The structural behavior of castellated beam with shape variation using finite element methods

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Abstract. Castella steel is an alternative material used in the structure of beams and columns in the construction of a building. Castella web holes in previous studies mentioned the following: hexagonal, honeycomb, octagonal, diamond, and hexagonal. The advantage of using the castella steel beam is that it has a higher web geometry without increasing its weight so that it could add up the inertia value of its profile. The purpose of this study is to analyze castella steel beams with various geometric shapes such as hexagonal, octagonal, and diamond with couple plates on the web weld joints to determine the behavior of castella steel beams when receiving axial loads using the finite element method of the abaqus. Analysis of the behavior of castella steel beams, with or without using of a plate, does not significantly influence the deflection that occurs. However, the addition of the coupled plate has a significant influence on the stress-strain value in the welded joints on the web. Hence, the addition of a plate coupled to the web joints of the castella steel beam profile is highly recommended to support strength resistance as a long-term structure. Analysis of the performance of castella steel beams by the addition of coupled plates for each castella hole with a load equal to 75 kN, resulting in the best capability on the value of the displacement is the hexagonal profile that is 12.839mm compared to other profile displacements of 14.433mm diamond hole profiles and 14.972 octagonal hole profiles.

1. Introduction

Castella steel is an alternative material that can be used in the construction of beam and column structural elements. Castella beam is a modification of the I-beam that experiences longitudinal and horizontal cuts in the web of Budi et al. [4]. Castella rods are I-profile rods with hexagonal holes in the web made from cutting a hot rolled steel profile I rod which forms a polygon pattern in which the web is halved and joined by welding at web position so that the profile increases 40-60% higher than original profile Sonck’s et al. [8]. The hole in the web of castella has several geometric shapes that have been done by research, among others: hexagonal, honeycomb, octagonal, diamond, and hexagonal with a cut corner. There are six possible patterns of failure in the castella beam, including the formation of the flexural mechanism, lateral torsion bending, formation of the Vierendeel mechanism, rupture of the welded joint, shear buckling and bending stress on the web of Jamadar and Kumbhar [3].

Castella steel beams have a higher web geometry with their weight that does not increase so it could increase the value of the inertia of the profile in accepting the load, this is an advantage of using castella. Research by Jamadar and Kumbhar [3] about holes in castella beam bodies generally hexagonal, circular, diamond, or square. The purpose of this study is to examine holes with hexagonal, circular, diamond, or square shapes. There are six possible patterns of failure in the beam, among others: the
formation of the bending mechanism, lateral torsion bending, the formation of the Vierendeel mechanism, rupture at the welded joint, shear buckling on the web and bending stress on the web. Sonck's research, et al. [8] about the lateral torsion bending resistance of castella steel beams with a modification of the residual stress pattern during the castellated beam manufacturing process will result in a resistance that lies about one bend curve lower than the resistance obtained using the original residual stress pattern. It corresponds to a maximum reduction in buckling resistance of around 13%. Research Budi, et al. [4] an optimizing the size and hole spacing of hexagonal geometric castella steel beams, led to the fact that the distance between holes affected the location of the maximum stress concentration. The maximum stress concentration is at the edge of the area of the hexagonal hole for a longer hole distance while the maximum stress concentration moves to the web connection area for shorter hole spacing. The basis of the increased strength analysis for the original profile and the location of the stress concentrations of all the models is 60 degrees, namely the angular size with the hole spacing which results in the optimum model of castella steel beams worth between 0.186ho to 0.266ho. Laboratory test results are approximately the same as FEM analysis with an average ratio of 1.011 and a COV value of 0.069. The method used for the analysis of castella steel beam models with FEM is valid. Yossef and Taher's research [10] regarding cost optimization in a composite floor system with castella steel beams, produces a way to reduce post-bending bodies, the ratio of openings to the web can vary between 19 to 34 and the ratio of openings to widths must be less than 2.28 with an angle (alpha) between 54.8 to 76.5 degrees with an average value of 62.12 degrees. Extending the distance from end to end is not recommended because it does not affect optimizing material values. Partial rigid joints with a restraint factor of R = 0.75 for the main girders make up 10% the price of composite plates compared to simple end connections. Weld becomes very important in the process of making castella steel beams. Understanding welding is the process of connecting the metal by making the parts that are joined merge (coalescence) into a single unit Dewobroto [1].

In this study, the aim is to examine the stress-strain analysis at the connection of the web with a castella couple beam plate with various geometric shapes, hexagonal, octagonal and diamond when receiving axial loads using the Finite Element Method of the Abaqus auxiliary program.

