



WALLAGA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

**PARAMETRIC STUDY OF STATIC ANALYSIS OF
CARBON FIBER REINFORCED POLYMER
STRENGTHENED CASTELLATED STEEL BEAM USING
FINITE ELEMENT ANALYSIS**

**A THESIS SUBMITTED TO THE COLLEGE OF ENGINEERING
AND TECHNOLOGY IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE
IN STRUCTURAL ENGINEERING**

BY

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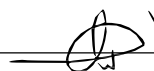


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DECLARATION

I Mrs Birhanu Damesa hereby declare and affirm that the thesis entitled “Parametric Study of Static Analysis of Carbon Fiber Reinforced Polymer Strengthened Castellated Steel Beam Using Finite Element Analysis” is my own work conducted under the supervision of DR.Kabtanu Getachew. I have followed all the ethical principles of scholarship in the preparation, data collection, data analysis and completion of this thesis. All scholarly matter that is included in the thesis has been given recognition through citation. I have adequately cited and referenced all the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and I have not misrepresented, fabricated, or falsified any idea / data / fact / source in my submission. This thesis is submitted in partial fulfillment of the requirement for a degree from the Post Graduate Studies at Wallaga University. I further declare that this thesis has not been submitted to any other institution anywhere for the award of any academic degree, diploma or certificate.

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ABBREVIATIONS AND ACRONYMS

AFRP	:	Aramid Fiber-Reinforced Polymer Composite
BFRP	:	Basalt Fiber-Reinforced Polymer
CFRP	:	Carbon Fibre Reinforced Polymer
EBR	:	Externally Bonded Reinforcement
FRP	:	Fibre Reinforced Polymer
FRCs	:	Fibre Reinforced Composites
GFRP	:	Glass Fibre Reinforced Polymer
HM-CFRP	:	High Modulus Carbon Fibre Reinforced Polymer
NFRCs	:	Natural Fiber-Reinforced Composites
NSM	:	Near-Surface Mounted
CSB	:	Castellated Steel Beam
SFRCs	:	Synthetic Fiber-Reinforced Composites
UHM-CFRP	:	Ultra High Modulus Carbon Fibre Reinforced Polymer

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ABSTRACT

Web openings in structural elements can introduce stress concentrations, leading to potential failure modes such as flexural failure, web-post buckling, Vierendeel bending, and lateral-torsional buckling. To address flexural failure, the use of Carbon Fiber Reinforced Polymer (CFRP) strengthening has become increasingly popular. Castellated steel beams, known for their lightweight and efficient load-bearing capabilities, often require reinforcement to improve their static performance under various loading conditions. This study investigates the structural performance of CFRP-strengthened castellated steel beams using finite element modeling in ABAQUS. A detailed numerical model was developed and validated against experimental data to ensure accuracy. A nonlinear analysis was conducted to examine the effects of parameters such as the number of CFRP layers, opening configurations, and opening dimensions on deflection, ultimate load, and the load-deflection curve. The finite element modeling of a castellated steel beam was validated through comparison with experimental results concerning the impact of opening dimensions. The convergence between experimental and numerical results was satisfactory, with an average difference of 8.61% in ultimate load and 7.56% in maximum vertical mid-span deflection. A parametric study was also performed to analyze which combinations of CFRP layers, opening configurations, and opening dimensions yielded optimal performance under loading. Sixteen models were utilized for this analysis. Results indicated that ultimate failure loads increased with CFRP thickness, ranging from 1.2 mm to 4.8 mm. Additionally, increasing hole height reduced the load-carrying capacity of the CFRP-strengthened castellated beams. Among four opening configurations studied—cellular circular and hexagonal openings at various locations—Type II achieved the highest ultimate load, while Type I showed the lowest. This information offers valuable insights for optimizing the design of openings in castellated steel beams.

Keywords: Carbon Fiber Reinforced Polymer; Castellated Steel Beam; Finite Element Analysis; Parametric Study; Static Analysis; Structural Strengthening

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Castellated steel beams (CSBs) are widely used in modern construction due to their lightweight design, increased depth, and utility integration capabilities. Web openings in structural elements can introduce stress concentrations, leading to potential failure modes such as flexural failure, web-post buckling, Vierendeel bending, and lateral-torsional buckling.

