Simulation and Modeling of Hexagonal Castellated Steel I-Beams Applied in Men's Dormitory Building

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ABSTRACT

Steel structures are widely used for construction due to high strength with high ductility. Generally, steel sections are satisfying on strength requirements, but do not satisfy for serviceability requirements. One of the most type of structure is castellated beam. According to Tsavdaridis, K. et al., (2014), castellated beam is a beam style where an I-beam is subjected to a longitudinal cut along its web following a specific pattern in order to divide it, and then reassemble the beam with a deeper web by taking advantage of the cutting pattern. The main objective of the study was to determine the most efficient cut in W4x13 and W6x25 hexagonal-shaped castellated beams with a cutting angle of 60° that provided reduced deflection from the initial steel beams. The beams simulated using COMSOL Multiphysics were subjected to fixed constraint boundary condition, gravity, and a uniformly distributed transverse load and produced results of vertical displacement, ultimate load capacity, and von Mises stress. After the analysis, castellated beams showed an outstanding performance from the simulations executed. Castellated beams were proven to have numerous advantages such as high strength to weight ratio than regular steel I-beams, long span capability, installation and direct cost savings, aesthetics, among others. For a detailed and accurate research, it is highly recommended that experimental set-up must be performed, as well as further simulations which include the analysis of failure modes of the castellated beam.

Keywords: castellated beam, fixed constraint boundary condition, uniformly distributed transverse load, vertical displacement, ultimate load capacity, von Mises stress

INTRODUCTION

Difficulty in transportation is one of the main reasons why a huge number of students in institutions choose to reside in dormitories. Dormitory provides convenience in terms of its location and practicality.

Cavite State University has five existing dormitories. Among these, the men's dormitory building can only accommodate a few number of students due to its limited housing units. This structure has been built years ago and needed development in terms of its function and capacity.

Castellated beams are used to pass under floor services ducts such as air ducts, water and sewage pipes, cables, etc. Fabrication of castellated beams poses several advantages such as reduction in total weight of the structure without greatly reducing its strength and reduction in quantity of steel used.

This study adopted Ragas and Venzon's(2019) work for the improvement of the selected I-beams of the structure using castellated steel I-beams. It determined the maximum deflection and ultimate load capacity of each castellated beam of different specifications. Also, it defined the ratio of load capacity between the castellated and initial beams and the stress at the center of the castellated beam. Von Mises stress was used to determine the failure conditions of ductile material such as steel.

Advantages based in the study of Coulson, *et al*. (2016) are enumerated as follows:

1. long span capability;

2. more flexibility in space planning of the building;
3. low floor vibration/high stiffness to weight ratio than regular steel beam;
4. minimizes the quantity of columns and reduced number of foundations, which is a direct cost savings;
5. reduced overall mass of the structure;
6. save in installation costs for the structure;
7. provide substantial direct material costs savings;
8. open access for future maintenance;
9. aesthetic appearance; and,
10. availability of smaller beams to be castellated if required size of steel beam (as planned) is not available in the market.

Hence, disadvantages of castellated beams based on the study of Kinget (2015) are listed as follows:

1. high fabrication costs;
2. stress concentration occurs near the perforation;
3. shear carrying capacity is reduced; and,
4. perforations introduce complex failure mechanisms, leading to a more complex design.

OBJECTIVES

The general objective of the study is to simulate and analyse hexagonal-shaped castellated beams.

Specifically, the following objectives have been devised to:

1. introduce a simulated model of a castellated beam with hexagon section for the four-storey men's dormitory building;
2. determine the maximum deflection of each castellated beam of different specifications;
3. identify the ultimate load capacity of each castellated beam based on the maximum deflection of the initial design of beam;
4. find the stress at the center of the castellated beam according to the design moment of the men's dormitory building and according to the ultimate load capacity of each castellated beam;
5. compute the ratio of load capacity between the castellated beams and the initial design of beams;
6. determine the most efficient cut of a hexagonal castellated beam that can carry the design moment of the men's dormitory building with a reduced deflection;
7. determine the wastage for each specification of hexagonal castellated beam; and,
8. calculate the difference in cost of castellated beam compare to initial I-beam.

METHODOLOGY

This chapter presents the outline of the research methods and techniques that were followed in the study. This provides and discusses the important specifications and descriptions of the materials used in the simulation based on its functionality and compatibility features.

Materials

COMSOL Multiphysics Software. COMSOL Multiphysics is the software used to geometrically and physically simulate beams. The program simulated the reaction of solid mechanic beam to load application. This software provided results for structural mechanics by the use of finite element method (FEM).

Adopted Study. The design moment given in the study of Ragas and Venzon (2019) was adopted for assigning force per unit area to be applied in the simulation of castellated beam.

Methods

Finite element modeling. The Finite Element Analysis is the mathematical approach of Finite Element Method (FEM) which was used in this study to simulate the castellated I-beam.

Applied study and multi-physics. The actuator models were governed by the structural mechanic's physics provided by the module available on the COMSOL simulation platform.

Solid mechanics physics. The structural mechanics branch contains the physics interfaces for analyzing the deformations, stresses, and strains of the solid structure. The solid mechanics interface is based on solving the equations of motion.

Material selection. The nodes under materials branch were used to add predefined or user-defined materials, to specify material properties using model inputs, functions, values, and expressions as needed, or to create a custom material library.

Meshing and discretization. COMSOL Multiphysics has powerful default mesh generator algorithms built-in, but also permits substantial user control over customization. Finite element method has a feature of permitting irregular and arbitrary meshes.

Stationary domain. The Stationary study and study step are used when field variables do not change over time, such as in stationary problems. The actuator models were computed for their deformation, stresses and strain response with application of force per unit area.

