407.20	IWF-18	15,451,200.00	1.081
19	CB-19	7,993,807.45	IWF-20	8,068,50,00	0.991
20	CB-20	9,359,006.90	IWF-22	9,495,000.00	0.986
21	CB-21	14,781,931.30	IWF-21	13,599,900,000	1.087
22	CB-22	10,675,680.00	IWF-21	13,599,900,000	0.785
23	CB-23	18.002.230.00	IWF-23	16,638,300.00	1.082
24	CB-24	20,345,760.00	IWF-24	18,891,900,000	1.077

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.

TABLE 7. The Comparison of Strength Capacity and Economic Value of Castellated Steel Beam and Its Equivalent IWF Beam

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

6	CB-06	IWF-11	1.319	1,359	1,708	C
7	CB-07	IWF-11	1.046	0.700	0.960	A
8	CB-08	IWF-11	1.222	0.806	1.088	B
9	CB-09	IWF-12	1.052	0.770	0.875	A
10	CB-10	IWF-14	1.069	0.646	0.854	A
11	CB-11	IWF-14	1,155	0.741	0.946	A
12	CB-12	IWF-15	1.020	0.689	0.763	A
13	CB-13	IWF-17	1.018	0.627	0.834	A
14	CB-14	IWF-17	1,161	0.751	0.954	A
15	CB-15	IWF-18	1.073	0.798	0.875	A
16	CB-16	IWF-15	1.048	0.415	0.516	A
17	CB-17	IWF-15	1.174	0.483	0.583	A
18	CB-18	IWF-18	1.539	1.002	1.081	C
19	CB-19	IWF-20	1,241	0.848	0.991	A
20	CB-20	IWF-22	1.089	0.849	0.986	A
21	CB-21	IWF-21	1.363	0.999	1.087	B
22	CB-22	IWF-21	1.095	0.701	0.785	A
23	CB-23	IWF-23	1.317	1,001	1.082	C
24	CB-24	IWF-24	1,189	1,000	1.077	C

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%) castella steel beam profiles that fall into the efficient category in terms of structural design and cost, there are 4 (16.67%) castella 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%) castella 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.

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