Due to the fact that this type of beam is lighter than the other with the same measurements and used as a long span system, economically it reduces the cost of steel structures. One of its practical applications is shown in Figure 1.1, where these beams are used as roof supports. Commonly, these provided web holes are utilized to supply service lines such as air ducts, waterlines, sewage lines sprinkler systems, telecommunications, instrumentation cables, heating and cooling systems, fire safety systems, and electrical and data communication systems. When creating a castellated beam, the web portion of an I section is cut along its center line in a zigzag pattern. Without adding or modifying any weight in that beam, the welding process turns and re-joins the split pieces, increasing the depth of an I-section.

This procedure will raise the beam's moment of inertia and section modulus, increasing its strength and stiffness in the process. The web apertures of castellated beams typically have hexagonal, circular, or octagonal shapes. Nonetheless, the castellated beam's structural behavior is completely different from that of a conventional webbed beam because the web portion's apertures could result in a number of failure modes which in turn negatively affect the strength and serviceability requirements of beams. The major failure modes of castellated beam are web-post buckling, flexure mechanism, vierendeel mechanism, rupture of welded joint, local failures under point load, overall lateral torsional buckling in case of laterally unsupported beams as described in (Cyril Thomas & Baskar, 2018). All of these failure types are brought on by the web portion's instability. The performance of the

castellated beam will be enhanced and these kinds of failures will be prevented with an appropriate strengthening procedure. There are different methods for strengthening of this kind of structures. Traditionally the welding of steel plates around openings is used to compensate for the loss of section as outlined in SCI P355(Lawson & Hicks, 2011). This conventional approach induces residual stresses which can weaken the fatigue performance(Shaker & Shahat, 2015). The practical and safety concerns of welding at height are additional drawbacks of this strengthening technique. There are many reasons to strengthen the steel structures such as design errors, construction errors, lack of proper maintenance, fatigue damage, and to increase the structure capability to carry excessive loads.

Investigating the behavior of strengthened castellated beams utilizing CFRP is the primary goal of this work. Strengthening steel structures with CFRP is one of the newer methods for strengthening and restoring steel structures. The reinforcement of steel components has become crucial for structural retrofits in recent years. The use of FRP material for the repair and rehabilitation of steel members hold numerous benefits over the traditional methods of bolting or welding of steel plates. While FRP repairs have also proven to have better fatigue performance compared to welded cover plates (Bocciarelli et al., 2009) concern over environmental durability and galvanic corrosion exists(Lenwari et al., 2006). Fiber reinforced polymers (FRP) are composite materials made up of polymer matrix embedded in high strength fibers such as carbon, aramid, glass, basalt, etc .

Because of its high tensile strength, low weight, high strength to weight ratios, and superior resistance to corrosion and environmental deterioration, CFRP is used more frequently than other materials for strengthening buildings. It is incredibly pliable, can take on a variety of shapes, and is manageable for building. Carbon FRPs (CFRPs) have been used heavily among other FRP materials for strengthening of steel structures, primarily because CFRP materials have relatively higher stiffness.



Figure 1. 1 Roof support beams(SAMEER S. FARES et al., 2016).

1.2 Statement of the Problem

Web openings in structural elements can introduce stress concentrations, leading to potential failure modes such as flexural failure, web-post buckling, Vierendeel bending, and lateral-torsional buckling. To enhance their structural performance, Carbon Fiber Reinforced Polymer (CFRP) composites have been employed due to their high strength-to-weight ratio and corrosion resistance. While existing studies have examined CFRP-strengthened solid steel beams, limited research has been conducted on CFRP-strengthened castellated beams, particularly in understanding the influence of key parameters on their static behavior. Finite Element Analysis (FEA) offers an efficient approach to model and analyze the complex behavior of CFRP-strengthened CSBs under static loading. However, there is a lack of comprehensive parametric studies evaluating the effects of CFRP layers, holes dimensions and opening configuration on the beam's load-carrying capacity and failure mechanisms. Most of the previous studies focused at the effect of normal-modulus CFRP composites configurations and material properties on the flexural and shear strength of the steel beams. Also Experimental and numerical bond characteristics and flexural behavior of ultra-high modulus CFRP strengthened steel girder bridge was studied. This study aims to address these gaps by conducting a parametric static analysis of ultra-high modulus CFRP-strengthened castellated steel beams using FEA.