Parametric sweep. Parametric sweep was used in order to find the solution to a sequence of stationary or time-dependent problems that arise when varying some parameters of interest. The parametric sweep includes multiple independent parameters directly for a full multi-parameter sweep.

Boundary point probe. The boundary point probe was used to monitor the development of a scalar-valued quantity (real or complex-valued number) from a dynamic simulation (time-dependent, frequency, parametric).

The facilities of the Simulation, Modeling and Measurement Laboratory (SiMMLab) located in Cavite State University Don Severino de las Alas Campus were used to conduct the study.

Castellated steel I-beams were modeled and simulated using COMSOL Multiphysics Software by following the activities below:

A. Pre-processor: Defining the Problem

Specify the title. Simulating a model needs to have a proper title that determines the content of the files to avoid confusion. Title must be clear and arranged orderly.

Set code and units. Parameters are used for setting the codes needed for the numerical values in making geometry.

Define nodes and elements. Finite element method starts in subdividing the modeling from domain up into smaller, simpler domains called elements.

Define materials. COMSOL contains several predefined materials grouped by application area that are used in simulation. Each material has initial properties installed in the software.

Define element type. Tetrahedral elements are the default element type for most physics within COMSOL Multiphysics. Tetrahedral is known as simplex, which means that any 3D volume, regardless of shape or topology, can be meshed accurately.

Define section. The cross-section of the model must be initially considered whether it is two-dimensional or three-dimensional. 2D uses a line model, while 3D creates a space model.

Define beam and shell properties. It is more efficient to use shell or beam elements in a model that consists of thin and slender components where it will result in extremely many small elements.

Mesh the model. Approximate solution to the problem is solved at discrete points in space defined by the mesh. For more accuracy of the results, finer meshes are recommended (see Figure 1).

B. Solution Processor: Assigning Loads and

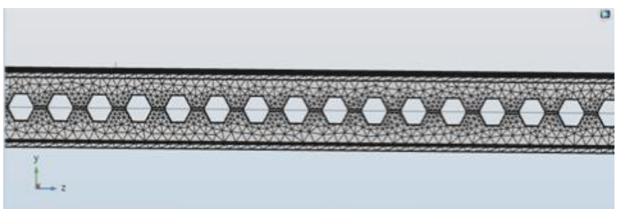

Figure 1. Mesh of structural steel material (finer size)

Solving

Apply displacement constraints. This is applied at a particular point on the model. Also, it can limit the displacement in one direction or in all directions.

Apply force per unit area load. It is also called as pressure load. Pressure is the force on an object that is spread over a surface area.

Define analysis type and analysis option. The Structural Mechanics branch contains physics interfaces for analyzing deformations, stresses, and strains of solid structures.

Specify boundary condition. It is a condition that is required to be satisfied at all or part of the boundary of a region in which a set of differential equations is to be solved.

Obtain solution. Solution data sets correspond to data stored by the solvers. It relies on information such as which solver is selected.

C. Post-processing: Viewing the Results

Enter the postprocessor and read results. Post-processing is the further processing of the raw data produced by the computation. Results could be displayed as a graph of data produced by computations.

Plot the deformed shape. Post-processing result generates after solution is obtained. Deformed shape shows the distribution of selected variable value such as stresses over the computational domain.

Export results. Results can be exported in type of Text file, Excel file, CSV file, etc. for easier viewing and analyzing of results.

RESULTS AND DISCUSSION

Static Analysis

The initial model of I-beam is presented in Figure 2. The study had three I-beams simulated: (1) W5x16 replaced by W4x13 with a length of 5.40 m; (2) W5x16 replaced by W4x13 with a length of 5.75 m; and, (3) W8x35 replaced by W6x25 with a length of 5.40 m.

This study determined the maximum deflection of each castellated beam of different specifications

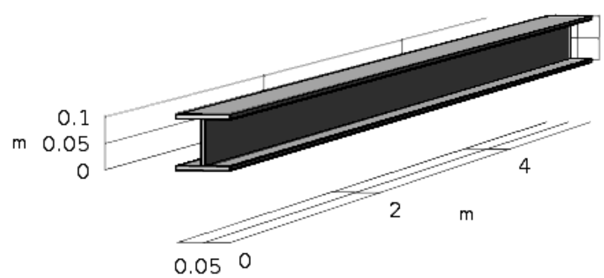

Figure 2. Initial I-beam model

(sample shown in Figure 3). Specifically, (1) W4x13 beam which measured 5.40 m ranged from 5 mm – 50 mm; (2) in W4x13 beam which measured 5.75 m ranged from 5 mm – 50 mm; (3) in W6x25 beam which measured 5.40 m ranged from 30 mm – 75 mm.

Initial I-beam of each specification was simulated using a Boundary Point Probe condition node.

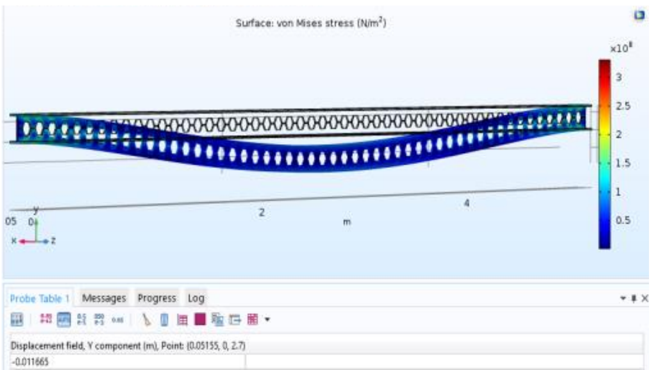

Figure 3. Deflection of castellated beam

The results are presented in Table 1 and 2.