2. Research Method

2.1. General

Analysis of castella steel beams with variations in the geometry hole mounted by a couple plate on the welding joint is applying the finite element method (FEM). The outline of this research is to find out the stress-strain behavior of castella steel beams with a variety of geometric holes mounted by a couple plate on the welded joints of the web when receiving axial loads. The analysis used the 2019 Abaqus program, an analysis program using the finite element method. Logan, D.L [5] describes the finite element method is a numerical way to solve physical-mathematical engineering and problems. There are 3 models with different castella steel hole geometric that will be examined and analyzed using steel material Grade, namely BJ41 with yield strength (fy) 250 MPa and tensile strength (fu) 410 MPa and BJ50 Grade that has a yield strength (fy) 290 MPa and with tensile strength (fu) of 500 MPa. It is explained in the following table 1.

| No. | Steel Profile (mm) | Mechanism of Steel | Hole of Castella Steel | Hole Type of Castella |
|-----|--------------------|--------------------|------------------------|-----------------------|
|     | H                  | B                  | tw | tf | Type | (fy) | (fu) | (%) | h | b (mm) | e (mm) | ntotal | e/ho (ratio) | α | s |                |
| 1   | 225                | 75                 | 5  | 7  | BJ41 | 250  | 410  | 18  | 149.74 | 43.50 | 39.83 | 48.00 | 0.27 | 60 | 166.7       |       |
| 2   | 225                | 75                 | 5  | 7  | BJ41 | 250  | 410  | 18  | 172.10 | 43.40 | 39.83 | 48.00 | 0.23 | 60 | 166.5       | Hexagonal |
| 3   | 225                | 75                 | 5  | 7  | BJ41 | 250  | 410  | 18  | 150.00 | 75.00 | 39.83 | 42.00 | 0.27 | 45 | 189.8       |       |
| 4   | 225                | 75                 | 5  | 7  | BJ50 | 290  | 500  | 16  | 149.74 | 43.50 | 39.83 | 48.00 | 0.27 | 60 | 166.7       | Diamond |
| 5   | 225                | 75                 | 5  | 7  | BJ50 | 290  | 500  | 16  | 172.10 | 43.40 | 39.83 | 48.00 | 0.23 | 60 | 166.5       | Octagonal |
| 6   | 225                | 75                 | 5  | 7  | BJ50 | 290  | 500  | 16  | 150.00 | 75.00 | 39.83 | 42.00 | 0.27 | 45 | 189.8       | Diamond |
Young modulus (E) of 200,000 MPa and a poison ratio of 0.3 and a plastic strain value used was 0.001 according to Irawan, C. [2]. The initial steel beam profile was WF 150x75x5x7 which was modified into 225x75x5x7 castella steel beam profile as detailed in figure 1, which was adopted from the research of Budi et al. [4].

![Figure 1. Preliminary details of castella steel beam profiles.](image)

2.2. Calculation Analysis
Perforations made on the castella web greatly affect the structural performance of the beam. Therefore, it is necessary to do a practical analysis to provide optimal perforation on the beam. Optimization of beam dimension profiles and beam hole detail in this study refers to the previous 3 researchers namely the Jamadar AM research, and Kumbhar P. D [3] for diamond holes, in the study of Budi, L., et al. [4] for hexagonal holes and in the Soltani MR study, [6] for octagonal holes. It is explained in figure 2, figure 3, and table 2.

![Figure 2. Detail profile of hexagonal and octagonal.](image)

![Figure 3. Detail Profile of Diamond.](image)
Table 2. Detail profil of castella steel beam 225x75x5x7.

| No. | Hole Type of Castella Steel | Hole of Castella Steel | Hole Type of Castella |
|-----|-----------------------------|------------------------|-----------------------|
|     |                             | ho^a (mm) | b^b (mm) | e^c (mm) | n-total^d | e/ho^e | f^f | s^g | hp^h |
| 1   | Hexagonal                   | 150       | 43,50    | 39,8     | 48,00     | 0,27    | 60  | 166,7 | -    |
| 2   | Octagonal                   | 172       | 43,40    | 39,8     | 48,00     | 0,23    | 60  | 166,5 | 21,7 |
| 3   | Diamond                     | 150       | 75,00    | 39,8     | 42,00     | 0,27    | 45  | 189,8 | -    |
| 4   | Hexagonal                   | 150       | 43,50    | 39,8     | 48,00     | 0,27    | 60  | 166,7 | -    |
| 5   | Octagonal                   | 172       | 43,40    | 39,8     | 48,00     | 0,23    | 60  | 166,5 | 21,7 |
| 6   | Diamond                     | 150       | 75,00    | 39,8     | 42,00     | 0,27    | 45  | 189,8 | -    |

Note
- ho^a: height of the castle hole
- b^b: projection of horizontal distance in the castella hole
- e^c: width of the horizontal distance on the web. \( L = (\frac{\alpha_{total} + 2b}{2n_{total}}) \)
- n^d: the total number of castella holes
- e/ho^e: ratio
- \( \alpha^f \): angle of the hole
- s^g: the distance between the hole points, Hexagonal and Octagonal = 2e + 2b; Diamond = ho + b
- hp^h: vertical height between holes = couple plate width
couple profile : 39.8mm long, 21.7mm wide and 2.5mm thick

In this study using the finite element method with modeling that refers to the research profile of Budi et al. (2017). Modeling indicators are stated verified by experimental test results if the results of finite element analysis of the compressive strength (displacement) produced no more than 5% of the results of previous studies.