1.3 Research Objectives

1.3.1 General Objectives

The main objective of this research is to conduct a parametric study on the behavior of CFRP strengthened castellated steel beam subjected to static loads using finite element software package ABAQUS.

1.3.2 Specific Objectives

- ❖ To develop and validate finite element models (FEM) in ABAQUS for comprehensive parametric analysis CFRP strengthened castellated steel beam
- ❖ To evaluate the effect of varying the number of CFRP layers on the structural performance of castellated steel beams
- ❖ To investigate the effect of opening configuration (combination and location) of opening on behavior castellated steel beam
- ❖ To study the impact of height of opening on ultimate strength of castellated beam under static loading condition.

1.4 Research Questions

- ❖ How can finite element models of castellated steel beams be effectively developed and validated in ABAQUS for parametric analysis?
- ❖ What the effect of varying the number of CFRP layers on the structural performance of castellated steel beams?
- ❖ What the effect of opening configuration (combination and location) of opening on behavior castellated steel beam?
- ❖ How does varying the height of web openings influence the ultimate strength of castellated steel beam under static loading conditions?

1.5 Significance of the Research

The suggested research on the parametric study of static analysis of CFRP-strengthened castellated steel beams holds significant importance for advancing structural engineering knowledge and practice. This investigation addresses critical gaps in understanding how Carbon Fiber-Reinforced Polymer (CFRP) strengthening can enhance the performance of castellated steel beams, which are widely used in modern construction for their material efficiency but face challenges due to their unique geometry. By systematically varying the of CFRP layers, holes dimensions and opening configurations(combination &location) through advanced finite element modeling in ABAQUS, this study will provide essential data for optimizing the design of these structurally complex elements.

The steel manufactures get benefits from the study as a source of information and foundation for the construction industry that can help to produce and provide the safest steel beam regarding to strength and simplicity of applying for low consumption of time in installation.

The study as a source of information helps the Structural Engineers to select optimal strengthening solutions based on construction project requirements. These findings offer engineers practical guidelines for balancing lightweight design (through optimized openings) with improved structural capacity (via CFRP), while the perfect bond analysis serves as a theoretical upper limit for assessing real-world adhesive performance

From a broader perspective, this research supports sustainable construction practices by promoting the use of lightweight, high-strength CFRP materials to increase the service life of existing steel structures rather than replacing them. The study's outcomes could influence future revisions of structural design codes and standards, particularly concerning composite-strengthened perforated steel members. By bridging the gap between theoretical knowledge and practical application, this work will provide valuable insights for academic researchers, structural designers, and construction professionals working with innovative material solutions for modern engineering challenges.

1.6 Scope of Study

This study focuses on the static analysis of castellated steel beams strengthened with ultra-high modulus Carbon Fiber Reinforced Polymer (CFRP) using the finite element software ABAQUS. The research involves a parametric investigation of key variables such as web opening configuration, CFRP layers and holes dimensions to evaluate their influence on the beam's structural performance. The scope is limited to nonlinear static analysis under mid-span vertical point loading conditions and the results aim to provide design insights for enhancing the strength and stiffness of castellated beams using CFRP reinforcement.

CHAPTER TWO

LITERATURE REVIEW

Fiber-reinforced polymer (FRP) is used as a strengthening technique in various fields such as civil engineering structures, aeronautical fields, naval industries, etc. (Schnersch & Rizkalla, 2008)(Colombi & Poggi, 2006b). FRP materials have found to be successful for flexural strengthening as well as for shear strengthening in case of concrete structures (Tawfik & Karunasena, 2010; Xia & Teng, 2005). Additionally, steel structures must be improved in terms of fatigue performance, load carrying capability, etc. This can be achieved by using FRPs to reinforce the steel parts. In comparison to all types of FRPs, carbon fiber-reinforced polymer (CFRP) has high strength to weight ratio, resistance to corrosion, lightweight, and easy for installation and therefore used for steel structures (Zhao & Zhang, 2007)(Naser et al., 2014). Steel plate girders are frequently found in bridges and structures because of their deep webs, which provide good flexural capacity and serviceability performance. Because of environmental factors, these members are prone to corrosion and may become weaker. Rehabilitating such areas may be quite challenging.