Data Analysis of the Deflection of Castellated Beams

Figures 4, 5, and 6 present the relationship of the deflection of the castellated beam with the different length of leg of hexagon. These data imply that as the length of each side of the hexagon increases, the deflection of beam decreases. Therefore, the length of each side of the hexagon is inversely proportional with the deflection of the beam.

Data Analysis of the Ultimate Load Capacity of Castellated Beams Based on the Maximum Deflection of the Initial Beam

Each beam was simulated using a study of parametric sweep to determine the ultimate force per area needed that would reach the maximum deflection of their respective initial beam.

The results in the simulation of castellated beams

Table 1. Maximum deflection of I-beams from the adopted study

I-BEAM SPECIFICATION	LENGTH OF SPAN	ADOPTED DESIGN MOMENT (kN m)	FORCE PER AREA (N/m^2)	MAXIMUM DEFLECTION (AT CENTER)
W5x16	5.40 m	-10.00	-79 829.8028	-0.009117 m
W5x16	5.75 m	-18.82	-132 506.2936	-0.018997 m
W8x35	5.40 m	-84.26	-449 156.6984	-0.017457 m

Table 2. Maximum deflection of the replacement I-beams

I-BEAM SPECIFICATION	LENGTH OF SPAN	ADOPTED DESIGN MOMENT (kN m)	FORCE PER AREA (N/m^2)	MAXIMUM DE-FLECTION (AT CENTER)
W4x13	5.40 m	-10.00	-79 829.8028	-0.020488 m
W4x13	5.75 m	-18.82	-132 506.2936	-0.043187 m
W6x25	5.40 m	-84.26	-449 156.6984	-0.028341 m

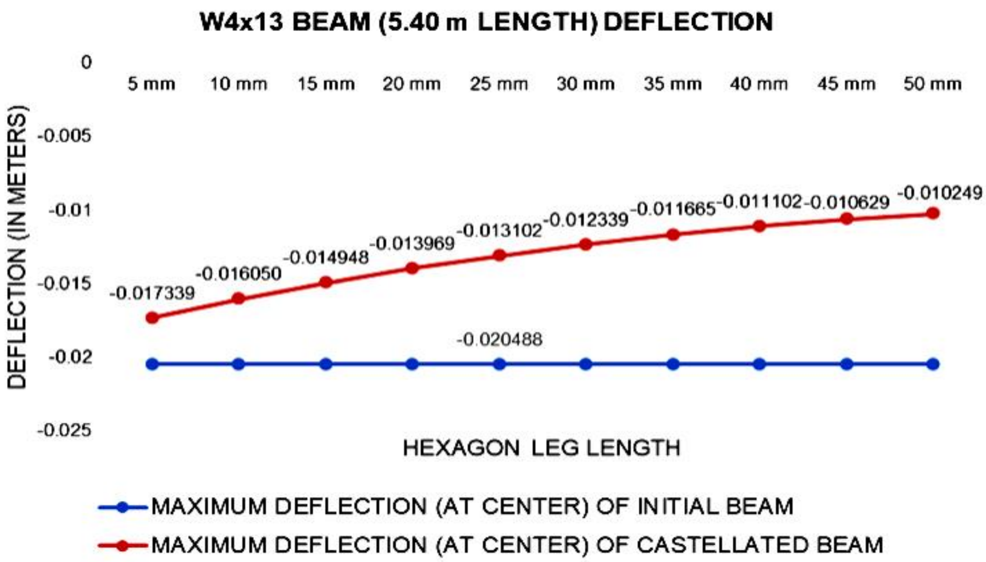

Figure 4. Relationship of deflection and hexagon leg length
(W4x13 beam – 5.40 m length)

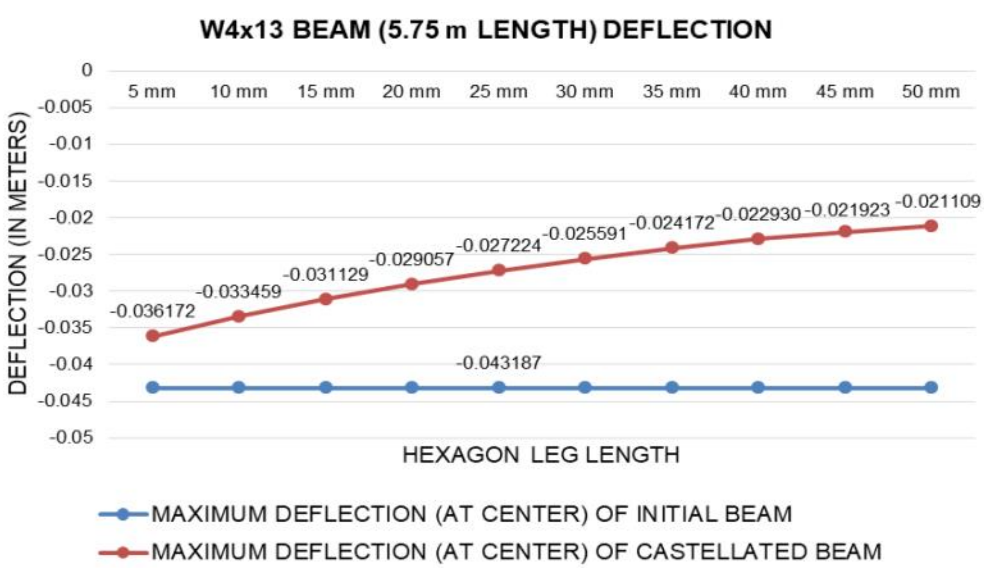

Figure 5. Relationship of deflection and hexagon leg length
(W4x13 beam – 5.75 m length)

