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INVESTIGATION THE STRESS BEHAVIOR OF CASTELLATED STEEL BEAMS

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IN

CIVIL ENGINEERING

BY

EMRE ŞEN

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M.Sc. Thesis

in

Civil Engineering

Gaziantep University

Supervisor

Assoc. Prof. Dr. Talha EKMEKYAPAR

by

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September 2020

I hereby declare that all information in this document has been obtained and presented the following academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Emre ŞEN

ABSTRACT

INVESTIGATION THE STRESS BEHAVIOR OF CASTELLATED STEEL BEAMS

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The deflection and stress values which occur at load-carrying elements of structures are become critical by increasing number of the structures which have long span and multi-story. In this deflection and stress values were evaluated according to type of web opening, different number of web opening, and the triangle plates which are welded to corner of the web openings. The investigated beams were drawn and analysis as shell element through SAP200 program. As a result of investigation, some points are observed that while maximum stresses occur at corner of web opening of castellated beams, the maximum stresses occur at the flange part of the I or H sectioned beam which are the root beam of castellated beams. In addition, the stresses are concentrated at castellated beams which have web opening according to sudden changing of cross-section of opening, however the stresses are distributed at the castellated beams which have web opening by smoot changing of cross-section. The deflection values of castellated beams are smaller than the I or H cross-section beam when design with same span and load concentration, because of the height of the castellated beam is higher than I or H cross-sectioned beam. Consequently, the design and analysis of castellated beams are necessary for specifying the behavior, deflection values of the castellated beams.

Key Words: Steel Beams, Castellated Beams, Web Opening, Shell Stress Analysis, Circular, Hexagonal, Rectangular Web Opening, Stress, Stress Concentration, Deflection.

ÖZET

BOŞLUKLU ÇELİK KİRİŞLERİN STRESS DAVRANIŞLARININ ARAŞTIRILMASI

ŞEN, Emre
Yüksek Lisans Tezi, İnşaat Mühendisliği
Danışman: Doç. Dr. Talha EKMEKYAPAR
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Geniş açıklıklı ve yüksek katlı yapıların artmasıyla beraber taşıyıcı elemanlarda oluşan dayanım ve sehim değerleri binanın kullanış amacına ve mimarisine göre statik olarak önem arz etmektedir. Bu tez çalışmasında farklı gövde açıklığı türüne, farklı gövde açıklık adetine ve gövde açıklığının köşe noktalarına eklenen farklı boyutlarda üçgen plaklar ile petek kirişlerde oluşan dayanım ve sehim değerleri incelenmişir. Düşünülen kiriş elemanları SAP2000 programında kabuk eleman olarak çizilmiş ve analizi yapılmıştır. çalışmanın sonuçlarına bakıldığında gövde açıklığına sahip petek kirişlerde oluşan maksimum gerilmelerin gövde açıklık köşelerinde oluşurken, petek kirişin yapıldığı I veya H kesitli kirişte maksimum gerilmeler kirişin üst başlığında oluştuğu gözlemlenmiştir. Aynı adet gövde açıklığına sahip petek kirişlerde gövde açıklığı kesitine göre ani açıklık kesit değişlimlerinde gerilmelerin yoğunlaştığı, daha yumşak ve ani olmayan kesit değişimlerinde gerilmelerin yayılı olarak dagıldığı gözlemlenmiştir. Petek kirişlerin yüksekliği yapıldığı I veya H kesitli kirişten daha fazla olduğu için ayni açıklıkta ve ayni yük ile tasarim yapıldığında petek kirişlerdeki sehimler yapıldığı I veya H kesitli kirişten daha az sehim değerine sahiptir. Sonuç olarak, gövde açıklığına sahip petek kirişlerin davranışlarının belirlenmesi için analiz ve sehim değerlerinin uygunluğu için kiriş tasarımı ve analizlerinin gerekli olduğunu göstermektdir.

Anahtar Kelimeler: Çelik Kirişler, Petek Kirişler, Gövde Açıklığı, Kabuk Gerilme Analizi, Dairesel, Dikdörtgen, Altıgen Gövde Açıklığı, Stress Yığılması, Sehim

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LIST OF SYMBOLS

$\mathbf{m^2}$	Meter Square
$\mathbf{m^3}$	Meter Cubic
$\mathbf{mm^2}$	Millimeter Square
$\mathbf{M_{max}}$	Maximum Moment
w	Section Modulus
σ	Stress
$\boldsymbol{l}$	Length

LIST OF ABBREVIATIONS

HVAC	Heating, Ventilation, and Air Conditioning
MPa	Mega Pascal
Kg	Kilogram
m	Meter
mm	Millimeter
2D	Two Dimensional
3D	Three Dimensional
N	Newton
kN	Kilo Newton
SVM	Stress of von Misses
S11	Direct stress in the axes 1

CHAPTER I

INTRODUCTION

1.1 Background

In the aspect of both small and large scales, steel construction is the most common option for the construction of the infrastructures and other types of buildings which has extreme conditions where the reinforced structures are not capable to cover related needs. These advantages of the steel structures are related to various advantages of steel as a construction material.

After several kinds of research to develop the advantages of steel, a new pattern of the steel beam has been figured out which is called a castellated beam. If any beam has holes within its web section, the only option for the related beam is being castellated beam. As mention above, the castellated beam most probably has circular or hexagonal openings which create certain differences between castellated beams and the others depending on its orientation openings its web part. These types of steel beams are producing by cutting into two halves a standard rolled steel section by specific shapes generally hexagonal or circular through the webs part of the cold cost H or I steel beams. The cutting process is generally applied by CNC machines in the construction steel producing factories. To get the form of a castellated beam, these two halves are rolled by cranes to put the top parts of the prepared halves into each other, then to connect these halves welding process starts immediately.

In the matter of castellated beam, the beam section of the beam is higher than the normal main steel section which is generally I section beam, and the ratio of the high is 1.5 because of the putting the cut section top of each other. In the fact that this specification of the castellated beam, structures which have long span needed to pass, and vibration specification is made the castellated beams best for using the related issue to solve. After the production process, the obtained beam will have higher

modulus and moment of inertia, also better slenderness due to higher web height by using the same amount of raw material. Besides this, by increasing slenderness, we are going to have smaller critical stress of yielding.

The main benefit behind of this idea is to decrease the cost of material and usage of raw material and more efficient characteristic properties due to cross-sectional shape than normal rolled sections which are commonly used in the construction sector. Opening in the web part of the beams has been used for very long lime to increase the moment of inertia by gathering areas away from the center of gravity as well as economic benefits. According to load concentration and usage area, the openings on the web part of the castellated beam might be changed as the shape of a hexagonal, circular, diamond, and octagonal which are shown in the figures below.

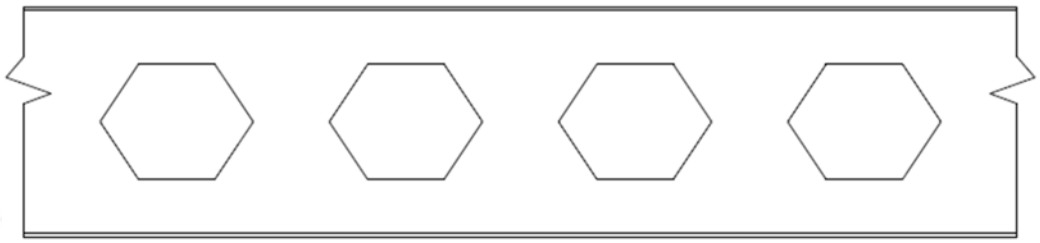


Figure 1.1 Hexagonal castellated beam

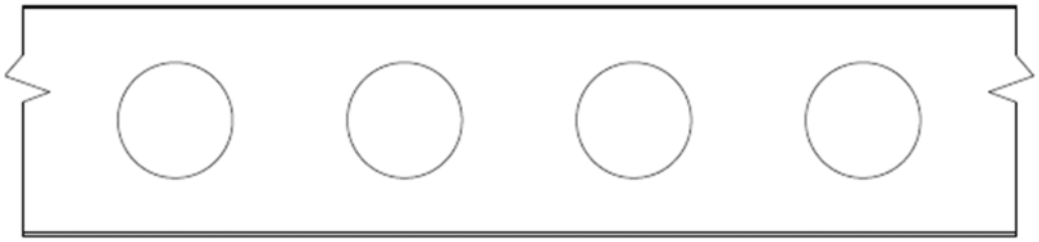


Figure 1.2 Circular castellated beam

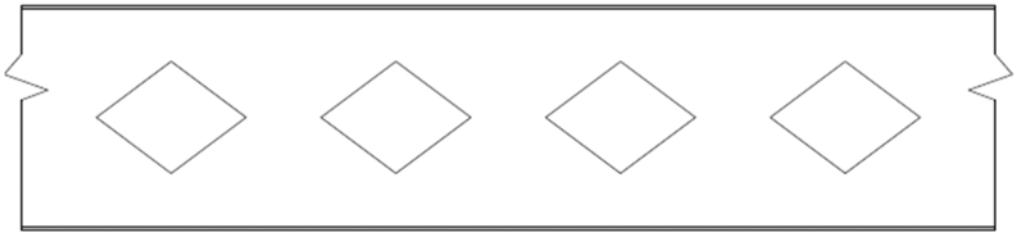


Figure 1.3 Diamond castellated beam

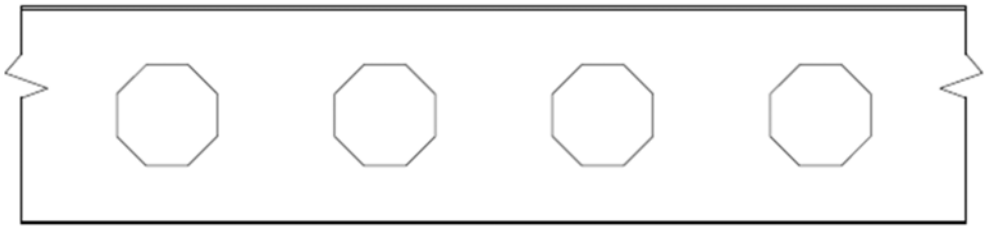


Figure 1.4 Octagonal castellated beam

According to application and practices, the shear forces which are near to connections are critical and needed to be supported to cover shear forces that occur in the related point. To achieve this support, steel discs plates are welded from both sides of the beam, and this procedure is generally used for these two reasons.

- The points which occur the higher shear forces generally under concentrated loads at end of beam.
- At the secondary beam's connections.

Besides these, the extra mass of the beam should not be in=creased while filling process implementation due to be safe side as the economic aspect.

1.2 Development of Castellated Steel Beams

Since the beginning of the 19th century, engineers have been eagled to figure out a beam as a structural element that has lower cost and higher mechanical properties to reach the most efficient cross-section or design in the steel constructions. Once several limitations have been forced the engineers to not make extreme changes in the design because of allowable deflections, the weight and capacity cannot be increased out of limitations to achieve the most efficient design. Consequently, the engineers have been figured out several new methods to improve the mechanical properties of steel beams, but the total weight of steel which is used in the design is not increasing. The most advantages beam is the castellated beam as basic structural elements in the design as well as the application of the steel structures in the whole world.

Once the problems that we faced are generally solved via mathematical equations, the mathematical based algorithms are using the solving optimization problems or optimization process. Even the mathematical based algorithms are commonly used, some optimization problems were not be solved during the last few decades. However,

scientists and engineers have been figured out functional mathematical based algorithms to solve the optimization problems which were impossible or difficult to solve within the last two decades.

The shear force loading in the vertical axes of the related beam at the edge of the frame structure can be viewed on the castellated beam as the T cross-section, due to bending moments and secondary moments that occur on the cross-section as the mechanical property of castellated beam.

1.3 Fabrication of Castellated Steel Beams

Regular patterns openings that are located the web part of the beams are needed to be existed in the beam to call castellated beams. The general pattern for cutting is illustrated in Figure1.7 which is the beginning of the fabrication procedure. Creating this pattern aims to divide the standard section into two halves by cutting from the web part of the standard section using CNC machinery or cutting by hand which is named as a torch. Just after the cutting process is completed, the halves should be welded again from the highest point of both of them to get hexagonal, circular, or any other shape that is desired to be created as in shown Figure 1.8. Besides this, the web height of the castellated beam needs to be increased to supply the moment of inertia according to the requirement of the design, in this case, the additional plate can be welded to the web part of the castellated beam like in Figure 1.9 which is shown below. As indicated before, the cutting process was completed manually before the invention of the special types of machinery for this process by engineers. Before this invention, the castellated beams had a high cost to produce because of this the success of the castellated beam idea could not reach one of the main aims. Right now the producing process which includes both cutting and welding process has been doing by machinery. As a result of this, castellated beams become more desirable and efficient in every corner of the construction area.

Figure 1.5 The cutting process of castellated beams by machinery as automated

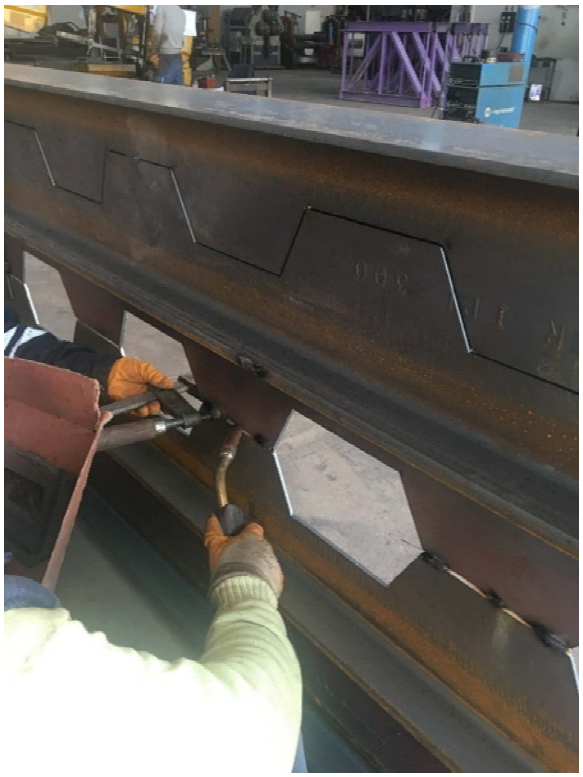


Figure 1.6 The welding process of castellated beams by full penetration butt weld using T beams which divided into two parts.

Machinery and automated cutting/welding process have the opportunity like creating any geometrical shape that has been desired or designed during the planning phase of the production. This is going to give a right to design or create various types of castellated beams with height, opening distance, opening shape, or any other physical properties to fit it according to criteria or needs of design to engineers or designers.

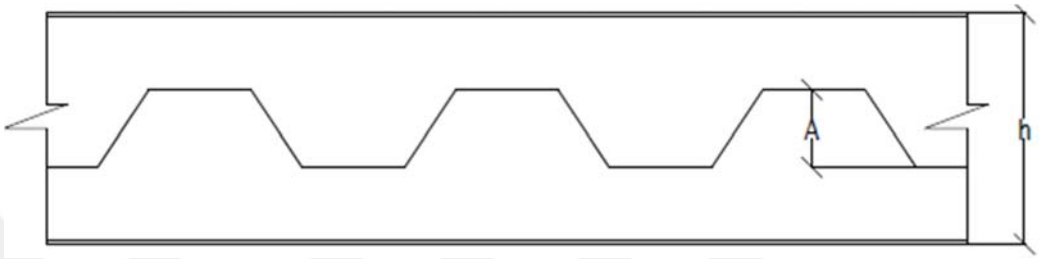


Figure 1.7 The most common and general cutting pattern of the typical T beam to convert it into a castellated beam.