Traditional rehabilitation methods involve welding stiffeners and steel plates to the broken web. The steel portion might sustain additional damage, though, if the welding procedure raises the temperature. So FRP laminates may offer an attractive alternative in such cases (Abdelmaksoud et al., 2013; Colombi & Poggi, 2006b). One of the most important criteria for the CFRP strengthened steel structures is the bonding between CFRP, adhesive, and steel surfaces(Narmashiri et al., 2011). It is seen that adhesively bonded composite joints can be significantly affected by the service environment: however, this is highly dependent on the joint type and materials involved(Ashcroft et al., 2006).

The behavior of externally bonded (EB) fiber reinforced polymer (FRP), which is utilized to strengthen and retrofit steel buildings, has been the subject of an exceptional research effort in recent years. Even many methods of strengthening structures are available such as: section enlargement, steel plate bonding and external post tensioning method, near-surface mounted (NSM) system and externally bonded (EB) system, strengthening

structures via external bonding of advanced fibre-reinforced polymer composite (FRP) has become very popular worldwide.

Over the last few years there has been much research in the area of using FRP materials to rehabilitate reinforced and pre-stressed concrete. However, very limited research is available in using FRP to strengthen steel structures (Al-Saidy et al., 2007). Bonding the FRP plate to tension flange of steel beams which had high tensile strength leads to increasing the bending moment resistance of the beams (Yu et al., 2011). Also Limited studies on the application of UHM CFRP composites to strengthen steel beams were found. Most research literature available at present on strengthening of steel structures has mainly focused on normal modulus CFRP. The flexural behavior of ultra-high modulus CFRP strengthened steel beams have been experimentally evaluated by (Schnierch & Rizkalla, 2008). Additionally, most existing studies in the literature on the steel beams subjected to fatigue loading involve the use of CFRP laminate but the study on the use of BFRP in fatigue strengthening of steel beam is scarce. Further, most of the studies in this area of research are experimental studies and a few studies that do implement finite element analysis (FEA) have utilized a basic approach for modeling which does not fully capture the nature of composite systems.

A common FRP material for fortifying steel constructions over the last 20 years is carbon fiber reinforced polymer, or CFRP. The main reason CFRP is so popular is due to its comparatively high rigidity when compared to other widely utilized FRP materials. CFRP laminates come in sheets, sections, and pultruded plates for use with steel constructions. Pultruded plates are typically bonded to the steel using a two part epoxy adhesive, while the sheets can be bonded the same way or with a compatible adhesive film (Cadei et al., 2004; M. Liu & Dawood, 2019).

FRP is utilized for structural purposes such as fracture prevention, energy absorption, and bridge construction. The usage of FRP to reinforce steel structures has grown dramatically in recent years. Various steel-structure strengthening procedures need a significant investment of both money and effort. FRP has great strength, Low weight, corrosion

resistant and appropriate for raising exploitation levels. In 2001, one of the first researchers to investigate the impact of FRP on metallic bridges published a paper(X. Liu, 2003; Youssef, 2006).

Numerous experimental, numerical and theoretical investigations into externally bonded carbon fiber polymer (CFRP) with steel components have been conducted; each study focused on a distinct parameter to identify the benefits of this material. Several studies applied CFRP to the bottom flanges of steel sections as a repair or strengthening means. (Deng & Lee, 2007) used different lengths and thicknesses of CFRP ($E = 212\text{GPa}$) in strengthening of ten $127 \times 76 \times 13\text{UKB}$ steel I 'sections of 1100 mm span under either three or four point static bending. It was determined that when CFRP plate thickness increased and its length decreased, the de-bonding mode of failure was initiated at lower load values. The beam that had the longest bonded length (500 mm) and the thinnest CFRP plate thickness (3 mm) had the greatest strength improvement (30%). It should be noted that for all the previous experimental investigations, the beams were laterally supported to prevent lateral torsional buckling.