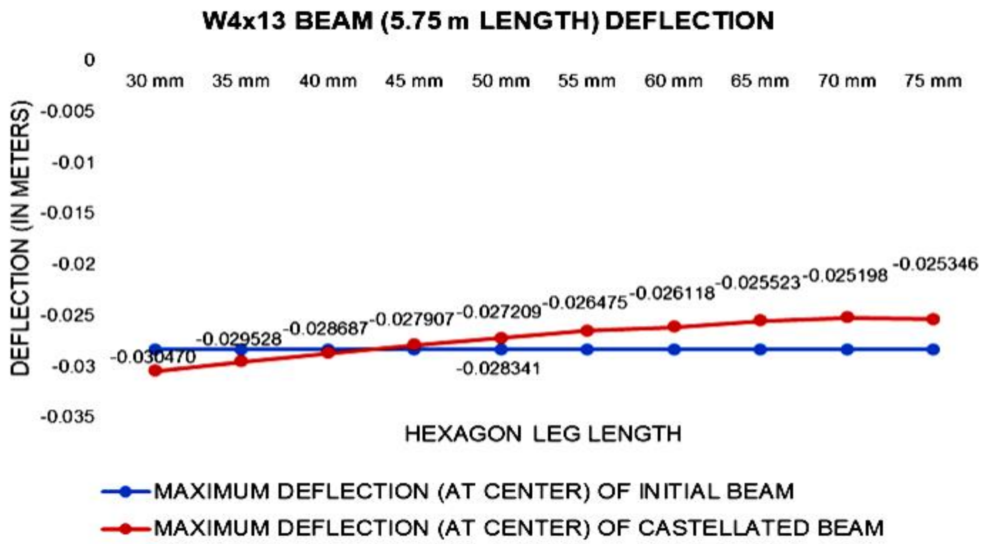

Figure 6. Relationship of deflection and hexagon leg length
(W6x25 beam – 5.40 m length)

in terms of ultimate load capacity showed safeness of the beam from deflecting, since it can carry a higher amount of force. Based on Figures 7, 8, and 9, the length of each side of the hexagon is directly proportional with the ultimate load capacity.

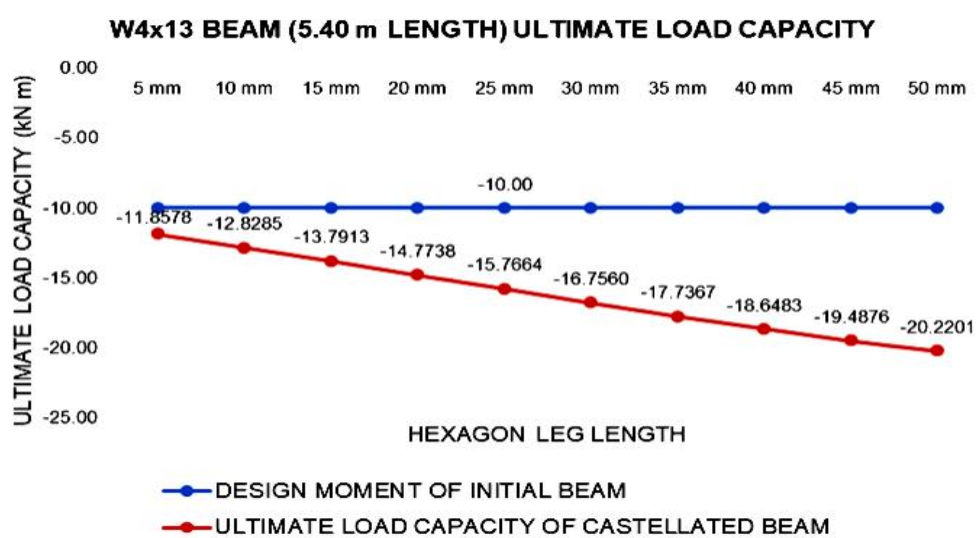

Figure 7. Relationship of ultimate load capacity and hexagon leg length
(W4x13 beam – 5.40 m length)

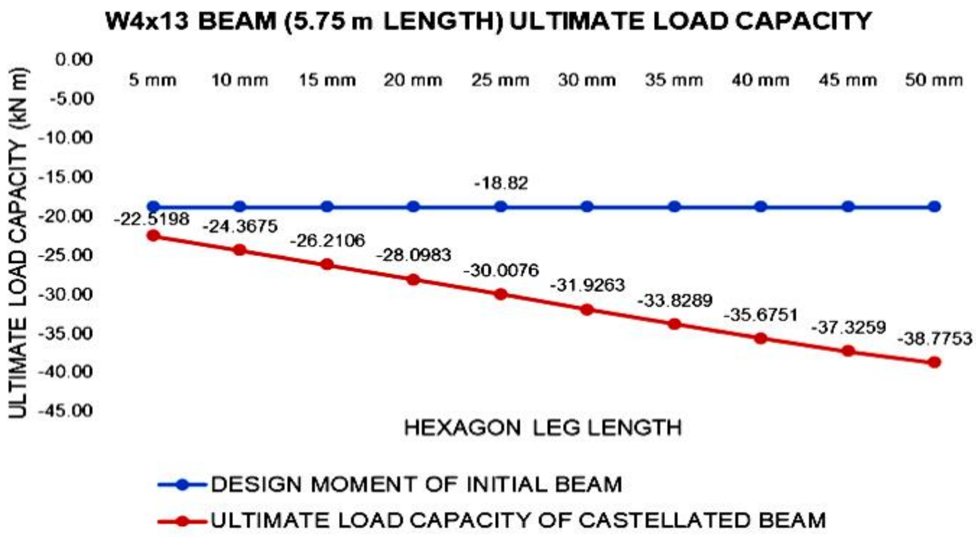

Figure 8. Relationship of ultimate load capacity and hexagon leg length
(W4x13 beam – 5.75 m length)