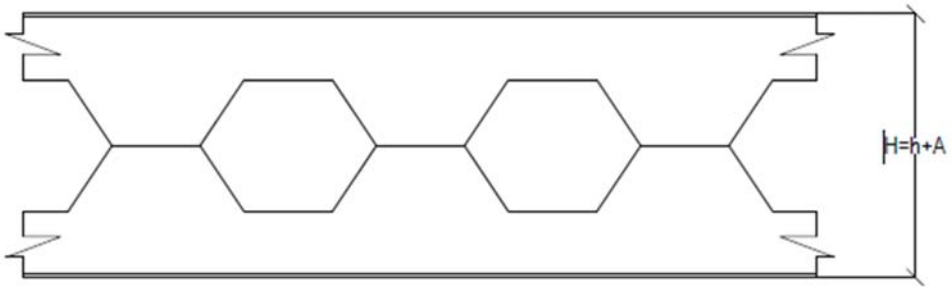


Figure 1.8 The welding process of the castellated beams.

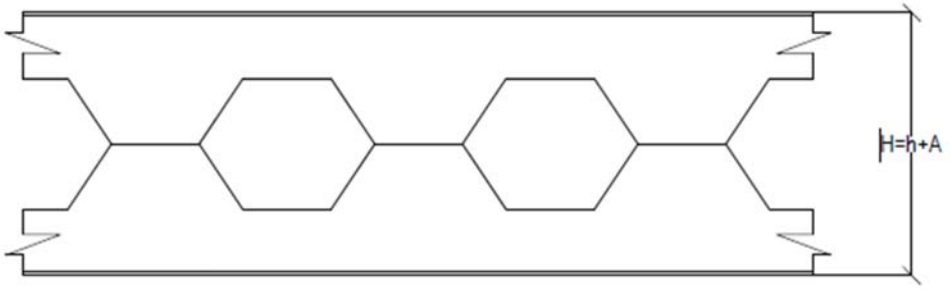


Figure 1.9 Welding an additional plate to increase both heights of the total beam and the moment of inertia to supply requirements of the design.

1.4 Purpose of the Thesis

The construction sector which is one of the effects of the fast-growing world economy is following the same path parallel with the complexity of the structures. Steel as a

construction element has become more vital in the aspect of steel construction with multi-story and long-span through the construction sector which is continuously expanding and developing. Together with increasing the number of structures that have a long span and multi-story and demand for steel construction elements, the steel construction elements become the most common structural element nowadays.

The castellated beams which obtain by the cast I and H beams are using frequently as a load-carrying structural element because of the cost efficiency, low weight, high moment of inertia, and flexibility of the castellated beams. The benefits of the castellated beams provide solutions that easily supply the limitation of capacity and serviceability which are applied by the codes for structural analysis and design.

The purpose of this paper is to obtain efficient economic and statical results by designing the types of the castellated beam which is obtained factors of theoretical, statical, and variable in the aspect of realism. Investigation of the effect on capacity and serviceability of castellated beams as a manner of the height of the web, type, and the number of the hole, types, and distribution of stresses, decreasing these stresses in the related areas especially at the around of the hole on the web, supplying the required security of the points which have high-stress value.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

The number of the researches which are related both theoretical and experimental is quite enough about the problems that occur during the implementation or design phase, improving the mechanical properties of the castellated beams, and develop the shape and strength of openings on the web part of the castellated beam. As mention before, the main aim of this thesis is not deeply investigating past research.

2.2 Literature Review

The naming of the castellated beam was derived from the I sectioned beam. The meaning of the castellated beam is "built like a castle having regular opens in walls like a castle". In the mid-1950s, the castellated beams were commonly used in Europe to decrease the cost of steel structures because of the low ratio of labor cost to material cost (Boyer, 1964).

In 1973, the castellated structural elements were analyzed according to their behavior concerning opening numbers on the by keeping other conditions the same with all samples. Besides this, according to the same shape of the openings, the mechanical properties were investigated by authors through the same paper. As a result, to reach ultimate strength according to opening size the throat distance of openings should be less as possible as to reduce the failure of the beam as specified in the related investigation (Hosain and Speirs, 1973).

Different samples of castellated beams with a section of W10x15 to research the behavior of expansion ratio analyzed with methods of plastic and elastic. To investigate the samples concentrated loads were applied to mid-span of them through the testing machine to get a realistic result by keeping the length of the span is the same for all samples. In the related paper the information was declared by the author

was only the ultimate load capacity of the beams, however detailed or more information was not mentioned in the investigation (Galambos et al., 1975).

The castellated beams have a very large usage area in the construction sector, one of the rare usage areas is investigated by Dabaon et al. (2003) with the subject of curved rolled and castellated steel beams in 2003. Instead of straight castellated steel beams, the curved castellated steel beams have been designed and investigated through the related paper. As a result of the research, torsion increases while the bending moment is decreasing, "The load-carrying capacity of beams curved in the plan increases with a small amount in case of angles of curvature $\theta > 10°$.", and ductility is higher than the standard castellated steel beams (Dabaon et al., 2003).

Through several different approaches to the investigation of the failure of the steel castellated beams, Amayreh, and Saka try to figure out the best approach for failure analysis, and prediction of the failure for steel castellated beams within the methods like Blodgett's approach, BS code approach, Roberts and Markovic approach, etc. in 2005. According to their method investigation, "It has been shown that artificial neural networks can effectively be used to predict the failure loads of castellated beams. It has also been shown that the network designed predicted the outputs with acceptable accuracy, covering the range from shallow to larger depth of castellated beams." (Amayreh and Saka, 2005).

Although there are several methods to decide the model of castellated steel beams, the ratio of depth is missing within all these methods. However, after the research conducted by Dervinis and Kvedaras (2008) rational depth for castellated steel beams is figured out via the related research to prevent obtaining fewer quality beams in 2008. During the investigation, finite element methods had been used to eliminate the difficulties of complex mathematical formulas and a pile of unknowns. The simple section of the castellated steel beam with hexagonal openings is used for the calculations by using the COSMOSM program which is used by the largely for finite element method. The general results of the research are depending on the charts and conditions which can be used easily by following the instructions in the charts. Besides, the research is mentioned that "It can be seen from calculation data that the higher the web, the more efficiently the beam material is used" (Dervinis and Kvedaras, 2008).

The aim of investigating the bending behavior and lateral-torsional buckling of unbraced castellated steel beams was handled by Showkati in 2008. During the investigation, the author has proposed some equations to figure out the bending coefficient of steel castellated beams. As a result of the related research, under uniform loading case, “Elastic bending capacities of I-shaped and CSB under uniform loading on the top flange have a difference of between 4.9% and 8.6%, depending on the section properties.” (Showkati, 2008).

In 2011, there were researched modes of buckling through theoretical and practical ways with castellated steel beams that have hexagonal openings. In case the main idea of the related paper is needed to clarify, the 3D finite element model and nonlinear material properties of nearly a hundred different models of castellated beams were created by the author via the ABAQUS program. With the support of nonlinear finite element modeling, the effect of changes in the geometry of various properties of the castellated steel beams like span length, the cross-section was investigated respect to the behavior of the castellated steel beams. As a result of this paper, the web distortional buckling directly decreases the ultimate strength which creates a certain increase in the load failure due to being parallel with the ultimate strength of castellated steel beams (Ellobody, 2011).

In 2012, according to an analysis of the author species that “It was observed that as the depth of opening increases, stress concentrations increase at the hole corners (Vierendeel effect) and load application point.” (Wakchaure and Sagade, 2012). Besides, as mentioned in the related research, mechanical behavior like the flexural of a castellated steel beam with hexagonal openings was investigated via finite element models. By applying two concentrated loads and under simple boundary conditions the castellated beam was investigated via the ANSYS software program. In the respect of maximum serviceability of the castellated steel beam, the height of the hexagonal opening should be 60% of beam height.

During 2013, authors have investigated a castellated beam by approaching the same method the common castellated beam but rare and different opening shape by using steel beams which called “Angelina castellated beam”. The analysis done by the computer program, which is called ANSYS for numerical modeling, SCIA has been used for shell-based numerical modeling of the beam. According to the analysis result

the statement of “It the beam span is short then there is no buckling of the flange but there occur limit stresses in around the cuts which are near the supports.” was done by the authors to support their design has smaller stress during the castellated steel beam (David, 2013).

Jamadar and Kumbhar (2014) declared that in their research “The castellated beams with circular, square and diamond-shaped openings give better shear transfer area and hence the optimization of castellated beams with such openings needs to be carried out”. Besides this, they figured out that the analysis of the castellated beams can be done by the Abaqus program by getting parallel results with analysis which is done by IS code methods.

In 2015, the specific results were taken by the authors via the ABAQUS program ver. 6.13. which are taken by investigation of hole-combined castellated beams that produced a combination of both diamond and circular holes on the web part of the castellated steel beams. In addition to software outcomes, the practical examinations were also checked by the author to support the outcomes of the software. Both of the outcomes from software and experiments are completely comparable and parallel with each other. This can be derived from the article when the comparison between the castellated steel beam with holes and the castellated beam with diamond holes is investigated, the diamond holes castellated steel beams are weaker as a local failure or more shear transfer area (Jamadar and Kumbhar, 2015).

Hence the depth of the castellated steel beam is high, several mechanical properties of the castellated steel beam dramatically decrease. The research which is done by Patil and Kumbhar tried to avoid these negative effects of the castellated steel beams by using stiffener in the different locations, sizes, and numbers in 2015. Results show that “Analysis and design of castellated beam need to be carried out by using stiffeners in a transverse direction and also along the edge of openings in order to minimize web post-buckling.” (Patil and Kumbhar, 2015).

To investigate the structural analysis of the castellated beam, research was done by Ajim and Harshal in 2015. The main aim of the investigation is the decrease the height of the castellated beam to decrease the erection cost of the castellated beam as well. While decreasing the height of the castellated steel beam, the loading capacity should

be determined as possible as high to reach a desirable capacity for any design. According to the investigation, the angle between the corners of the openings should be 45^{o} to get a smaller height with maximum load-carrying capacity. “For a good design, the depth of stem of the t-section at the minimum beam cross section should not be less than by 4 of the original beam sections.” (Ajim and Harshal, 2015).

An analysis was developed via ABAQUS/ CAE by authors in 2016 to investigate the castellated steel beam with hexagonal openings under monotonic loading. The common type of castellated beam with the hexagonal opening was investigated to figure out the most efficient section properties of the related beam by using three different samples which have opening sizes 6 mm, 9 mm and 12 mm, and the opening angle of 50^{o}, 60^{o}, 70^{o}. According to analysis results, it is shown to get better load capacity with a 6 mm opening and 60^{o} angle for the hexagonal openings (Richard, 2016).

For investigating the effect of opening sizes of hexagonal castellated beams on stiffness and the ultimate strength, which was done by Thabhawee in 2016. Besides, other variations of the physical properties of castellated steel beams were added to enlarge the variety of results like the number of holes. According to research, “ From the test results, it is observed that best dimension of castellated steel beam was (span length to holes space ratio L/S = 8.0); hole depth to Castellated beam depth ratio is h/H=0.56, and hole space to the castellated beam depth ratio is S/H = 1.03. The ultimate strength of the castellated steel beam was increased about (50%) stronger than the original beam.” (Thabhawee, 2016).

In 2017, after the research was done by the author the result obtained as “ Diagonal strut mechanism of the mortar at the web holes can be used to calculate the shear strength of full height rectangular opening castellated steel beam partially encased in reinforced mortar but further study is still required to analytically determine the appropriate size of the hole (Satyarno, 2017).”.

In 2017, authors researched to figure out more clear failure analysis of the castellated steel beams by investigating different types, and the number of web openings by using the ANSYS computer program. Accordingly, the state was clarified as “Openings depth up to 75% of the depth of the section found to be effective.”, and the castellated

steel beams with circular holes are more efficient compared with the other types (Morkhade and Gupta, 2017).

After the research by Budi, Sukamta, and Partono the result has been obtained that "The distance of each hole influences with the location of maximum stress concentration. The maximum stress concentration was at the corner area of hexagonal holes for wider hole distance holes. While the maximum stress concentration moves to the weld joint area in web posts for shorter hole distance (Budi, 2017).

By using the ANSYS program to get flexible results, "Analysis results also indicated that the use of ring steel stiffeners around web opening of castellated beams can effectively contribute to minimizing deflection and maximizing ultimate strength. These stiffeners which were provided to strengthen the edge of web opening can reduce the stress concentration along openings" (Thabhawee and Kannoon, 2018).

2.3 Usage Areas and Advantages of Castellated Steel Beams

The main aim of usage of castellated beams is to provide the statical requirement for long spans by lower section properties. To increasing the floor plan of the area that structure is built the elements which supply vertical loads are needed to decrease as quantity. For this, the beams generally preferred to span longer distances. Besides this, decreasing vertical structural elements utilize the possible features of area planning or future changing plans that can be possible to create by the user of the area. Once the castellated and cellular beams are using to span long distances in the structures parking garages, industrial and warehouse facilities, office buildings, schools, and hospitals are the most possible areas that could be benefitted from the castellated or cellular steel beams.

The castellated beams can be used in different areas as a main or secondary structural element because of the lightweight and satisfying section properties of castellated beams to pass three types of distances like short, medium, or long. Besides, the number of the publication started to increase after the system of quick production of the castellated beam has been getting wide. According to the property of the castellated steel beam which is decreasing the total weight of the structure neatly half, castellated beams can be used for the structure which has a multi-story. When the mechanical property of soil is poor to construct any structure the castellated steel elements have a

huge benefit to supply required section properties. Comparing with this information, the castellated beams have very large usage area of applications, such as:

1. Especially under the high or low floor loads, the castellated beams are using floor girders or vertical load-carrying elements.
2. In the simple and cantilever elements of the roof beams,
3. In the bridge construction which has pipes.

As the castellated beams have various advantages in the structural element, the usage areas of castellated beams are very large. Some of the advantages of the castellated steel beams are given below.

1. Because of the mechanical benefits, the castellated steel beams either increase the strength and economical advantage.
2. As the aspect of aesthetic, it gives a different and unique view to structure due to holes on the web part of the castellated steel beams.
3. Even the castellated steel beams are effective to supply long span and high loads, it is also effective and economical for low loads.

2.3.1 Usage in Parking Lots

In the last two decades, the usage of the castellated steel beams has been sharply increased in the parking lots. Generally, parking lots have long spans to pass, because of the nature of parking lots, the structure needs high serviceability and an effective floor plan to make easy the movement of vehicles. The spans of the parking lots which are generally more than 18 meters are strongly longer than the other structures. While using the castellated steel beams the net weight of the section that is going to be used for passing long span will decrease nearly 33% of the I or H steel beams which are available in the sector. These situations dramatically decrease the material cost of the whole construction, and the overall weight of the structure as well. Because of this, the design load which is depending on the overall mass of the structure will change. For parking garages with low inter-story heights, the brighter interior gives the appearance of being more spacious than similar structures with solid-web beams (Churches et al., 2004). The examples of the usage of castellated beams are shown in Figure 2.1 and Figure 2.2 in the parking lots.

Figure 2.1 The exterior of the parking garage utilizing cellular beams (Fares, Coulson and Dinehart, 2016).

Figure 2.2 Parking structure during the day (Fares, Coulson and Dinehart, 2016).

2.3.2 Usage in Industrial Structures

The industrial structures generally have high story height because of the heavy machinery which is using in the structures. Some port of this type of structure needs to be built mezzanines for getting the extra area to use for office works or as storage. Because of the mechanical characteristic which helps to pass long spans while being safe side, castellated or cellular steel beams are widely using the mezzanine structures in the industrial facilities. The long-span capabilities of castellated and cellular beams perform very well for this application. Besides, once the vibration characteristics of castellated steel beams are quite satisfied for the mezzanine constructions as shown in Figure 2.3.

Figure 2.3 Industrial facility with mezzanine (Fares, Coulson and Dinehart, 2016).