(Colombi & Poggi, 2006a) tested four steel beams of 2500 mm span under static three-point bending. Two $120\text{ mm} \times 1.4\text{ mm}$ layers of CFRP plate ($E=200\text{GPa}$) were used to strengthen beams and the ends of the CFRP plates were wrapped with CFRP sheets which were extended up along the web to provide anchorage and prevent de-bonding. Even though the testing were stopped before failure, after excessive deflections were observed at mid-span, the results showed that the strength and stiffness achieved an increase of 40% and 14%, respectively over the un-strengthened section.

FRP composites have also been used to prevent web buckling in steel plate-girders by providing additional stiffness to the webs.(Okeil et al., 2009) carried out experimental and finite element (FE) modelling on glass fibre reinforced polymer (GFRP) strengthening applied to the end web panels of plate-girders. According to test results, specimens with GFRP stiffeners positioned vertically and diagonally had respective increases in ultimate load capacity of 1.40 and 1.56 times respectively. The failure in the GFRP-strengthened

specimens was initiated by a breakdown of the steel-GFRP bond followed by immediate out-of-plane buckling of the web.

Some investigations concentrated on CFRP de-bonding since the ability of the adhesive substance to sustain the connection with steel is the primary factor in load transfer between steel and CFRP composite. An experimental study of fatigue failure showed that de-bonding of CFRP plates started in the zones of high stress concentration at the plate ends (Bocciarelli et al., 2009). The bonding failure or delamination between steel and CFRP composite is considered the most common failure due to the weakness of the adhesive bond and the maximum value of the adhesive shear stress occurring at the edges of the FRP sheet (Youssef, 2006; Zhao & Zhang, 2007)

To date, investigations of FRP strengthened steel sections have primarily focused on un-altered, integral sections. The introduction of openings in the web decreases the strength and stiffness of beams which results in larger deflections. This paper presents a novel method to maintain cross-sectional capacity and stiffness through the bonding of CFRP plates. A proposed numerical model capable of capturing key phenomena including de-bonding, built using the finite element programme ABAQUS (2012), has been validated using available experimental results in the literature; namely (Deng & Lee, 2007). The suggested numerical model is then used to simulate CFRP-strengthened steel sections with various web opening locations and strengthening configurations.

Steel Strengthening with Fiber Reinforced Polymer, types of fiber-reinforced Composites, synthetic fiber-reinforced composites, applications of fiber reinforced polymer composite will be discussed in this chapter.

2.2 Steel Strengthening with Fiber Reinforced Polymer (FRP)

As seen in Figure 2.1, fiber reinforced polymer (FRP) is a composite material made up of two parts: fiber reinforcement and polymeric resin (matrix). The fibers enhance the strength and stiffness of the FRP composites whilst the matrix allows the load transfer between the individual fibers, and protects them from mechanical and environmental damage. The

properties of the FRP composite depend on the properties of the matrix and the fiber as well as the fiber volume ratio and the fiber orientation.

Composite materials include multicomponent substances created by combining several materials artificially to get qualities that a single component cannot achieve on its own. The ideal characteristic and application of modern composite materials, which are largely mechanical, is fibers or particles surrounded by another matrix material. Composite materials are made up of multiple layers of components that give them the unique characteristics of a composite material with a specified application. Fibers without a matrix can't withstand a load, but when the matrix is in them, fibers of various compositions are joined by the matrix and give them unique characteristics. Reinforcing materials are often designed to absorb a high load while also providing desired characteristics (Srinivasakumar, 2013).

Advanced composites have become one of the most popular methods of repairing and/or strengthening civil infrastructure in the past couple of decades. The use of Fiber Reinforced Polymer (FRP) laminates plates and fabric for the repair and strengthening of reinforced concrete structures is well established with design guidelines in the form of ACI 440-02(Soudki & Alkhrdaji, 2005)and European fib bulletin 14(Externally Bonded, 2001)The FRP material for the repair and rehabilitation of steel members hold numerous benefits over the traditional methods of bolting or welding of steel plates. FRP materials have the benefits of high strength to weight ratio, corrosion resistance, can be adhesively bonded, and have a stiffness comparable to that of steel. Project costs are reduced due to low transportation and handling costs as well as low application, and labor costs. As compared to traditional repair methods, FRP is less disruptive to regular service during the repair process. Furthermore, repairs that employ FRP contribute minimal additional dead load to the structure. Bonded FRP strengthening also creates less stress concentration as compared to mechanical fastening. While FRP repairs have also proven to have better fatigue performance compared to welded cover plates(Bocciarelli et al., 2009)(b), concern over environmental durability and galvanic corrosion exists (Lenwari et al., 2006).