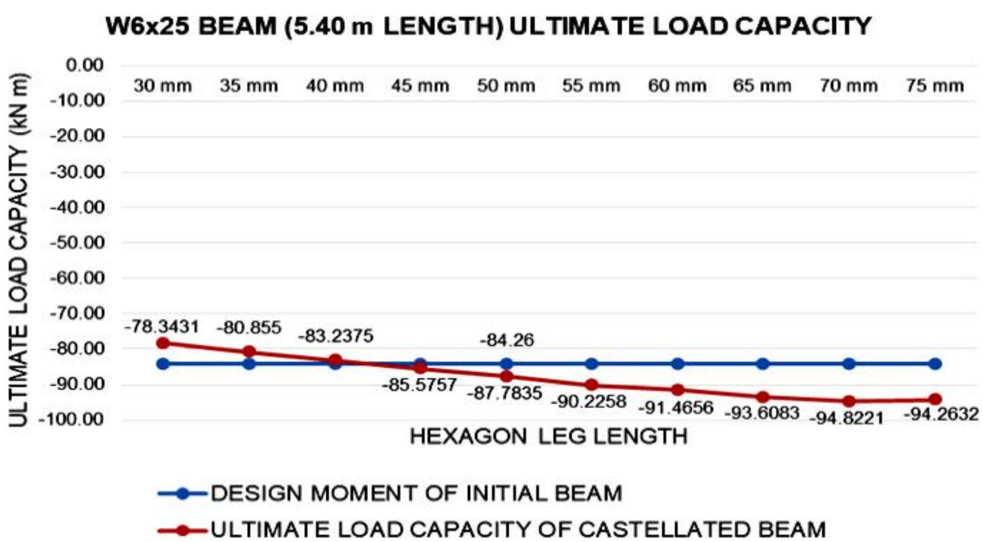

Figure 9. Relationship of ultimate load capacity and hexagon leg length
(W6x25 beam – 5.40 m length)

Data Analysis of von Mises stress at the Center of Castellated Beams According to the Design Moment and Ultimate Load Capacity

From the given design moment and ultimate load capacity, the stress at the center of the beam was determined by the Boundary Point Load condition. As observed in the simulation results in Figures 10, 11, and 12, von Mises stresses of the castellated beams were varying and did not have a constant relationship with the length of each side of the hexagon.

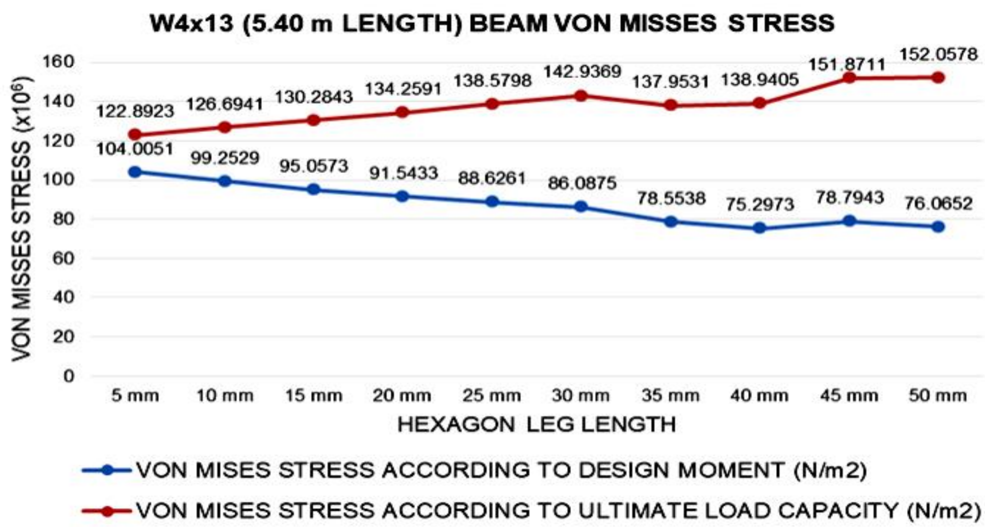

Figure 10. Relationship of von Mises stress and hexagon leg length (W4x13 beam – 5.40 m length)

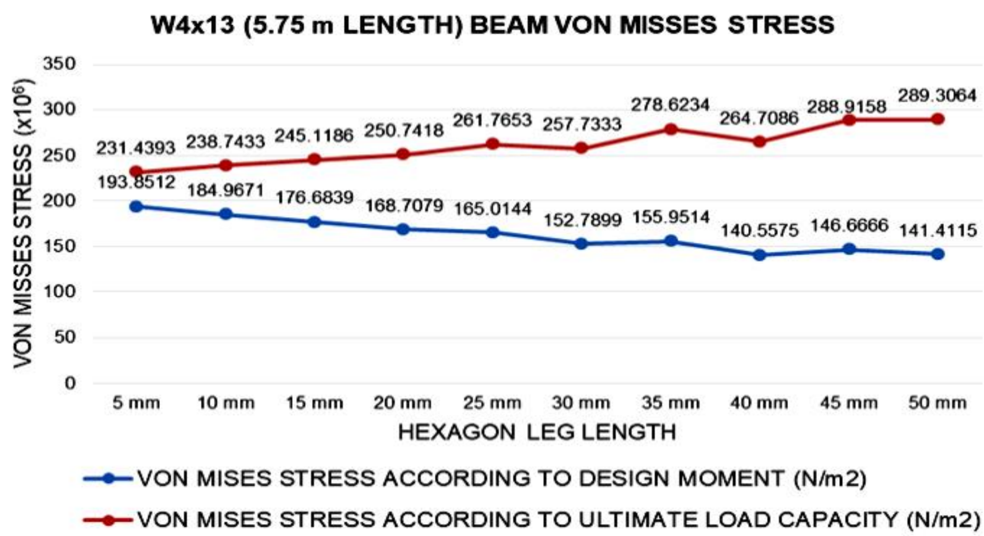

Figure 11. Relationship of von Mises stress and hexagon leg length (W4x13 beam – 5.75 m length)