2.3.3 Benefits of Holes

Mechanical implementation of any construction like piping, HVAC, or any cabling trays is the most problematic situation during the construction process especially in the infrastructures because of the huge requirement of both mechanical and electrical projects. As a solution for these problems, holes are needed to be opened at the required point of the beams, however, this process is really dangerous because of the possibility to damage or decrease the strength of the related beam. Generally, the parking lots which have low story height, mall, or any other infrastructure that needs a huge amount of utilization materials, suffer from this problematic situation. Once the nature of the castellated or cellular steel beam has numerous holes on the web part of the beam with enough size to fit utilization material through inside of the holes. As shown in Figure 2.4 the cellular or castellated steel beams gives a big opportunity to implement utilization through the inside of the hole in its web part. The hospital structures have a significant amount of piping because of the medical gases that need to be delivered to different parts of the structure. Usage of the castellated steel beams is dramatically beneficial for infrastructure either statical or mechanical aspects.

Figure 2.4 Openings are utilized for conduit and HVAC routing (Fares, Coulson and Dinehart, 2016).

2.3.4 Efficiency of Castellated Beams on Structure

The castellated and cellular beams have significantly high efficiency which directly or indirectly affects the mechanical characteristics of construction materials. In the structure which has a long-span, the number of the vertical load-carrying elements are demanded to be reduced as possible as, because of the increasing the floor plan in the structure. Besides, the smaller number of the vertical load-carrying structure elements always decrease the implementation and fabrication duration, erection cost. One of the most critical parts of the construction is the schedule of the implementation because some of the delays might occur even the schedule of the implementation is set up while thinking every possibility. Consequently, the castellated beams in the structure decrease the duration of the construction schedule regarding the other types of structural elements.

2.3.5 Resistance of Castellated Beam to Vibration

Castellated and cellular beams have higher web height regarding standard steel beam sections like I, or H beams. This property of the castellated and cellular steel beams increases the stiffness of the structural system. As a result of this increase, the castellated or cellular beams directly affect the vibration resistance which may affect the selection of the type of beam as a structural element in the construction.

2.3.6 Asymmetry of Castellated Beams

As specified before during the production process, the castellated beams are fabricated by dividing the root beam into two equal parts. The parts that are divided into two parts are welded after to create asymmetric holes. The asymmetric characteristic of castellated beams is advantageous for a composite that is using in concrete slab structures. In the composite design, it is cost-effective because of the asymmetric of the castellated or cellular beams.

2.3.7 Aesthetics

The castellated beams or cellular beams supply a big opportunity to a designer by giving various options to make their design efficiently as the aspect of architecturally. As known widely, the concrete beams con not be shaped easily due to their physical properties. However, the castellated beams are produced by steel, the castellated steel beams can be shaped, when these beams are subjected to heat. Even the shape requested to be given as curved, the shaping procedure will be easy because of the mechanical properties of steel. Because of the holes on the web part and giving shape easily, this makes castellated beams significantly effective and preferable as aesthetical structural elements during architectural design and implementation.

2.4 Other Considerations

2.4.1 Concentrated Loads

Although cellular and castellated beams are typically used for uniform load applications, they may also be used to support concentrated loads or in a combined case with uniform and concentrated loads (Fares, Coulson and Dinehart, 2016).

2.4.2 Effect of Depth on Castellated Beams

As the main property of the castellated beams are being holes on the web part, the dimensions of the hole are exactly depending on the web part of the main root beam. To supply the requirement of both statical and architectural design, usage of the castellated beams gives flexibility to the designers by any depth of castellated beam but a maximum depth as 165 cm. For instance, the web height should be 100 cm

according to requirements in the structural project, this requirement can be especially specified in the design.

2.4.3 Erection Efficiency

Because of the lightweight, the castellated beams are cost-effective during the implementation process, lifting, and transportation, and decrease the total erection weight of the structure. For the bracing, the most appropriate beams are the castellated beams because of the lower self-weight and nearly the same load-carrying capacity.

2.5 Disadvantages of Castellated Steel Beams

As specified during this thesis, in the presence of the hole on the web part of the beam due to the presence of the holes in the web, the mechanical specifications of the castellated and cellular beams are different from the plain beams which have plain web part in its structure. Change in the web part of the plain beam creates new modes of failure as it can be easily seen in the analysis.

Instead of structures with a long span, when the structure with a short span is needed to be designed the castellated shear beams are not appropriate because of the low shear capacity of the castellated and cellular steel beams.

CHAPTER 3

METHODOLOGY

3.1 General

The main aims in all structures in the construction sector are maintaining the structure without getting any damage under the loads which are effecting the structure by carrying the loads to the foundation by the easiest, safest, and secure way. The loads which are effecting the structure like death loads, live loads, wind loads, snow loads, and earthquake loads are changing according to the location and using the purpose of the related structure. Both design and analysis of the load-carrying elements are specifying according to these loads. The load effect to the slabs and roofing of the structure is firstly getting by the beams, then the load is transferred to the columns, consequently to the foundation, so the load-carrying system completes its responsibility on the structure. The importance of the load-carrying elements is vital for the carrying load to the ground.

Nowadays, the beams are the most important element in the long span structures due to the architectural design of the structure. Depending on this, beams should be designed appropriately according to capacity, serviceability, and cost-efficiency. Because of the long span and high loads, the sizes of beams are increasing. In this situation, the most appropriate design of the beams should be done while considering capacity, serviceability, and cost-efficiency.

Generally, steel structure elements are preferable to pass long spans, because of the fabrication, low weight, and feasibility of steel beams. The most common beam types for passing long spans are truss steel beams, castellated steel beams, and vaulted beams.

In this thesis, the mechanical behaviors of the castellated steel beams are investigated. The castellated steel beams which have different openings with sizes and types are

investigated regarding with capacity and serviceability while determining the stresses and deflections which occur on the beams.

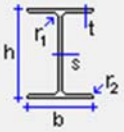
Hence the purpose of this thesis is the analyzing the mechanical properties of the steel construction element in a various way, one of the unique programs for civil engineers which are SAP2000 was used during this thesis to get more realistic outcomes and evaluate the outcome into details. SAP2000 gives more detailed results especially in the critical points of the investigated area. The general steps or layout of the analysis or project can be gathered under the main topics like modeling, analyzing, designing, and reporting of the project. By using SAP2000, the structural elements which have a complex geometrical shape are analyzing with the method of finite elements by dividing the element into a finite number of small areas as particularly for each area. Then, the results of each area are gathered to obtain the correct stress analysis for whole elements which is impossible to analyze at once. These functions of SAP2000 clearly show that it is an appropriate program for modeling of both complex and simple structures.

3.2 Description of Study Case

In this thesis, the analysis results which are belonging to castellated steel beams are obtained by finite elements method. Because of the using the finite element method, the head and web parts of the beam are designed separately as shells. To obtain realistic results, the designed elements have realistic specifications as physically and mechanically. For example, the wall thickness of the I section beam is assigned to the program as the real wall thickness of the related I sectioned beam. The values and quality of the real I beam was used to input the mechanical specification of the related cross-section into the analyzing program. In this way, obtaining more realistic results and investigating the stresses at the around of the holes which are located on the castellated beams was aimed.

Hexagonal, rectangular, and circular holes are going to analyze during this study, by analyzing the castellated beams with web openings of twelve, six, and three for each opening type. The comparison of mechanical results between castellated steel beams which are design with the IPE500 I beam, the root beam of related castellated steel beams which is an undeformed form of IPE500 I beam and the I beam designed as

built-up section by steel plates which have the same physical properties with IPE500 I beam is done separately. The physical properties of the IPE500 I beam are 16 mm flange thickness, and 10,2 mm web thickness. The built-up section was designed according to the properties were given as 16 mm flange thickness and 10 mm web thickness. However, in the markets, the plates which have a web thickness of 10,2 mm are not available except special orders, so the design of the built-up beam was done according to available materials in the markets to be parallel with reality. Thus, the obtained beams are investigated deeply, and the results are going to compare with reality regarding with variable parameter between them.



Property	Sy...	Value	Unit
Height	h	500.00	mm
Width	b	200.00	mm
Web thickness	s	10.20	mm
Flange thickness	t	16.00	mm

Figure 3.1 The physical properties of root beam.

Detailed of span length, cross-section, and thickness of flanges designed IPE500 beam and the castellated beam which is designed by IPE500 are given the figures below.

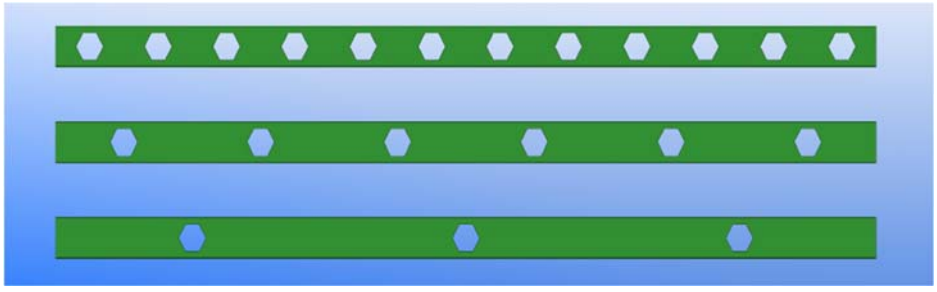


Figure 3.2 Three types of a hexagonal castellated beam with a different number of holes.

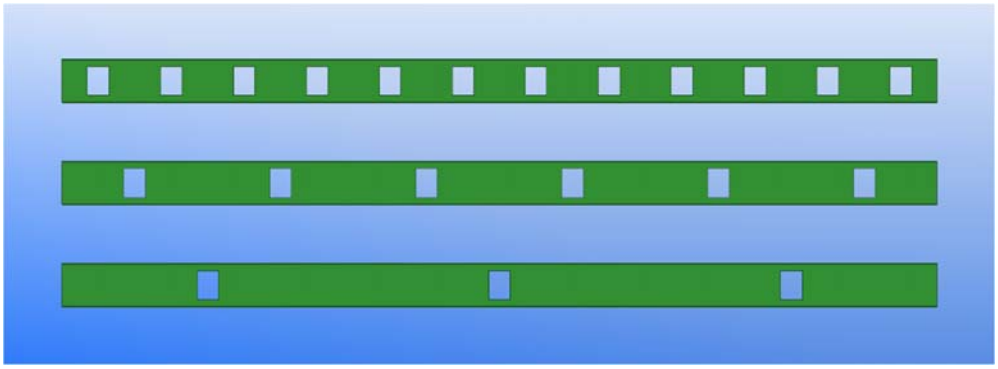


Figure 3.3 Three types of a rectangular castellated beam with a different number of holes.

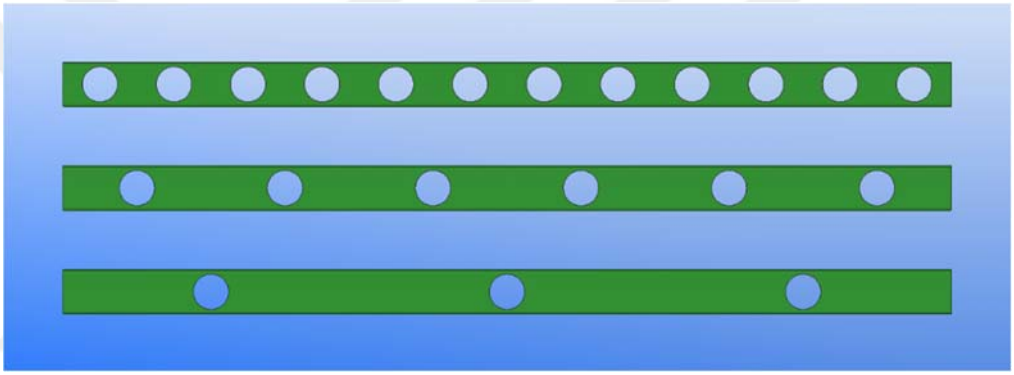


Figure 3.4 Three types of a circular castellated beam with a different number of holes.

The most important part of designed beams is being the same area of each hole. The area of the hexagonal hole is considering the main area for the other holes to get an equal area for each hole even the different holes. Besides, the total weight of each beam is going to be the same for every case. In this way, the beams which have the same length, weight, and hole area just to focus on the effects of holes on the webs. The details of the castellated beams are shown in Figure 3.5 according to the type of opening.

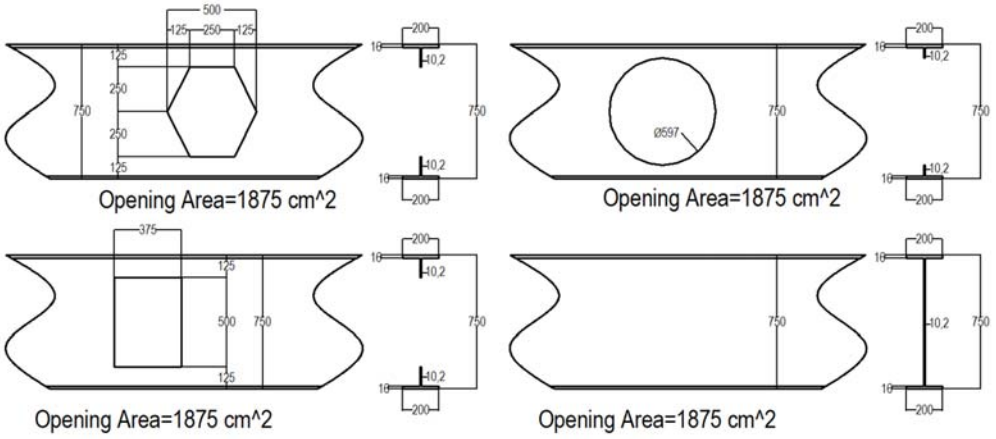


Figure 3.5 The same area for each hole.

The local axes are designated as shown in Figure 3.6 to be named of internal forces of each part which are obtained from divided elements according to the finite element method. The axes which are important for the direction of affected forces are shown in the figure.

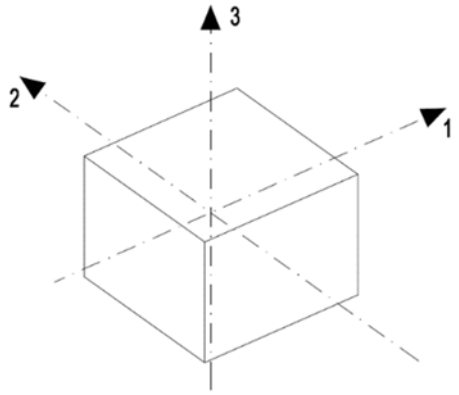


Figure 3.6 Typical axes for any structural element

3.3 Analysis by the Computer Program

As mentioned before, the modeling, analyzing, and reporting of modeled beam are going to be conducted by the SAP2000 software program. During this chapter, the evaluating process of the designed castellated beam is going to be explained. This process is important for analyzing and controlling of the castellated beam should be realistic. Because of that, this process should be done with realistic specifications as

possible. The name of SAP2000 derived from the first letter of the word “Structural Analysis Program”.

The general operation of the SAP2000 can be gathered under four main topics.

- Modeling
- Analyzing
- Designing
- Reporting

Under favor of the finite element method, complex geometrical shapes dividing into the finite number of elements, and each element can be analyzed separately. While results are combining, analysis can be done for the stress of the whole element which is possible together as one element. SAP2000 is an appropriate program for the design and analysis of any structure whether it can be complex or simple.

The same methods are respectively using the solution for any structural element or system in SAP2000. Firstly, the parameters which indicate the height and width are specified by the method of axes (grids) command to the program. The physical properties of the element in the system are mounted to the SAP2000. During this process, the program may suggest to the user the default parameters or properties. The program generally suggests to the user default properties of aluminum, steel, concrete, cold-formed, rebar, tendon, however, we can obtain any material that we want to use by entering the real property of the related material. The specified material type occurs during the entering data of section property. For instance, the program doesn't suggest to the user the material property of the timber. However, we can define and obtain the material while entering the property of timber like weight per unit volume, modulus of elasticity, Poisson ratio, coefficient of thermal expansion, minimum yield stress, minimum tensile stress.