2.3 Fiber Reinforced Composite Types

Fiber-reinforced composites are often categorized on the basis of the nature of their reinforcement (fibers), and not the matrix. Each type's naming scheme comes after the reinforcement's source. Consequently, there are essentially two kinds of fiber-reinforced composites: synthetic fiber-reinforced composites (SFRC) and natural fiber-reinforced composites (NFRC).

2.3.1 Composite Materials Reinforced with Synthetic Fibers

This is a form of composite material that has synthetic fiber reinforcements. They are often used in applications that need a high strength-to-weight ratio.

The reinforcing fibers in this form of the composite are extracted filaments of traditional materials such as carbon, glass, and basalt, among others. Basalt fiber-reinforced polymer (BFRP), Aramid fiber-reinforced polymer composite (AFRP), Glass fiber-reinforced polymer (GFRP), and carbon fiber-reinforced polymer (CFRP) composites are prominent examples of this composite form widely used in manufacturing (Kopeliovich, 2012).

The comparison of the physical and mechanical properties of natural fibers against synthetic fiber is illustrated in Table 2.1

Table 2. 1 Mechanical properties of synthetic and natural fibers (adopted from (MALKAPURAM et al., 2009; Saba et al., 2015))

Fiber	Density (gr/cm ³)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elastic at Break (%)
Sisal	1.5	511 - 635	9.4 -22	2.0 – 2.5
Jute	1.3	293 - 773	26.5	1.5 -1.8
Pineapple	1.56	170 -1627	60 - 82	2.4
Flax	1.5	500 - 1500	27.6	2.7 – 3.2
Hemp	1.47	690	70	2.0 - 4.0
Kenaf	1.45	930	53	1.6
Cotton	1.5-1.6	400	5.5 – 12	7.0 – 8.0
Carbon	1.4	4000	230 -240	1.4 – 1.8
Aramid	1.4	3000 - 3150	63 - 67	3.3 – 3.7
E-glass	2.55	3400	71	3.4

The most commonly used fiber constituents for FRP in civil engineering applications are glass fiber (resulting in GFRP) or carbon fiber (resulting in CFRP). The research community is beginning to pay attention to more recent naturally generated fibers such as basalt fibers, whereas aramid fiber is another less widely utilized fiber. Materials and costs for these kinds of composites vary greatly. Steel strengthening typically uses CFRP composite because of its similar strength and stiffness to steel. CFRP composite is normally used in steel strengthening because its strength and stiffness are comparable to the steel material. CFRP laminates for application on steel structures are available as pultruded plates, as preimpregnated (prepreg) sheets and as non-impregnated sheets as shown in Figure 2.2. The layup of non-impregnated laminate sheets, though common in concrete strengthening, is typically not used for steel strengthening as the fiber volume fraction, orientation, and other mechanical properties of the final composite are heavily dependent upon the quality of the application process. Pultruded plates are typically bonded to the steel using a two part epoxy adhesive, while the sheets can be bonded the same way or with a compatible adhesive film (Hollaway & Cadei, 2002).

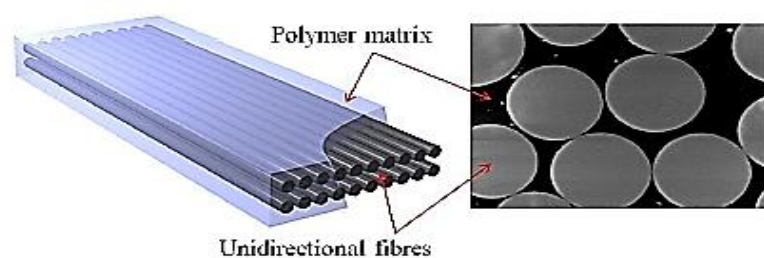


Figure 2. 1 Schematic and microscopy image of FRP composite (adopted from (Mohammed & Abed, 2012))