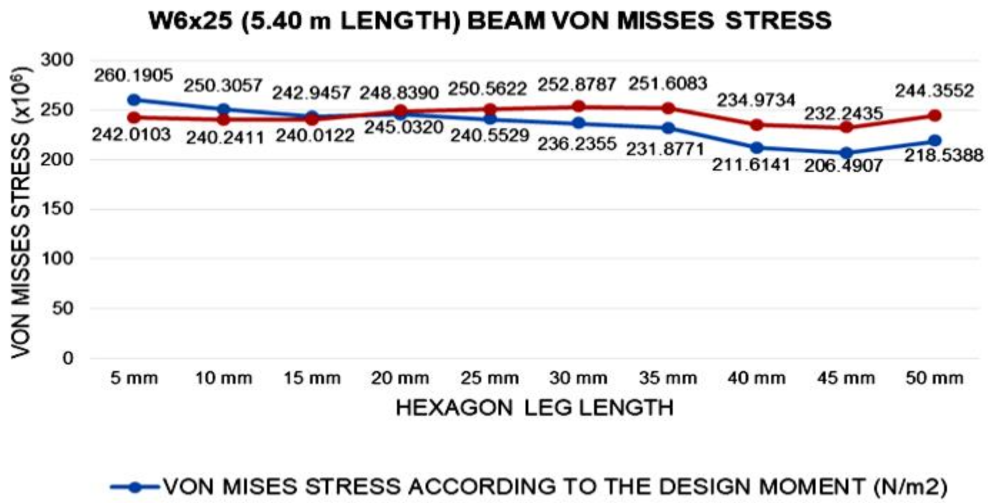

Figure 12. Relationship of von Mises stress and hexagon leg length
(W6x25 beam – 5.40 m length)

Ratio of Load Capacity between the Castellated and Initial Beams

The ratio of load capacity of castellated beams to initial beams had a significant effect on the analysis of its performance. It illustrated the capacity of the beam to continue to perform its function when supporting the bearer of the loads.

In simulated castellated beams, only three of W6x25 beams attained a ratio of less than 1, which denotes weak performance of the beam. Consequently, moment ratio is directly proportional with hexagon leg length of the castellated beam.

Factors Considered in Selecting the Most Efficient Cut of Hexagonal Shaped Castellated Beam

1. Deflection of the beam

From the data analysis of the deflection of castellated beams compared to the initial beam, castellated beams of W4x13 (5.40 m and 5.75 m length) were able to withstand the force per unit area applied without reaching the maximum deflection of the initial beams. The castellated beams provide a much safer performance of the beam.

2. Total height of the castellated beam

The total height of the castellated beam is an important factor in selecting the most efficient cut for the reason that it should maintain the height of the initial beam designed for the Men's Dormitory Building. W5x16 beam has an initial depth of 127.30 mm, while the initial depth of W8x35 beam is 206.20 mm (Tables 3 and 4).

3. Ratio of load capacity

In this factor, all the ratios of the ultimate load capacity to the adopted design moment presented were higher than 1 (refer to Figures 13 -15), except for W6x25 beams (5.40 m length) with 30 mm to 40 mm length of hexagon side. These results indicate that the castellated beams are safe to the design moment applied.

Table 3. Total height of castellated W4x13 beams (5.40 m and 5.75 m span)

HEXAGON LEG LENGTH	TOTAL HEIGHT (mm)
5 mm	115.0301
10 mm	119.3602
15 mm	123.6903
20 mm	128.0205
25 mm	132.3506
30 mm	136.6807
35 mm	141.0108
40 mm	145.3410
45 mm	149.6711
50 mm	154.0012

Table 4. Total height of castellated W6x25 beams (5.40 m span)

HEXAGON LEG LENGTH	TOTAL HEIGHT (mm)
30 mm	193.0807
35 mm	197.4108
40 mm	201.7410
45 mm	206.0711
50 mm	210.4012
55 mm	214.7313
60 mm	219.0615
65 mm	223.3916
70 mm	227.7217
75 mm	232.0519