After the finalizing of mounting the material, the constitutive elements of the system should be mounted to the system which are constitutive elements of the system like columns, beams, diagonals, etc. Lastly, the model of the system completes by mounting the strip elements, walls, slabs, shearwalls through the method of finite elements, and different types of supports according to the demand of the design. To the connection point of structural elements that can be the same or different type, the

default supports assigned by the program may be accepted or special support types may be mounted to the related points.

In general, the small portion of the system is created at the beginning of the design, then the properties of the program which are “copy-paste”, “replicate”, “mesh areas”, “quick draw” might be used to complete the drawing of the whole system. Before assigning the loads to the system, each load is specified in advance like concentrated load, distributed load, triangle or trapezoidal loads, the difference of temperature. Then, these loads are mounted to the program to assign them nodal points, strip elements, or finite elements. The death loads, live loads, earthquake loads, coating load, wind loads, snow loads can be defined as load combinations depending on the designer, and related codes to assigned them to the system.

The system will be appropriate for the analysis and design after the materials, section, and loads properties are assigned. In the system which is analyzed and designed a report can be obtained through the SAP2000 program.

The elements of the load-carrying system which are modeled at the SAP2000 program can be analyzed by different approaches through the program. Types of the analysis which can be done through SAP2000.

- Analysis of the system composes of strip elements and shell elements with respect to the finite element method.
- Analysis of the system designed as 3D and composes of a solid structural element, or elements.
- Linear or nonlinear analysis
- Bridge analysis
- P-delta analysis

In this thesis, the steel shell elements which have a different type of body span under certain loads are analyzed, stresses and deflections are investigated in the constitutive part of beams according to finite elements. The conducted analysis is designed at the SAP2000 program.

3.3.1 Modeling

In this part which mentions before designed beam as 2D, details of the modeling of each beam corresponding to related study case, and how to model them according to updated construction codes will be explained.

First of all, the mechanical and characteristic specification of I beam IPE500 should be clarified because of being the main element of modeled beams. One of the mechanical specifications of the IPE500 beam is the qualification of S355. As the first step of modeling is the specifying material property from the material property section of the program as material grade; 355 MPa, weight of per unit volume; 7850 Kg/m^3, modulus of elasticity; 210000 Kg/mm^2, Poisson ratio; 0,3 in Figure 3.7 below.

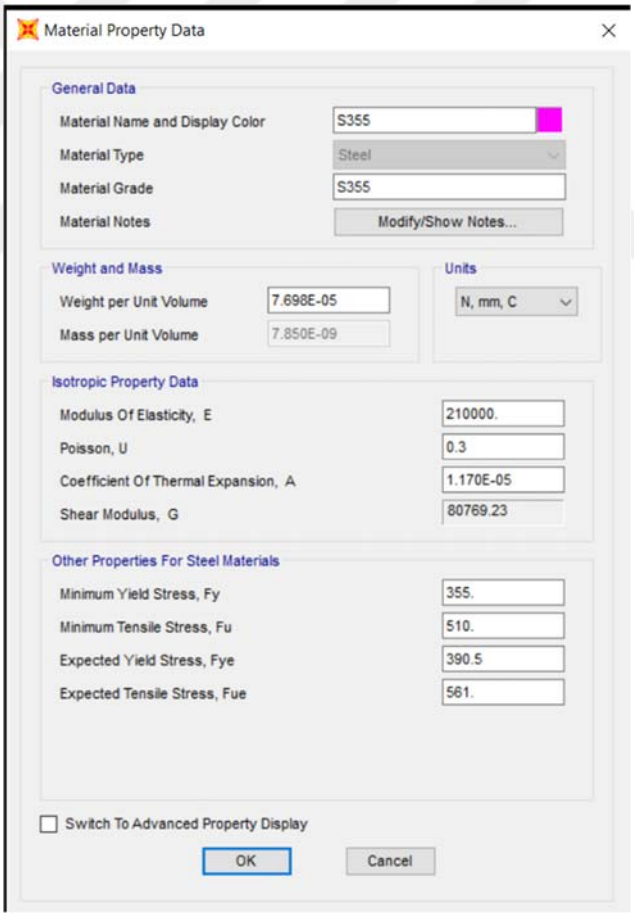


Figure 3.7 Mechanical property is entered into the software.

After the specification of the beam was set up, the flanges and web part of the beam should be considered as plate, and information of these plates should be defined as a plate from section properties of software. Besides, the flanges and web parts of the

beam should be defined as shell areas, also the type of shell select as shell-thin with the value of membrane and bending 16 mm, for web 10,2 mm. In this part, the mechanical property of the material is defined as S355 just before this process.

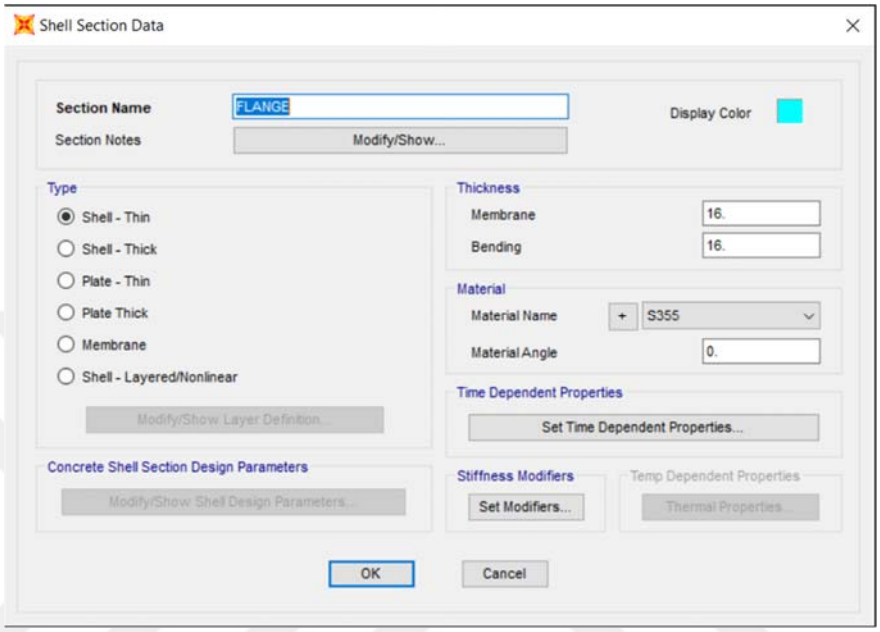


Figure 3.8 The shell properties of the flange part of the castellated beam.

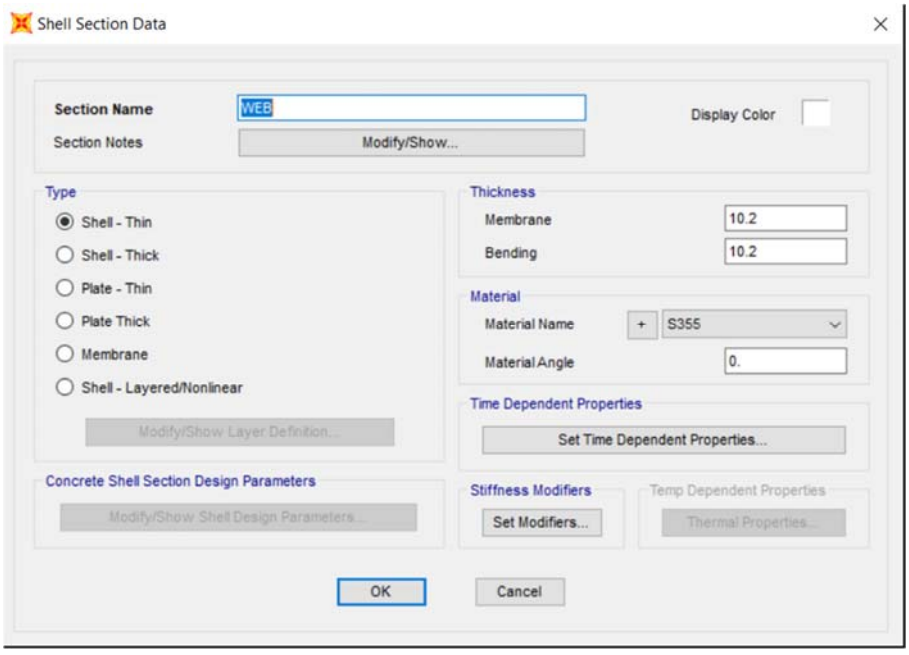


Figure 3.9 The shell properties of the web part of the castellated beam.

After defining the flanges and web parts as shell area elements, the 3D modeling process can be started. During this process, assigning the axes which cross from

specified web holes, span, and height are very important. By using the defined command of SAP2000, the direction of the beam is defined as the direction of width as x x-axes, span direction y axes, and height direction z axes.

The physical properties of the beam are defined to the program as the span of 15000 mm, height 750 mm, and the width 200 mm. Besides, the additional axes are defined for corners of holes through x-direction for span, z-direction for height, just before the modeling of structure. After the defining axes, the flange part of the beams was drawn by using draw rectangular area specification of the program at z = 750 mm on x-y, and at z = 750 planes. For the web part of the beam, plates should be placed to the axes according to the geometrical shape of the castellated beam on the x-z plane at y = 100 mm.

When the drawing of flanges and web parts of the beam is defined to program as a plane, the most important part of modeling which is dividing plates into areas should be started. As the first process of diving starts from flange elements, the flange elements should be divided to equal areas though x and y axes by using a command of divide area into objects of this maximum size (quads and triangles only), the edge from 1 to 2 (25 mm), and along the edge from 1 to 3 (25 mm) as shown Figure 3.10 below. Then the process of modeling and diving into areas of web part should be conducted. During the modeling of the web part of the beam, the most important point is placing the holes according to number and size on the cross-section of the castellated beam. When axes are placing, the additional vertical and horizontal axes are placed to every corner of the intersection point passing, by using these axes requested plates of web holes are placed to the web of the castellated beam. To divide these areas into equal parts, two types of divide property of program which are the property of divide area using general divide tool based on selected point and frames with a maximum size of divided objects, and the property of making same on age if adjacent corners have same local axes definition under local axes for added points are used as shown in Figure 3.11 below.

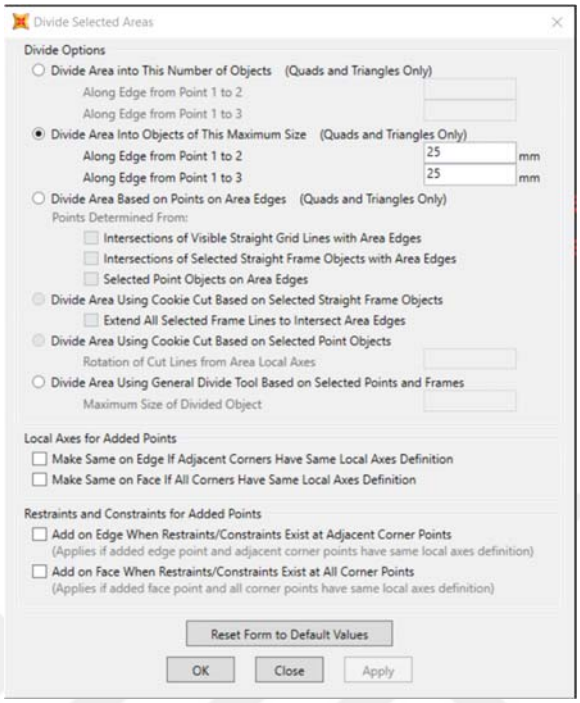


Figure 3.10 The data should be entered to divide into small areas for the flange.

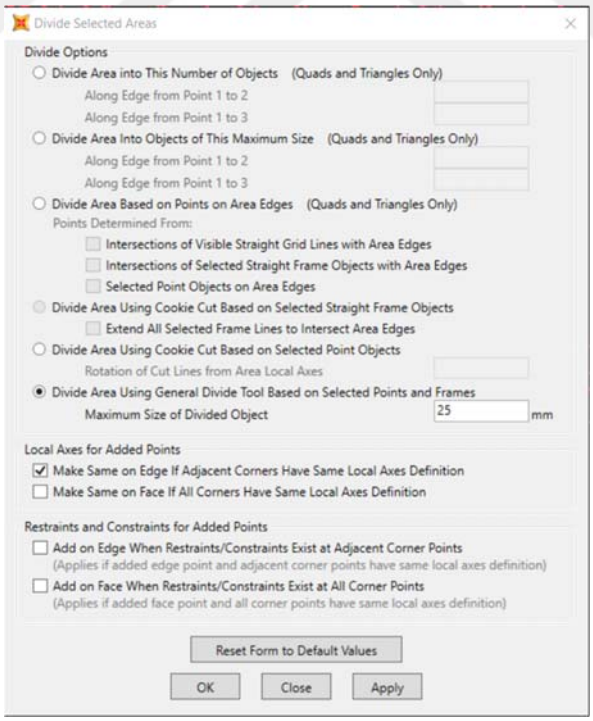


Figure 3.11 The data should be entered to divide into small areas for the web.

The corner point of some areas might be connected in the intersection point of two different plates especially case when the elements are divided into equal and similar areas. Because of this, the load transfer between structural elements might be wrong.

To prevent this problem, the corner points which are not connected by each other should be connected by using a command of merge joints which is one of the properties of the command divide areas. In this way, the wrong load transfers between points can be eliminated. The other issue is the divided areas can be smaller than the requested area. As a solution to this issue, the same method of the previous example should be used in smaller areas. After the plates dividing into small areas as mentioned above, 3D models and 2D view of the castellated beam is shown below.

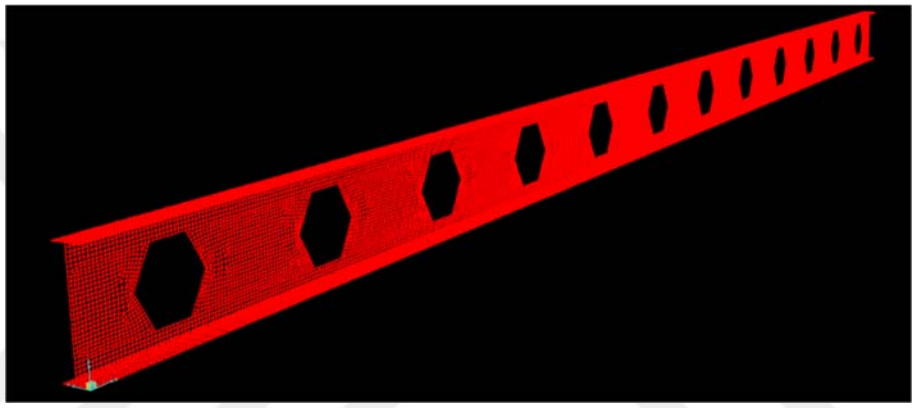


Figure 3.12 3D model view of the hexagonal castellated beam.

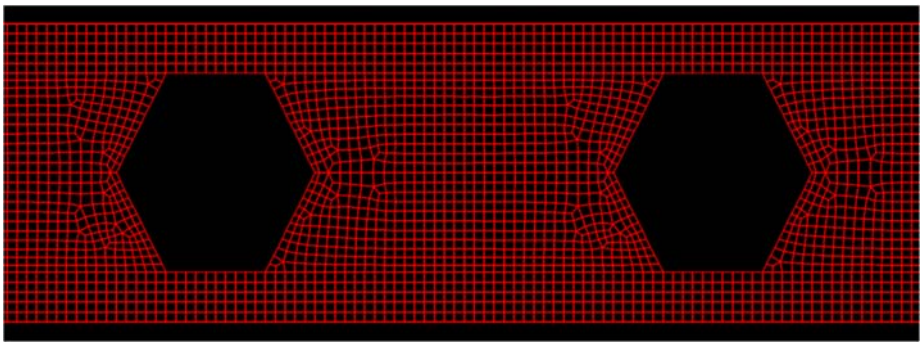


Figure 3.13 2D model view of the hexagonal castellated beam.