![Figure 4. Loading of Castella Steel Beams.](image)

Wang, et al. [9] conducted a study on the capacity of vertical shear buckling in the body of castella steel beams with a hexagonal hexagonal body hole. Comparison between bending mode simulation is obtained from the results of experimental tests with the results of bending failure occurring on the body. Prediction of deformation changes using finite element simulation gives very good results.

3. Result of Analysis
In this study, the results of the analysis will be compared with the previous studies. Indicators of this verification stage are load values and experimental test displacement and finite element analysis results as described in table 3.
Table 3. Verification of analysis results and prior research results.

| Vicky (2020) | FEM | Eksperimental | Ratio |
|--------------|-----|---------------|-------|
| (a)          | (b) | (C)           | (b/a) | (c/b) | (c/a) |
| Force (kN)   | 74,377 | 73,958 | 75,021 | 0,994 | 1,014 | 1,009 |
| Displacement (mm) | 12,762 | 12,772 | 13,790 | 1,001 | 1,080 | 1,081 |
| Ratio (F/Disp) | 5,828 | 5,791 | 5,440 | 0,994 | 0,939 | 0,933 |

Average 0,996 1,011 1,008
Deviation 1,478% 0,360%

The results of the modeling analysis show the deviation difference from the results of previous studies is quite good, with a deviation result below 5%. Therefore, the modeling stages are declared feasible to be used in further profile analysis. Figure 5 shows a verification graph showing the results coinciding between previous research data and this study.

Figure 5. Verification results of modeling analysis.

Figure 6 shows the performance graph profile of each castella steel beam hole with a comparison of the displacement value that occurs to the load (P) which is the same as the hexagonal hole results have the best performance in terms of the smallest displacement value among other hole profiles.
Figure 6. Comparison of displacement values to the load given to each castella hole is diamond, hexagonal, and octagonal hole.

From table 4, it can be concluded that the castella steel beam with the best performance in receiving the same static load is indicated by the smallest displacement (displacement) is on the castella steel beam with the hexagonal hole profile.

| Type         | Diamond 45° | Hexagonal 60° | Octagonal 60° |
|--------------|-------------|---------------|---------------|
| P (kN)       | 75          | 75            | 75            |
| Displacement (mm) | 14,42       | 12,84         | 14,97         |
| Phase Load Es - Ps | 140,38     | 135,88        | 104,38        |
| Phase Disp Es - Ps | 26,06      | 31,28         | 25,44         |

Further review of the ability of castella steel beam material in accepting loads up to the plastic phase has different performance categories between profiles. Even further review is on the stresses that occur in each section of the beam. Figure 7 show the result of the stress values of each castella steel beam hole profile in the middle span position and the pedestal position. The comparison result of the stress values of each castella steel beam in table 5.
Figure 7. Example of von mises stress castella diamond steel beams in the middle span with BJ-50 steel grade.

Table 5. Results of Comparison Analysis of Castella Steel Beam Stresses.

| Grade                | Profil Stresses (MPa) |       |       |       |       |       |
|----------------------|-----------------------|-------|-------|-------|-------|-------|
|                      |                      | Middle Span | Support |       |       |       |
|                      |                       | Hexagonal | Octagonal | Diamond | Hexagonal | Octagonal | Diamond |
| BJ41-Coupled         | 242                   | 407     | 410    | 287    | 256    | 400    |
| BJ50-Coupled         | 234                   | 340     | 256    | 213    | 507    | 403    |
| BJ50-Uncoupled       | 366                   | 474     | 256    | 446    | 500    | 424    |
| **Average**          | **281**               | **407** | **260** | **315** | **421** | **409** |

The table 5 shows that the optimal average stress value is in the profile of castella steel beams with hexagonal orifice profiles. It shows that the hexagonal hole profile has the best structural performance in receiving loads by reviewing the average stress value generated from the stresses in the center of the span and support, average values is 298MPa for the hexagonal hole; 414MPa octagonal hole; and 334MPa of diamond holes.

Figure 8. Stress – Strain curve of steel grade BJ-50.
Figure 7 show the steel grade BJ-50 have the best stress - strain values is diamond hole profiles castella steel beam. This shows different behavior according to the grade of steel and the type of castella hole profile used.

4. Conclusion
Based on the results of the analysis and discussion the following points can be summarized:

- Analysis of the behavior of castella steel beams with or without the addition of coupled plates has no significant effect on a deflection that occurs.
- Strain stress analysis on castella steel beams influences the use of coupled plates, and it does not use coupled plates that occur in welded web joints. The value of stressed steel beams with a coupled plate is smaller when compared to steel beams that do not use a coupled plate. Thereby, the addition of a plate coupled to the web joints of the castella steel beam is highly recommended to support the durability of the strength profile as a long-term structure.
- Analysis of the performance of castella steel beams with the addition of coupled plates for various hole profiles with a load of 75 kN, resulting in the best capability on the hexagonal profile in terms of the value of the displacement which occurs is 12.839mm smaller when compared to other profile displacement is 14.433mm for diamond hole profiles and 14.972 for the profile of the octagonal hole.

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