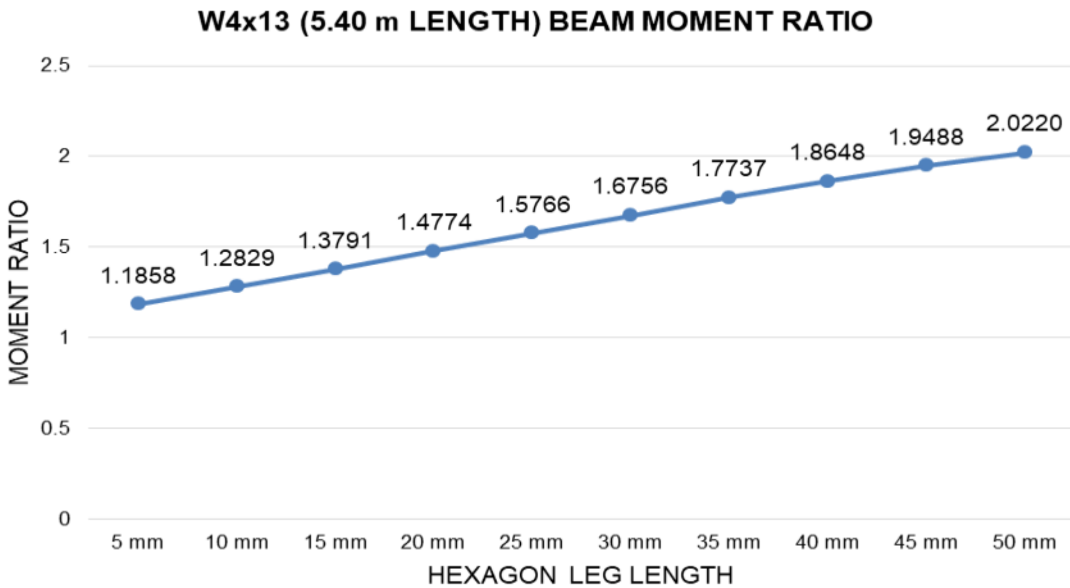

Figure 13. Relationship of moment ratio and hexagon leg length
(W4x13 beam 5.40 m length)

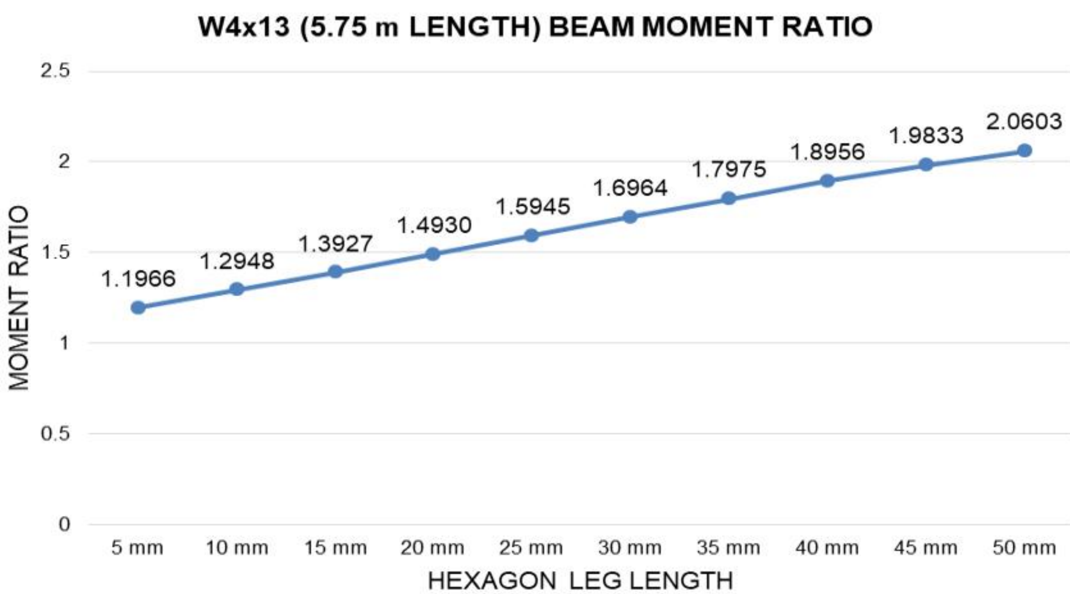

Figure 14. Relationship of moment ratio and hexagon leg length
(W4x13 beam 5.75 m length)

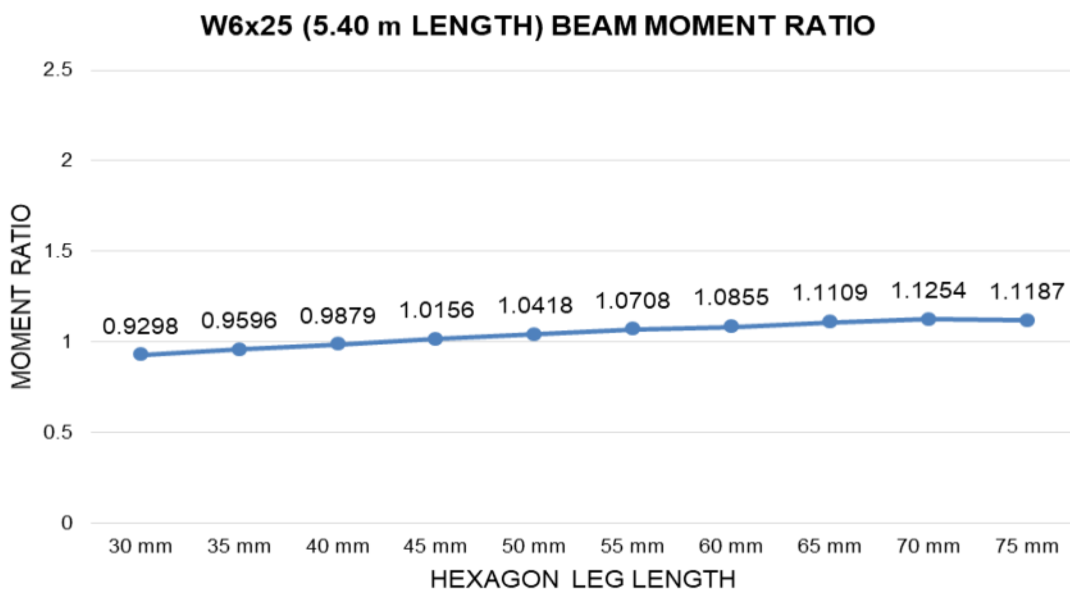

Figure 15. Relationship of moment ratio and hexagon leg length
(W6x25 beam 5.40 m length)

4. Ease of manufacturing

The use of castellated beams with hexagonal openings was common because of its simplicity in fabrication. Manufacturing of castellated beams with smaller depths could become a difficulty in the fabrication process. Therefore, depths of 5 mm, 10 mm, and 15 mm in the castellation of W4x13 beam were avoided alike with 30 mm, 35 mm and 40 mm of W6x25 castellated beam.