The modeling process of the castellated beam which has hexagonal holes was explained clearly. By flowing the same procedure, the castellated hexagonal beams which have twelve, six, and three holes are modeled. The same procedures are applied to obtain the castellated beam with rectangular with the number of holes as twelve, six, and three.

Once the circular small areas cannot be obtained due to the properties of SAP2000, the circular castellated beam is modeled as polygon with sixteen sides. As a result, this shape is going to be assumed as circular. The modeling procedure of the circular castellated beam is the same with the hexagonal castellated beam which is shown in Figure 3.14 below.

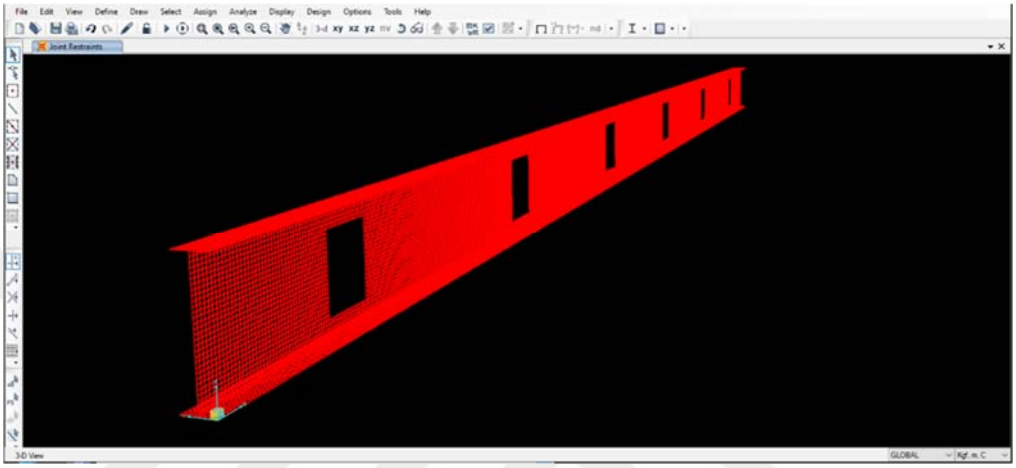


Figure 3.14 3D model view of the rectangular castellated beam.

For the purpose of controlling the stress values on the corners of the castellated steel beams which have different types and number of holes, the triangle plates that have the same wall thickness with beam are welded to the corners of the holes. The additional plates create a sudden o smooth section changes at the corners of the holes on the beams, and the mechanical behavior changes are aimed to be observed especially at these points.

To add these plates, a new axes system that passes through the corner of plates is created at the corner point of the hole on the beam, appropriate geometrical shapes are obtained commensally these axes. The wall thickness of the additional plates which are added to the corner points of the holes of castellated steel beams are same as the web H beam, and this property of the additional plates is mounted to the program efficiently.

The additional plates in the castellated steel beams which have hexagonal openings make the corner smoother until a certain size, however, while the size of plates increases a sudden area changes occurs in the corner points of the holes. So, according

to the additional plates, the additional plates might cause a sudden or smooth change in the area at the corners of the openings.

The sudden change in area is decreased because of the additional plates which are added to the castellated beam with rectangular openings. As a result of additional plates, the angle of hole on the web part of castellated steel beams with rectangular openings which have 90^{o} is increased. This situation causes a decrease in a sudden change in the area.

The castellated steel beams with hexagonal or rectangular openings which have different number of opening are designed according to size of the additional plates. In the castellated steel beams with circular openings, the additional plates are not used because of the circular openings don't have any corner points. Each of the additional plates which is added to the castellated steel beams with hexagonal or rectangular openings are designed as shell elements separately in the SAP2000 program, the shell elements for each beam design are divided into the smaller areas which are needed to get suitable design for analysis.

After the modeling of plates, the next step is specifying the support point of the beam. The support means that an intersection points of a structural element with any point out of beam. The beams model as a simply supported beam and this type of support is an assumption. As the nature of the simply supported beam is required, one of the end supports is assigned as pinned while the other end is assigning as restrain.

The supports are defined in SAP2000 according to freedom of rotation and translation as same with reality. One end of the beam is defined as pinned support which has all three translational freedom are restrained through span, the support was defined as fully supported because there are no forces through perpendicular to the direction of the span. Another end of the castellated beam is assigned as roller support, so the vertical (z-translation 3) degree of freedom is restrained. As same with pinned supported point, this support is not assigned any restriction through perpendicular to the direction of the span.

The loads are assigned on the x-z plane even though the modeling of the castellated beam is done 3D, so the castellated beam is only supposed to load with the direction of global gravity. Besides, the beam is assumed that there is no vertical load that is

affected by the beam. The examples of supports which are assigned in SAP2000 according to translation and rotation.

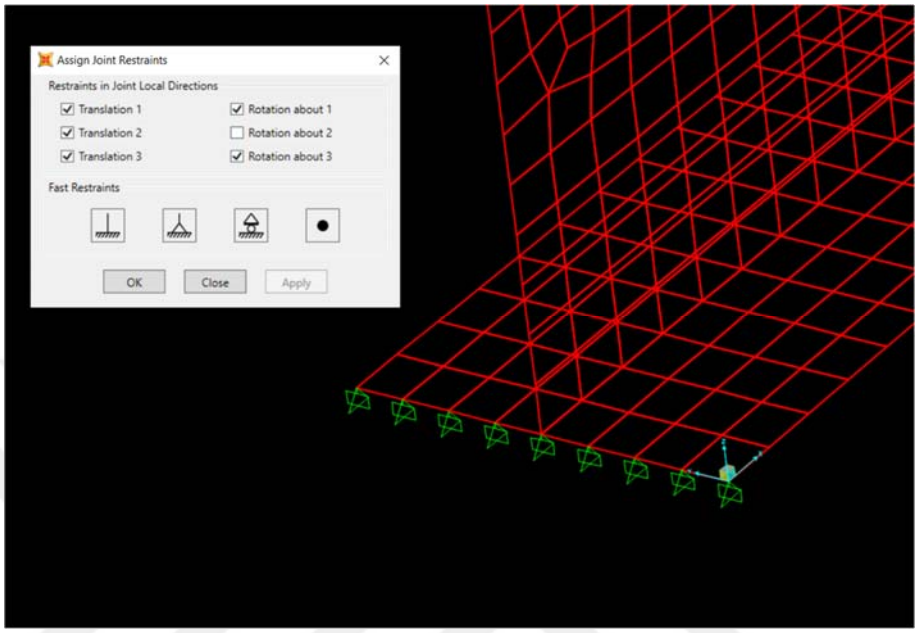


Figure 3.15 Example of pinned support.

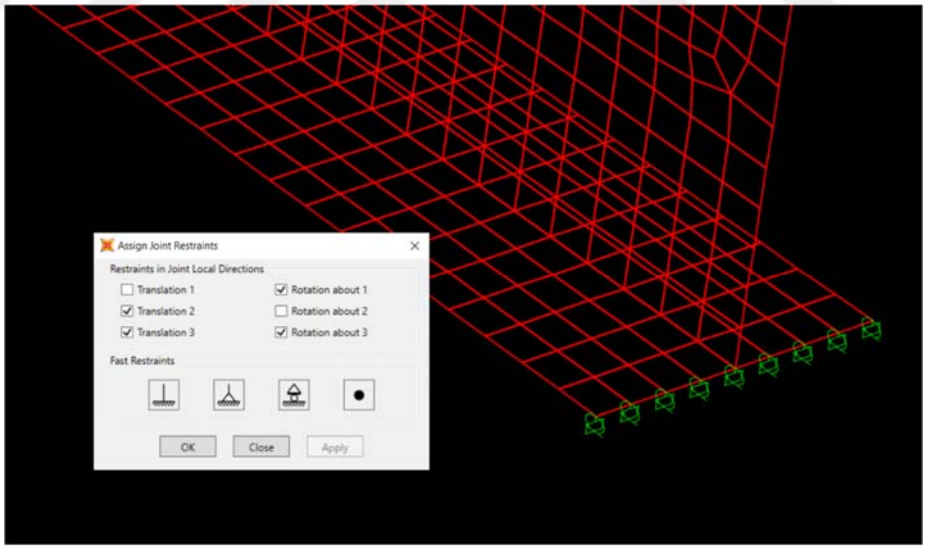


Figure 3.16 Example of roller support.

3.3.2 Analysis Procedure

After these processes which are mentioned above are completed, the loading of beams should be taken into consideration. The loads which are affecting the mainframe should be assigned according to structural loads. For instance, the snow load can not be applied to the second floor of the multi-story building which has five floors, or the

wind load can not be applied to the internal slab of the building which is covered by walls. The selected loads will be different according to the type and location of the building.

In this thesis, the loads are applied to the flange part of beams which is divided into smaller parts internally via the SAP2000 program. The dead and live load which should be applied to the beam are applied to small and equal areas in the flange with the direction of global gravity.

The specified load is equal to the yielding capacity load of the IPE500 beam. Comparison between the IPE500 beam and the IPE500 castellated steel beam, which both beams have been applied the load which fails both of them in a 15-meter span, with different types and number of holes according to capacity and serviceability is done during the thesis.

The IPE500 beam which is the quality of S355 material has 355 MPa yielding capacity. The procedure below should be followed during the calculation of the yielding capacity of the IPE500 beam that is the quality of S355 with a 15-meter length.

$$\sigma = \frac{Mmax}{W}$$

$$M_{max} = w * \frac{l^2}{8}$$

$$w = 8 * \sigma * \frac{W}{l^2} = 8*355*\frac{1928000}{15000^2} = 24{,}3 \text{ N/mm}^2$$

To convey the load in SAP2000, firstly the distributed load was multiplied by the length of the beam, and the total load which is applied to the beam was found. Then, the load of every small area on the flange was found by dividing the total load to the area of flange. Because of the flange of the IPE500 beam has a width of 200 mm and length of 15000 mm, the total area was calculated as $3m^2$.

$$w = 24{,}3\text{MPa} * \frac{15000mm}{3m^2} = 121{,}5 \text{ kN}/m^2$$

In this case, the load of 121,5 kN/m^2 does not include the self-weight of the beam. While assuming that the weight of IPE500 beam per meter is 0,9 kN, the new load combination was calculated as:

$$w= 121,5\text{-}0,9 = 120 \text{ kN}/m^2$$

After the load is assigned to the beam which is modeled as shell and 3D, the analysis check procedure should be started. As mentioned before, even the beam was modeled as 3D, the analysis was done according to 2D on the x-z plane. The result will be prevented as reality because there is no lateral load assigned to the beam.

Firstly, the displacement of elements of the beam which is already analyzed is check. After the analysis finished by the SAP2000 program, the deflection values of each structural element that belonging to the beam were found by clicking each element's results and joints in the section of analysis result, and these results are investigated in Chapter 4.

Another parameter that is controlled during analysis is the stress of shell areas. The shell area stresses are very important due to beam elements are defined as small areas. The S11 and SVM (Von Misses Stress) values are also controlled during the analysis result check according to load defined to the beams.

3.4 Von Misses Stress

Von Mises stress, also known as Huber stress, is a measure that accounts for all six stress components of a general 3-D state of stress. Notice that Von Mises stress is a non-negative, scalar stress measure. Von Mises stress is commonly used to present results because the structural safety for many engineering materials showing elastoplastic properties (for example, steel or aluminum alloy) can be evaluated using von Mises stress. "The maximum von Mises stress failure criterion is based on the von Mises-Hencky theory, also known as the scalar-energy theory or the maximum distortion energy theory. The theory states that a ductile material starts to yield at a location when the von Mises stress becomes equal to the stress limit."(Kurowski, 2012).

CHAPTER 4

ANALYSIS

4.1 Computational Results

In this chapter, analysis results that are obtained according to different web opening types and opening numbers of castellated beams are going to be evaluated. Using a different type of castellated beams defined as hexagonal, rectangular, and circular, the most suitable web opening type and web opening number are tried to be determined, deflections and stress changes interpreted according to variable and constant parameters (span of beam, number of web opening, and type of web opening, the weight of beam). In the designed beams, it was observed that there was huge stress in the corner of the web opening. To reduce the stress at that points 10 mm triangular plates that have size 25x25x10 mm, 50x50x10 mm, 100x100x10 mm were added, and stress and deflections parameters controlled.

The designed beam types are listed below.

1. According to the type of web opening.
    - Hexagonal web opening,
    - Rectangular web opening
    - Circular web opening,
2. According to the number of webs opening.
    - With three opened,
    - With six opened,
    - With twelve opened,
3. According to plate size, that added at the corner of the web opening.
    - 25x25x10 mm plate added,
    - 50x50x10 mm plate added,
    - 100x100x10 mm plate added,

4. According to beam type without web opening.
    - IPE500
    - Built-up section (Height is the same as hexagonal, rectangular, and circular castellated beams)

The stress values formed in the parts of the beams close to the support and in the middle part of the beam, where stress and deflection controls are made, are examined separately. Analysis and deflection controls were firstly started from the IPE500 beam. The load-carrying of the IPE500 beam to the yield stress point at 15 meters was determined and the same load which is found after the determination was used for each beam type. Maximum stresses (355 MPa, yield stress) in the IPE500 beam and beam without web opening designed from the built-up section occurred at the top of the flange in the middle of the span but the maximum stress in beams that have web opening occurred at web opening corners. Besides, in castellated beams with web opening, the stresses at the points with sudden angle changes at the corners vary according to the opening type. Especially in castellated beams with rectangular web openings, it was observed that the stresses intensified at these points due to the 90-degree corner change. To reduce the stress in corner changes that occur depending on the opening section, as mentioned above, 25x25x10 mm, 50x50x10 mm, 100x100x10 mm width plates with the thickness of the web were added and the stress values were checked in these regions.

The following figures and tables below show the stress values of the designed beams and where the stresses increase and decrease. As seen from the figures and tables, there is a noticeable difference between the beams that have different opening types and opening number.

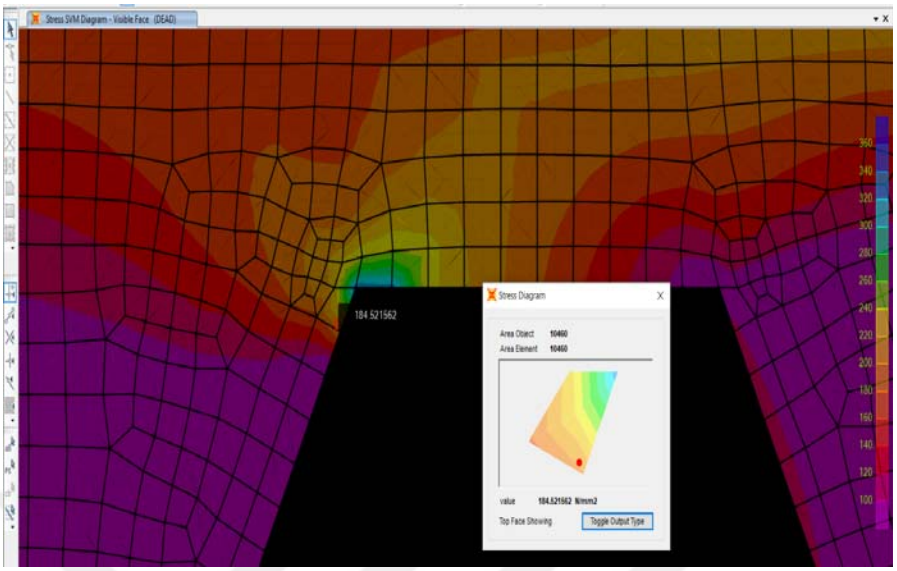


Figure 4.1 Stress distributions on the edge of the hexagonal web opening.

Table 4.1 The maximum S11 and SVM stress of castellated beams compare with web opening type and the number of web opening.

Type Of Beam	Number Of Opening	Maksimum S11(MPa) On Edge Side	Maksimum SVM(MPa) On Edge Side	Maksimum S11(MPa) On Middle	Maksimum SVM(MPa) On Middle
Hexagonal	12	482 MPa	495 MPa	339 MPa	327 MPa
	6	460 MPa	446 MPa	374 MPa	354 MPa
	3	420 MPa	440 MPa	308 MPa	300 MPa
Rectangular	12	700 MPa	755 MPa	444.5 MPa	437.5 MPa
	6	606 MPa	642 MPa	388 MPa	381 MPa
	3	430 MPa	472 MPa	215 MPa	240 MPa
Circular	12	260 MPa	280 MPa	381 MPa	368 MPa
	6	291 MPa	335 MPa	355 MPa	353 MPa
	3	294 MPa	305 MPa	359 MPa	352 MPa

The stresses occurring at the edge and middle regions of the beams according to the web opening type and the number of the web opening are clearly stated in the table above.

It has been determined that the stresses in beams with web opening are higher than the stresses in the built-up section without web opening.

Table 4.2 The maximum S11 and SVM stress on Ipe500 and built-up beam.

Type Of Beam	Maximum S11(MPa)	Maksimum SVM(MPa)	Location
Ipe500	355 MPa	358 MPa	Top flange
Built-up beam	219 MPa	222.3 MPa	Top flange

Due to the increase in the stress caused by the sudden cross-sectional variation in the opening edges of the web opening beams, the web thickness of 25x25x10 mm, 50x50x10 mm, 100x100x10 mm width triangular plates added in the castellated beams with 6gen and rectangular section web openings. Stresses changing by adding plates of the same thickness clearly shown in the following tables and figures.

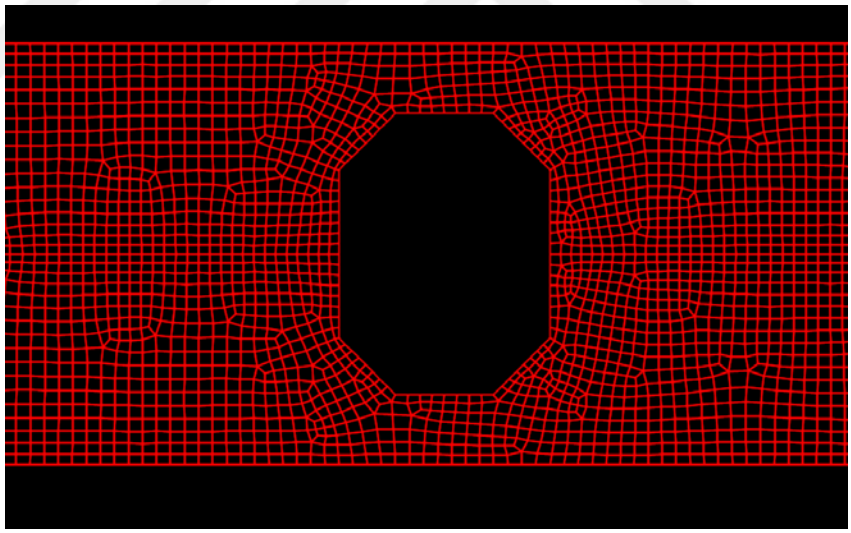


Figure 4.2 100x100x10 mm mm placed the additional plate on the edge of the rectangular castellated beam.

Table 4.3 The maximum S11 and SVM stress value on hexagonal castellated beams compare to an additional plate.

Type Of Beam	# Of Holes	Additional Plate size(mm) t=10 mm	Max S11 (MPa) On Edge Side	Max SVM (MPa) On Edge Side	Max S11 (MPa) On Middle	Max SVM (MPa) On Middle
Hexagonal	12	25x25	352 MPa	412 MPa	320 MPa	307 MPa
	12	50x50	277 MPa	358 MPa	321 MPa	285 MPa
	12	100x100	194 MPa	284 MPa	460 MPa	576 MPa
Hexagonal	6	25x25	390 MPa	388 MPa	342 MPa	328 MPa
	6	50x50	365 MPa	354 MPa	327 MPa	325 MPa
	6	100x100	340 MPa	576 MPa	380 MPa	366 MPa
Hexagonal	3	25x25	358 MPa	344 MPa	305 MPa	293 MPa
	3	50x50	314 MPa	328 MPa	312 MPa	300 MPa
	3	100x100	320 MPa	334 MPa	337 MPa	344 MPa

Table 4.4 The maximum S11 and SVM stress value on rectangular castellated beams compare to an additional plate.

Type Of Beam	# Of Holes	Additional Plate size(mm) t=10 mm	Max S11 (MPa) On Edge Side	Max SVM (MPa) On Edge Side	Max S11 (MPa) On Middle	Max SVM (MPa) On Middle
Rectangular	12	25x25	591 MPa	592 MPa	404 MPa	399 MPa
	12	50x50	583 MPa	572 MPa	365 MPa	360 MPa
	12	100x100	366 MPa	406 MPa	375 MPa	372 MPa
Rectangular	6	25x25	517 MPa	522 MPa	377 MPa	356 MPa
	6	50x50	424 MPa	496 MPa	396 MPa	426 MPa
	6	100x100	350 MPa	372 MPa	368 MPa	355 MPa
Rectangular	3	25x25	326 MPa	407 MPa	216 MPa	204 MPa
	3	50x50	331 MPa	360 MPa	240 MPa	321 MPa
	3	100x100	324 MPa	346 MPa	242 MPa	323 MPa

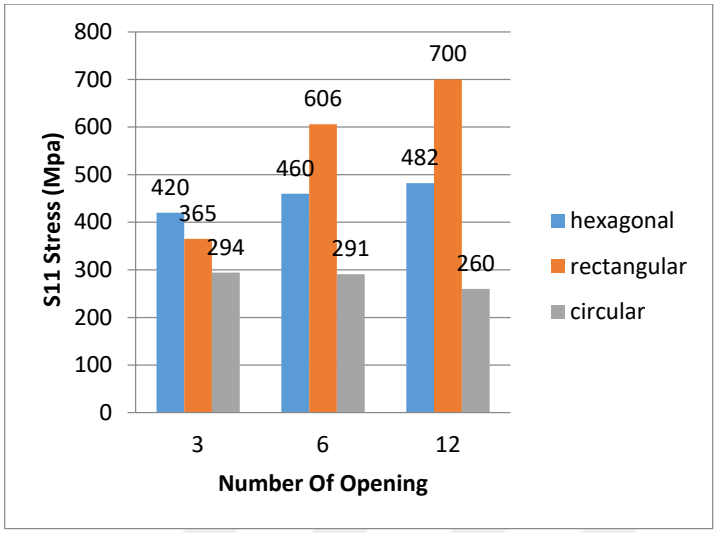


Figure 4.3 The number of opening vs. S11 distribution of hexagonal, rectangular, circular castellated beams on the edge side.

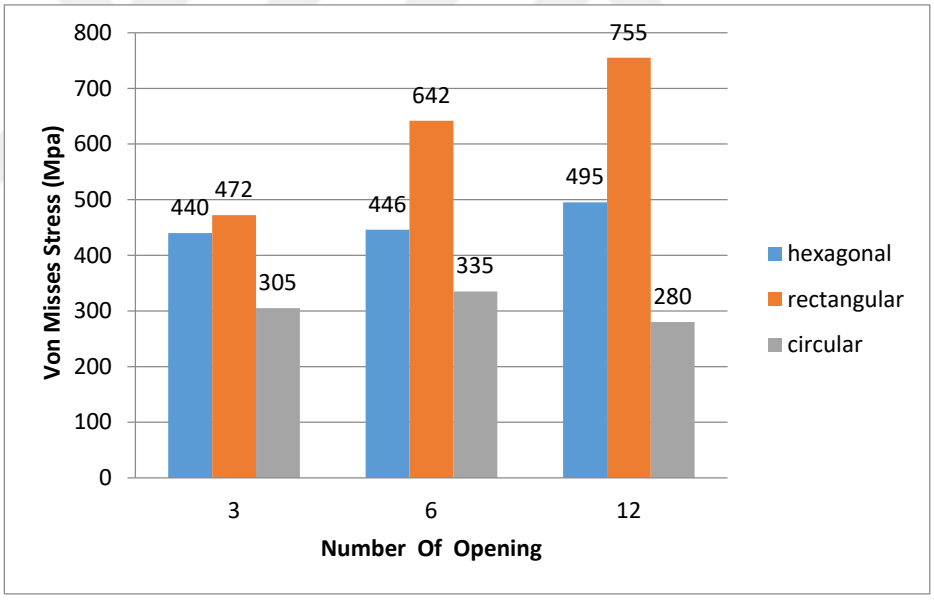


Figure 4.4 The number of opening vs. SVM distribution of hexagonal, rectangular, and circular castellated beams on the edge side.

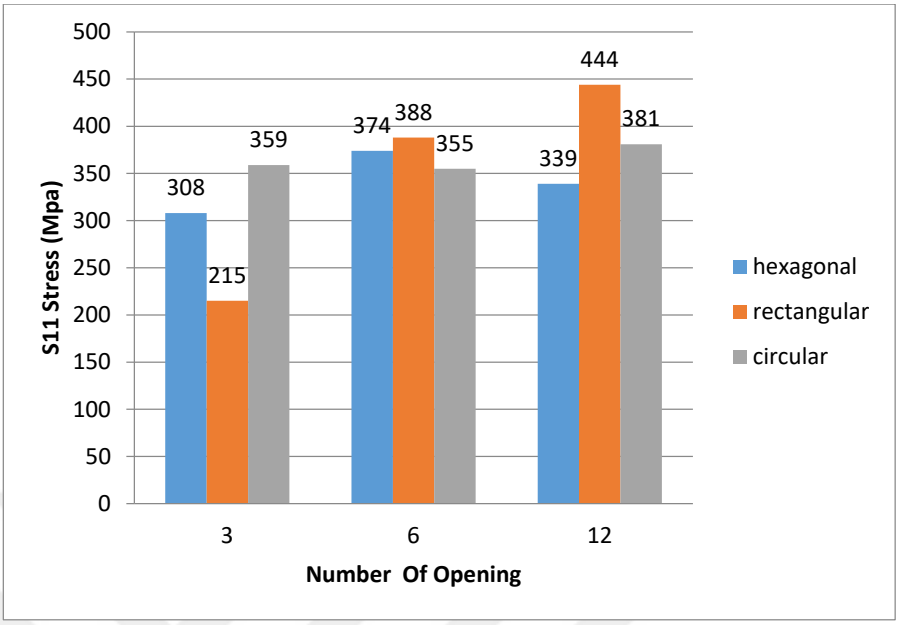


Figure 4.5 The number of opening vs. S11 distribution of hexagonal, rectangular, and circular castellated beams in the middle.

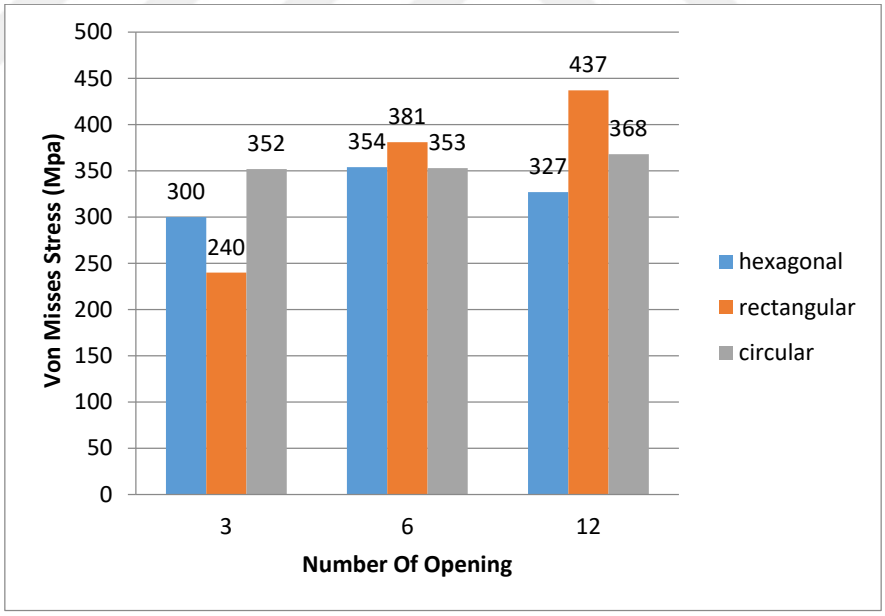


Figure 4.6 The number of opening vs. SVM distribution of hexagonal, rectangular, circular castellated beams in the middle.

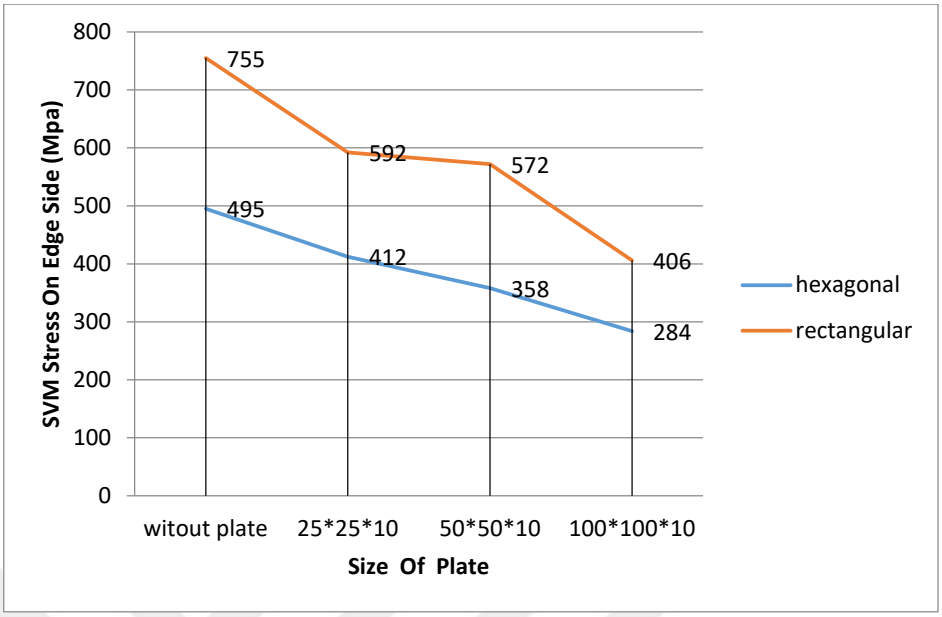


Figure 4.7 Twelve web opening hexagonal and rectangular castellated beams edge side SVM distribution compare to additional plate size.

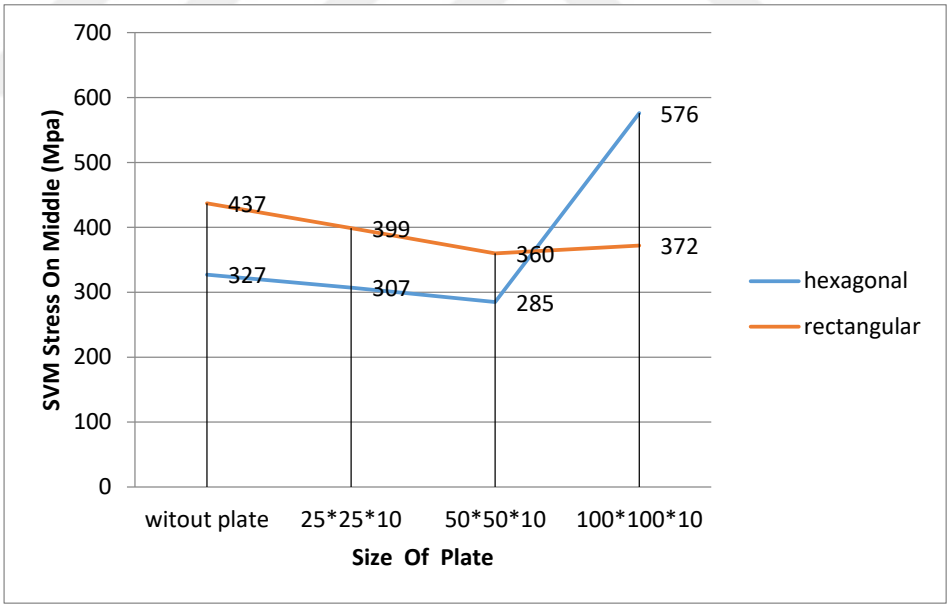


Figure 4.8 Twelve web opening hexagonal and rectangular castellated beams middle side SVM distribution compare to additional plate size.