5. Wastage and cost of fabrication

Castellated beams with hexagonal openings were recommended in the study of Jamadar & Kumbhar (2015) because of great savings in materials and construction costs. It required smaller amount of steel materials. Overall, castellated beams showed an outstanding performance from the simulations executed. Therefore, using W4x13 castellated beams, the most efficient cut of hexagonal-shaped section ranged from 20 mm to 50 mm length of each hexagon side. Using W6x25 castellated beams, 45 mm to 75 mm length performed the best results in this research.

Wastage for Each Specification of Castellated Beams

There are two kinds of span available in the market. These are the 6- meter and 9- meter span. In this study, the length of the castellated beams was 5.40 m and 5.75 m. In order to have a minimal wastage, 6 m span of steel I-beams were chosen. For castellated beams with 5.40 m and 5.75 m length, wastage would be 0.60 m and 0.25 m length each, respectively.

Difference in Cost of Castellated Beams Compared to Initial Beams

In this study, the weight of steel beams was

Table 5. Quantity of initial and castellated steel beams used in the men's dormitory building

STEEL I-BEAM	QUANTITY (pcs)	WEIGHT PER BEAM (kg/m)	TOTAL WEIGHT (tonne)
W5x16	94	23.70	13.3668
W8x35	54	52.30	16.9452
W4x13	94	19.40	10.9416
W6x25	54	37.20	12.0528

Table 6. Estimated cost of initial steel beams used in the men's dormitory building

STEEL I-BEAM	TOTAL WEIGHT (tonne)	PRICE (₱/tonne)	AMOUNT (₱)
W5x16	13.3668	15,780.00	210,928.10
W8x35	16.9452	15,780.00	267,395.26
		TOTAL COST	478,323.36

Table 7. Estimated cost of castellated steel beams used in the men's dormitory building

STEEL I-BEAM	TOTAL WEIGHT (tonne)	PRICE (₱/ tonne)	AMOUNT (₱)	CASTELLATION AMOUNT (₱)	TOTAL AMOUNT (₱)
W4x13	10.9416	15,780.00	172,658.45	470,000.00	642,658.45
W6x25	12.0528	15,780.00	190,193.18	270,000.00	460,193.18
				TOTAL COST	1,102,851.63

Table 8. Difference in cost of castellated and initial steel beams used in the men's dormitory building

STEEL I-BEAM	TOTAL AMOUNT (₱)
Castellated beam	1,102,851.63
Initial beam	478,323.36
COST DIFFERENCE	₱ 624,528.27

manually estimated. Fabrication process of this study includes cutting of beams in desired specifications and then welded to produce castellated beams. From the field investigation, the Production Industrial Engineer of Dynamic International Precision Technology & Tooling quoted ₱5,000.00 for the castellation process that consists the cutting and welding of each beam.

The percentage of amount saved in using castellated beams as replacement was solved using the equation:

$$\% = \frac{\textit{Initial beam cost} - \textit{Castellated beam cost}}{\textit{Initial beam cost}}$$

Therefore, fabrication of castellated beams showed that it is ₱624,528.27 more expensive than the initial steel beams used in the adopted study.

The cost of the castellated beams was 130.57 percent more than the price of initial I-beams. The reason for this difference was the popularity of castellated beams. These kinds of beam were not commonly practiced in the country. Additionally, the equipment needed in the fabrication were expensive and should be operated by professionals (see Tables 5, 6, 7, and 8).

CONCLUSIONS

From observation, the maximum vertical displacement of the castellated beams was located at the center of the span. Based on the simulation, the length of each hexagon side is inversely proportional with the deflection and directly proportional with the ultimate load capacity of the castellated beam.

Second, since the maximum deflection occurs at the center of span, von Mises stress of each beam at center was tested. Based on the results, von Mises stresses of the castellated beams are varying and do not have a constant relationship with the length of each side of the hexagon.

Third, from the computation of all castellated beams, only three specifications of W6x25 castellated beams had a ratio lower than 1 (30 mm, 35 mm and 40 mm) which indicates weak performance of the beam.

Then, the most efficient cut was determined by the consideration of several factors. In W4x13 castellated beams (5.40 m and 5.75 m length) and W6x25 castellated beams (5.40 m length) are from 20 mm to 50 mm and 45 mm to 75 mm, respectively.

And, wastage in the fabrication of castellated beams was calculated by subtracting the length of the castellated beam span from the available size in the market. Thus, the estimated cost of fabrication of castellated beams showed a difference of ₱624,528.27 more than the initial steel beams used in the adopted study. It is 130.57% of the price of initial I-beams.

RECOMMENDATIONS

Based on the results of the study, the following are highly recommended:

1. performing of an experimental set-up to verify the accuracy of the analytical method;
2. heightening of the quality of mesh;
3. inclusion of other loads resisted by the simulated beam;
4. simulation of castellated beams with different types of opening;
5. addition of shear stiffener along the web opening of the castellated beam;
6. finding cheaper fabrication cost of castellated beams; and
7. determining the limit states or failure

modes associated with castellated beams such as:

a. Compactness and local buckling
b. Overall beam flexural strength
c. Vierendeel bending of tees
d. Web post and lateral-torsion buckling
e. Axial tension/compression
f. Horizontal and vertical shear

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