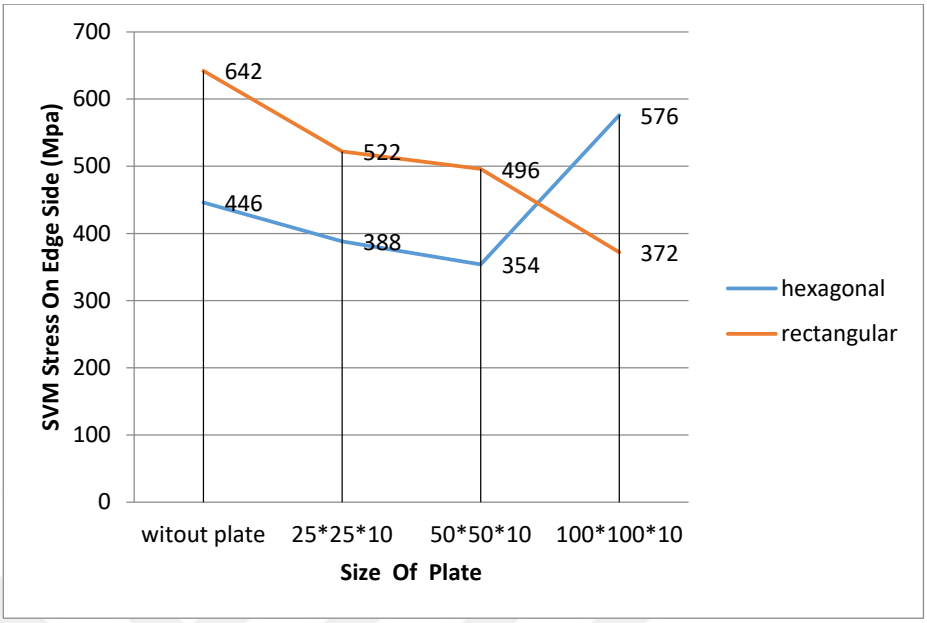


Figure 4.9 Six web opening hexagonal and rectangular castellated beams edge side SVM distribution compare to additional plate size.

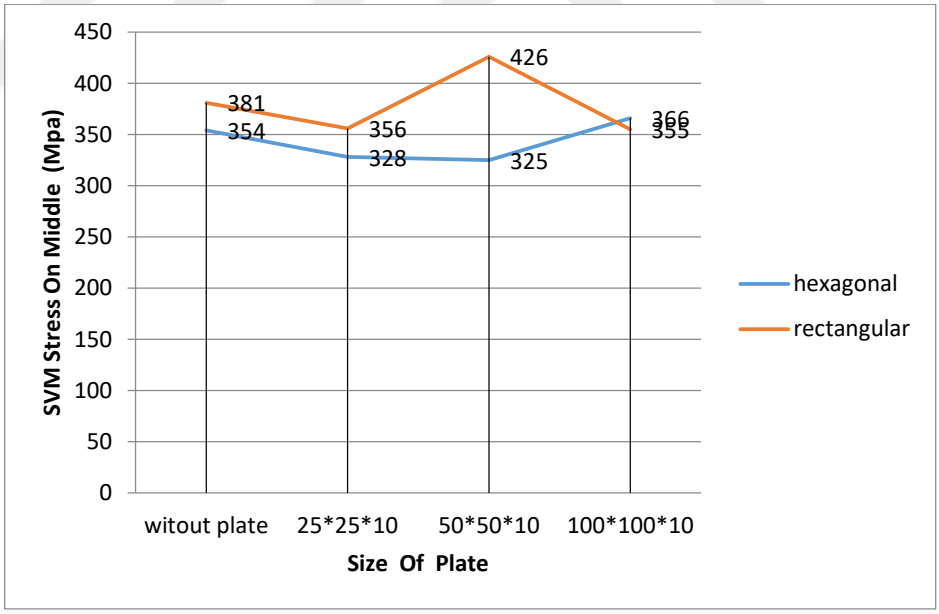


Figure 4.10 Six web opening hexagonal and rectangular castellated beams middle side SVM distribution compare to additional plate size.

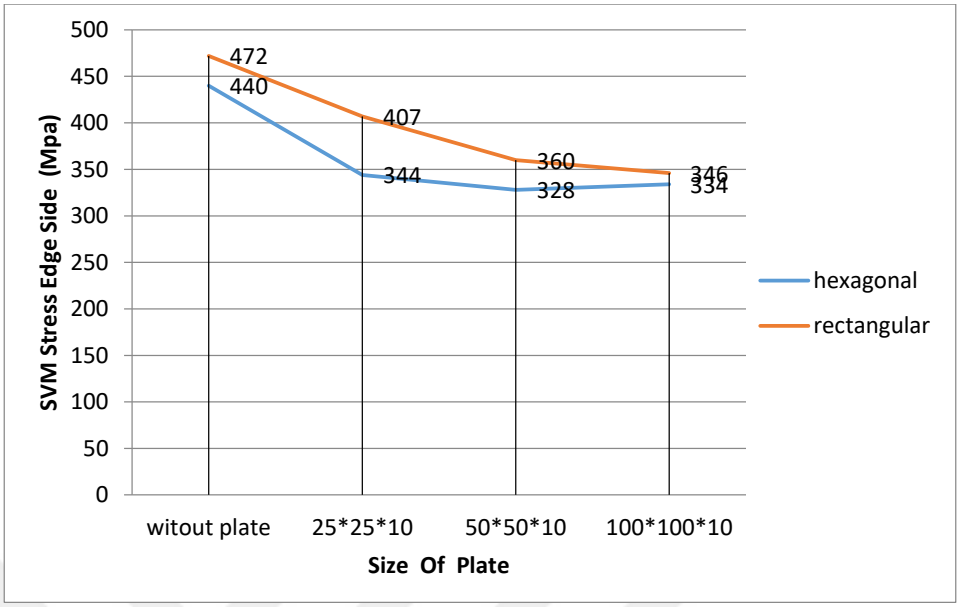


Figure 4.11 Three web opening hexagonal and rectangular castellated beams edge side SVM distribution compare to additional plate size.

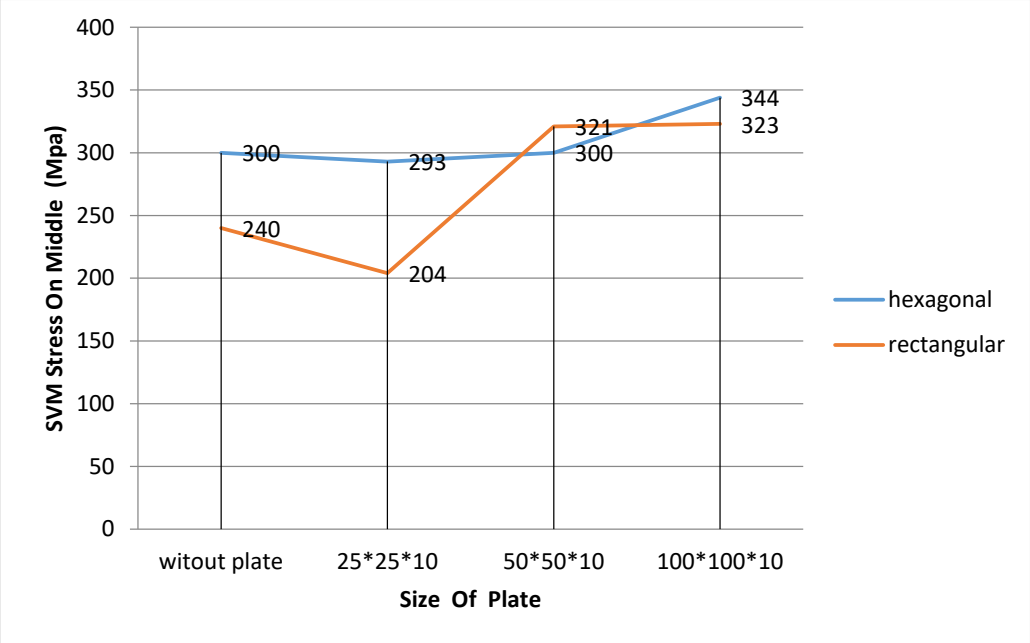


Figure 4.12 Three web opening hexagonal and rectangular castellated beams middle side SVM distribution compare to additional plate size.

In designed beams, deflection values are as important as tensile values. The deflection values of each designed beam will also be clearly stated in this unit and the results obtained according to web opening type and web opening quantity will be shown in designed beams.

While the deflection value formed in the IPE500 beam with a span of 15 meters is 129 mm in the SAP2000 program, the deflection value obtained in the beam obtained from the built-up section that is without web opening has decreased approximately by half and SAP2000 has been calculated as 59 mm.

Deflection values calculated on beams with web opening are calculated approximately as close to the beam deflection value obtained from the cross-section and these important values are clearly stated in the ongoing tables and figures.

Table 4.5 Maximum deflections on IPE500 and built-up beam.

Type Of Beam	Maximum displacement on the middle of span (mm)
Ipe500	129 mm
Built-up beam	59 mm

Table 4.6 Maximum deflection on castellated beams compares to web opening type and number of opening.

Type of Beam	Number of Opening	Maximum displacement on the middle of span (mm)
Hexagonal	12	64,31 mm
	6	61,8 mm
	3	60,6 mm
Rectangular	12	66,3 mm
	6	62,8 mm
	3	61,2 mm
Circular	12	63,5 mm
	6	61,4 mm
	3	60,4 mm

Table 4.7 Maximum deflection on hexagonal castellated beams compares to additional plate size.

Type of Beam	Number of Opening	Additional Triangular Plate size(mm) t=10 mm	Maximum displacement on the middle of span (mm)
Hexagonal	12	25x25	64,06 mm
	12	50x50	63,7 mm
	12	100x100	62,9 mm
Hexagonal	6	25x25	61,7 mm
	6	50x50	61,58 mm
	6	100x100	61,2 mm
Hexagonal	3	25x25	60,5 mm
	3	50x50	60,4 mm
	3	100x100	60,03 mm

Table 4.8 Maximum deflection on rectangular castellated beams compares to additional plate size.

Type of Beam	Number of Opening	Additional Plate size (mm) t=10 mm	Maximum displacement on the middle of span (mm)
Rectangular	12	25x25	65,7 mm
	12	50x50	65,1 mm
	12	100x100	63,7 mm
Rectangular	6	25x25	62,5 mm
	6	50x50	62,2 mm
	6	100x100	61,5 mm
Rectangular	3	25x25	55,2 mm
	3	50x50	55 mm
	3	100x100	54,7 mm

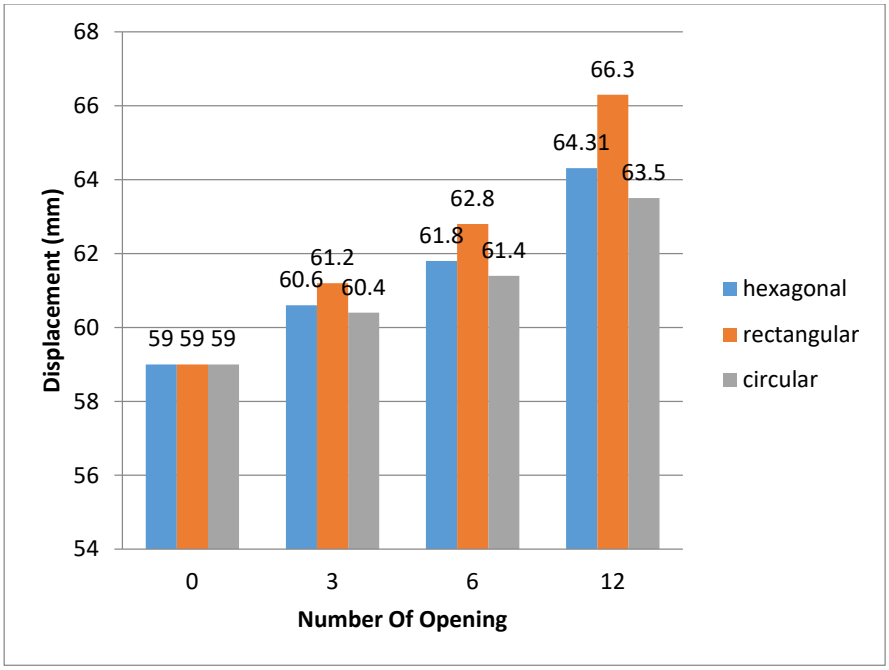


Figure 4.13 The number of opening versus deflection distribution hexagonal, rectangular, circular castellated beams on the edge side.

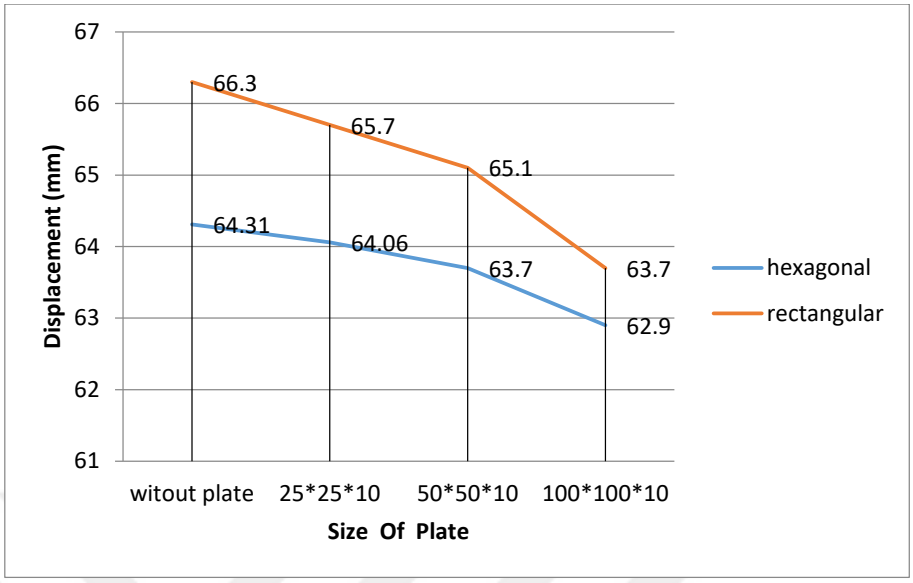


Figure 4.14 Maximum deflection distribution of twelve web opening castellated beams compare to additional triangular plate size.

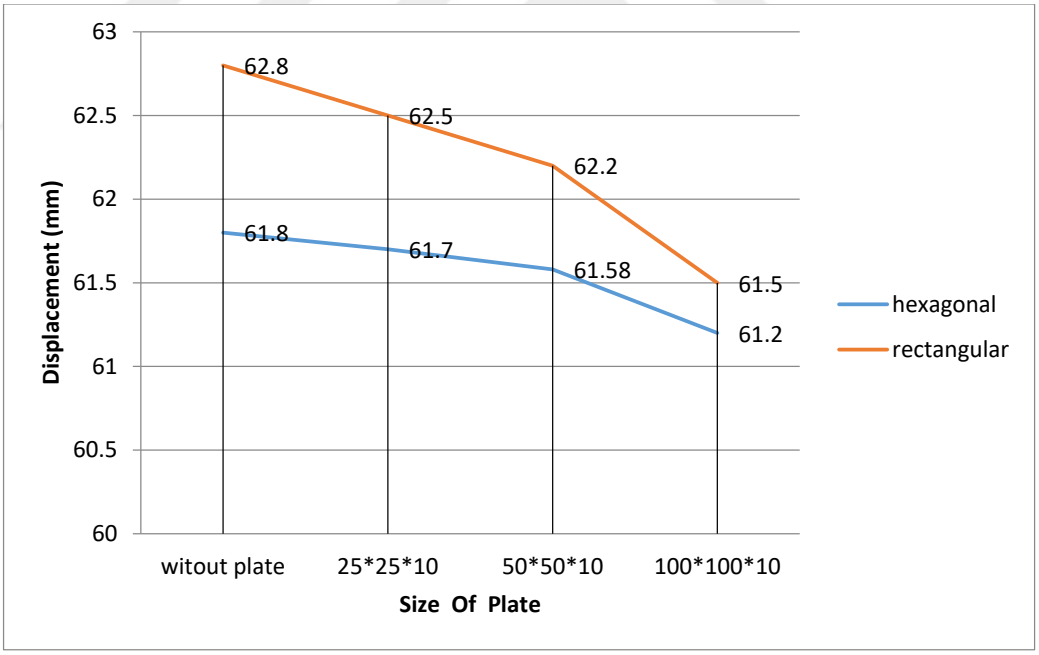


Figure 4.15 Maximum deflection distribution of six web opening castellated beams compare to additional triangular plate size.

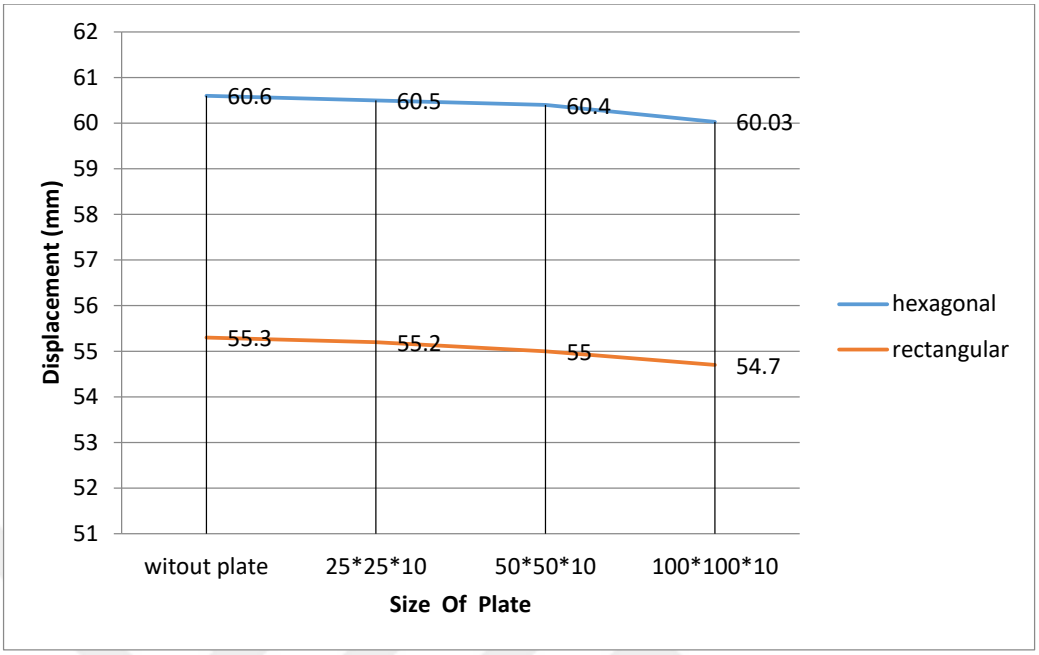


Figure 4.16 Maximum deflection distribution of three web opening castellated beams compare to additional triangular plate size.

4.2 Discussion

Stress and deflection values were investigated according to the structural analysis results obtained in Sap2000. When the number of web opening and web opening areas is kept constant, it is determined that the stress and deflection values are higher especially in castellated beams that have rectangular section web opening.

In the beams of hexagonal and rectangular web opening, it was observed that the stresses occurring in the web opening corner points decreased according to the different plate sizes added, but since the added plate size increased, more stresses were observed in the corner points of the opening because of the more sudden cross-sectional changes in the web opening corners.

It has been observed that deflection values increase as the number of web openings increases. While the deflection value calculated on the IPE500 beam with a span of 15 meters is 129 mm, in the beam without web opening obtained from the built-up section, the deflection is almost halved and calculated as 59 mm.

The opening type of web opening, number of web opening were affected the S11 stress and SVM stress, displacement result for the castellated beams;

- As shown in Figure 4.3, Maximum S11 values obtained in the edge areas of beams with twelve web openings are 700 MPa, 482 MPa, 260 MPa, in castellated beams with rectangular, hexagonal, and circular opening web opening, respectively.
- As shown in Figure 4.3, the maximum S11 values obtained in the edge areas of beams with six web openings are 606 MPa, 460 MPa, 291 MPa, respectively, in castellated beams with rectangular, hexagonal, and circular opening web opening.
- As shown in Figure 4.3, the maximum S11 values obtained in the edge areas of the beams with three web openings are 420 MPa, 365 MPa, and 294 MPa, in castellated beams with hexagonal, rectangular, and circular opening web opening, respectively.
- As shown in Figure 4.4, the maximum SVM values obtained in the edge areas of the beams with twelve web openings are 755 MPa, 495MPa, 280 MPa, in castellated beams with rectangular, hexagonal, and circular opening web opening, respectively.
- As shown in Figure 4.4, the maximum SVM values obtained in the edge areas of beams with six web openings are 642 MPa, 446 MPa, 335 MPa, in castellated beams with rectangular, hexagonal, and circular opening web opening, respectively.
- As shown in Figure 4.4, Maximum SVM values obtained in the edge areas of beams with three web openings are 472 MPa, 440 MPa, 305 MPa, in castellated beams with rectangular, hexagonal, and circular opening web opening, respectively.
- As shown in Figure 4.5, maximum S11 values obtained in the middle regions of beams with twelve web openings are 444 MPa, 381 MPa, 339 MPa, in castellated beams with rectangular, circular, and hexagonal opening web opening, respectively.
- As shown in Figure 4.5, maximum S11 values obtained in the middle regions of beams with six web openings are 388 MPa, 374 MPa, 355 MPa, in castellated beams with rectangular, hexagonal, and circular opening web opening, respectively,

- As shown in Figure 4.5, maximum S11 values obtained in the middle regions of beams with three web openings are 359 MPa, 308 MPa, 215 MPa, in castellated beams with circular, hexagonal, and rectangular opening web opening, respectively.
- As shown in Figure 4.6, the maximum SVM values obtained in the middle regions of beams with twelve web openings are 437 MPa, 368 MPa, 327 MPa, in castellated beams with rectangular, circular, and hexagonal opening web opening, respectively.
- As shown in Figure 4.6, the maximum SVM values obtained in the middle regions of beams with six web openings are 381 MPa, 354 MPa, 353 MPa, in castellated beams with rectangular, hexagonal, and circular opening web opening, respectively.
- As shown in Figure 4.6, the maximum SVM values obtained in the middle regions of beams with three web openings are 352 MPa, 300 MPa, 240 MPa, in castellated beams with circular, hexagonal, and rectangular opening web opening, respectively.

In the designed hexagonal and rectangular castellated beam types, stress values of 25x25 mm, 50x50 mm, 100x100 mm of 10 mm thickness are added to the web opening corners, and the stress values at the edges and midpoints of the beam are examined, and the stresses obtained at these points;

1. As shown in Figure 4.7, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of rectangular beams with twelve web openings, SVM values in the beam edge regions are 592 MPa, 572 MPa, and 406 MPa, respectively,
2. As shown in Figure 4.7, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of hexagonal beams with twelve web openings, SVM values in the beam edge regions are 412 MPa, 358 MPa, and 284 MPa, respectively,
3. As shown in Figure 4.8, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of rectangular beams with twelve web openings, SVM values in the middle of the beam are 399 MPa, 360 MPa, and 372 MPa, respectively,

4. As shown in Figure 4.8, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of hexagonal beams with twelve web openings, SVM values in the middle of the beam are 307 MPa, 285 MPa, and 576 MPa, respectively,
5. As shown in Figure 4.9, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of rectangular beams with six web openings, SVM values in the beam edge regions are 522 MPa, 496 MPa, and 372 MPa, respectively,
6. As shown in Figure 4.9, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of hexagonal beams with six web openings, SVM values in the beam edge regions are 388 MPa, 354 MPa, and 576 MPa, respectively,
7. As shown in Figure 4.10, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of rectangular beams with six web openings, SVM values in the middle of the beam are 356 MPa, 426 MPa, and 355 MPa, respectively,
8. As shown in Figure 4.10, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of hexagonal beams with six web openings, SVM values in the middle of the beam are 328 MPa, 325 MPa, and 366 MPa, respectively,
9. As shown in Figure 4.11, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of rectangular beams with three web openings, SVM values in the beam edge regions are 407 MPa, 360 MPa, and 346 MPa, respectively,
10. As shown in Figure 4.11, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of hexagonal beams with three web openings, SVM values in the beam edge regions are 344 MPa, 328 MPa, and 334 MPa, respectively,
11. As shown in Figure 4.12, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of rectangular beams with three web openings, SVM values in the middle of the beam are 204 MPa, 321 MPa, and 323 MPa, respectively,
12. As shown in Figure 4.12, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of hexagonal beams with

three web openings, SVM values in the middle of the beam are 293 MPa, 300 MPa, and 344 MPa, respectively,

The deflections obtained in the designed beams vary depending on the type of web opening, the number of web opening. The deflections obtained in beams with rectangular and hexagonal web opening have changed according to the dimensions of the 25x25x10 mm, 50x50x10 mm, 100x100x10 mm triangular plates added to the web opening corners.

While the maximum deflection value obtained in the S355 quality Ipe500 beam with a span of 15 meters is 129 mm, the maximum deflection value formed in the built-up beam that is no web opening with the same span and quality has been calculated as 59 mm.

Deflection values obtained in beams designed according to web opening type, web opening number, and plate dimensions added to web opening corners.

1. As shown in Table 4.6, The maximum deflection value formed in the castellated beams with hexagonal web opening having 12, 6 and 3 web openings, is 64.31 mm, 61.8 mm, 60.6 mm, respectively,
2. As shown in Table 4.6, The maximum deflection value formed in the castellated beams with rectangular web opening having 12, 6 and 3 web openings, is 66.3 mm, 62.8 mm, 61.2 mm, respectively,
3. As shown in Table 4.6, The maximum deflection value formed in the castellated beams with circular web opening having 12, 6 and 3 web openings, is 63.5 mm, 61.4 mm, 60.4 mm, respectively,
4. As shown in Table 4.7, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of hexagonal beams with twelve web openings, the maximum deflections are 64,06 mm, 63,7 mm, and 62,9 mm respectively,
5. As shown in Table 4.7, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of hexagonal beams with six web openings, the maximum deflections are 61,7 mm, 61,58 mm, and 61,2 mm respectively,
6. As shown in Table 4.7, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of hexagonal beams with

three web openings, the maximum deflections are 60,5 mm, 60,4 mm, and 60,03 mm respectively,

7. As shown in Table 4.8, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of rectangular beams with twelve web openings, the maximum deflections are 65,7 mm, 65,1mm, and 63,7 mm respectively,
8. As shown in Table 4.8, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of rectangular beams with six web openings, the maximum deflections are 62,5 mm, 62,2 mm, and 61,5 mm respectively,
9. As shown in Table 4.8, when 25x25x10 mm, 50x50x10 mm, 100x100x10 mm plates are added to the web opening corner points of rectangular beams with three web openings, the maximum deflections are 55,2 mm, 55 mm, and 54,7 mm respectively,

Maximum stresses in the IPE500 beam and the built-up beam which do not have a web opening occurred in the upper flange of beams in the middle of the span. In beams with web opening, it is observed that maximum stress occurs in web opening corners.

It was observed that the maximum stresses occurring at the edges of the web opening are generally higher in beams with rectangular web opening. The maximum SVM value observed in the edge areas of the castellated beam with a rectangular web opening with 12 web openings was observed as 755 MPa. This the maximum stress occurred in the corner of the web opening. The maximum stresses occurring in the middle parts of the beams are generally higher in beams with rectangular web opening as at the edge regions. Looking at the middle areas of the beams that have web opening, it is observed that the maximum SVM stress in rectangular web opening castellated beams 437 MPa.

Deflection values in castellated beams designed in different web opening types and numbers are close to each other. The maximum deflection value in the beams analyzed is in beams with rectangular twelve web opening as 66,3 mm. The maximum deflection value in the beams analyzed is in beams with circular three web opening as 60,344 mm. While the deflection value formed in the IPE500 beam with a span of 15 meters is 129 mm in the SAP2000 program, the deflection value obtained in the beam

obtained from the built-up section that is without web opening has decreased approximately by half and SAP2000 has been calculated as 59 mm.

As can be seen from the results above, the stress and deflection values of different types and pieces of castellated beams have been examined one by one according to the changing and fixed parameters and the results have been displayed. The design of castellated beams to be designed with a certain span and under certain loads is important.

CHAPTER 5

CONCLUSIONS

5.1 Conclusion of Study

In this study, the investigations about stresses and deflections of the corner of web holes through the castellated beam with different types and number of web holes. The results are obtained via SAP2000 by analyzing stresses, and these results are explained clearly by observations, and tables are explained clearly. The data has been obtained by a various and constant parameter which are changing with type, quantity, and additional corner plates of web holes. The results are given below:

1. As can be seen in the results, the maximum stresses of the modeled IPE500 and built-up sectioned beams (which does not have web holes) occur in the middle point of flanges, while the maximum stresses of the castellated beams which have web holes occur in the points near to supports.
2. The stresses that are near to supports and mid-points of castellated beams are changing according to the number of web holes even the types of web openings are the same. Especially in hexagonal and rectangular castellated beams, S11 and SVM values are increasing with the number of web holes increase.
3. The stress of circular castellated beams that have the same web hole quantity with the other types of castellated beams is lower while the stress of hexagonal and rectangular castellated beams is less under the same conditions.
4. The stresses at the corner of web openings change according to instant differences on the cross-sections of the web. As smooth as the corner of the cross-section, the stresses between internal structural elements will be straight and closer to each other.
5. The stress values are decreasing until sharp corners will occur while additional plates which are the same wall thickness with a cross-section of castellated beams are placing to holes on the web. According to the sizes of plates, the stresses will increase when the corner of the web hole became sharper.

6. The deflection value of the castellated beams is less rather than the original steel beams because of the height of castellated beams are higher than the root beam even the types and number of holes are different.
7. The deflections of hexagonal and rectangular castellated beams are less than the built-up section beams (does not have web holes) which have the same height as regarding castellated beams.
8. The maximum deflection values are increasing at the castellated beams with the same type of web holes while the number of web holes is increasing.
9. The maximum deflection occurs at the rectangular castellated beams, and the minimum deflection occurs at the circular castellated beams under the same conditions that are the same type and number of holes.
10. The additional plates which are placing to the corner of web holes decrease the deflection values of the castellated steel beams.

5.2 Future Studies and Recommendations

The result of this study will be helpful especially steel structure engineers in the research, select as the best of castellated steel beam-type according to its web opening type, number of web opening, and if it is necessary additional plate that uses in the edge of the web opening edge. The proposed results that calculated in this study need to be verified by further case studies, for example,

- The same research can be done by using another software, by changing the height of the castellated beam, the number of web openings, the length of the span, the applied loads.
- A new study can be done by a different type of adding plates that different thicknesses and geometries in the web opening corner points.
- New studies can be done by changing the type of web opening.

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