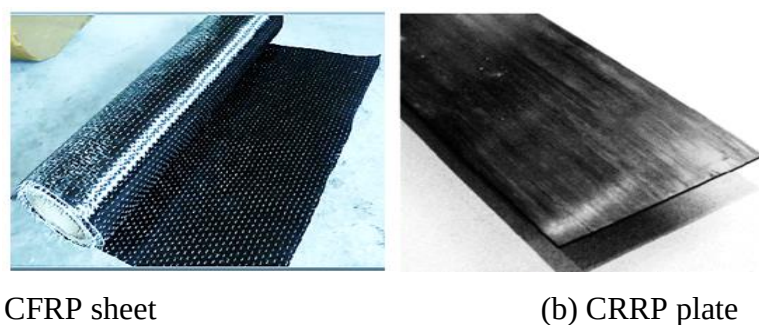


Figure 2. 2 CFRP products used in strengthening

The elastic modulus of commonly used CFRP plates varies from 150 – 450 GPa (21.76×10^6 - 65.27×10^6 psi)(Zhao & Zhang, 2007). Researchers have classified CFRP laminates as "low modulus," "normal modulus with a stiffness less than steel," "high modulus with a stiffness similar to steel," and "ultra- high modulus with a stiffness higher than steel" based on the modulus of the CFRP material.

Therefore, HM-CFRP and UHM-CFRP are preferred in strengthening steel structures hence they will carry the stresses before the steel is yielded. Given that no universally accepted classification system currently exists, the following categorization based on multiples of the modulus of steel, given in Table 2.2 is proposed and adopted in this study.

Table 2. 2 Classification of CFRP according to modulus of elasticity (Zhao & Zhang, 2007)

Category	E_{CFRP} to E_{steel}	E_{CFRP} (GPa)
Low Modulus	$E_{\text{CFRP}} \leq 0.5 E_{\text{steel}}$	≤ 100
Normal Modulus	$0.5 E_{\text{steel}} \leq E_{\text{CFRP}} \leq E_{\text{steel}}$	100-200
High Modulus	$E_{\text{steel}} \leq E_{\text{CFRP}} \leq 2 E_{\text{steel}}$	200-400
Ultra –high Modulus	$E_{\text{CFRP}} > 2E_{\text{steel}}$	> 400

2.3 Applications of Fiber Reinforced Polymer Composite

In general, strengthening of an existing steel structure may be required for a number of reasons e.g. change of use and load requirements, geometric modifications or damage e.g. introduction of web penetrations, loss of section from corrosion etc (Cadei et al., 2004). FRP composite, as previously said, is the preferred material in many reinforcing applications due to its lightweight nature, appropriate strength and stiffness characteristics, and ease of on-site installation. Bonded externally FRP-strengthening is a potent method for increasing the lifespan of structures, particularly steel ones. FRP materials are quick and simple to handle on site with no disruption to facility use, and the total cost of the strengthening operation can be as competitive as utilizing traditional materials. In some circumstances, FRP composites are the only realistic material that could be used for strengthening especially in the places where neither access of heavy machinery is possible nor closure of the facility is practical.

The rising need for FRP composites as efficient engineering materials to meet the vast human needs in various areas has boosted many industrial sectors. Due to the depletion of crude oil reserves and the need for a suitable replacement for synthetic(non-renewable) composites, experimental research and the use of FRP composites, particularly natural (renewable) composites, has been needed(Scarponi et al., 2015). The list of application areas is not fully completed since it contains both consumer and industrial applications.

The enormous advancement in technology in recent years has also sparked the need for stronger and more reliable engineering materials. Although it is commendable to improve a design's cost-effectiveness, it is also vital to prioritize the most critical aspects of the design's potential use, such as reliability, eco-friendliness, and re - usability or recyclability (Al-Oqla & Sapuan, 2014). In advanced engineering applications, like those in the aerospace industry, reduced weight materials of high quality including flexural rigidity are required (Swolfs et al., 2014). Although certain traditional materials include a few of these characteristics, their engineering applications have several drawbacks. In the end, this primarily leads to their replacement. As a result, selecting the right material for an engineering design is a difficult task that necessitates careful consideration(Ashby & Cebon, 1993).

As a result, they are very challenging and useful, based on a detailed understanding of FRP composites' excellent mechanical, thermal, and physical properties. Here are some of the applications of fiber-reinforced polymer composite materials:

Civil infrastructure/building construction: Because of their reducing weight, corrosion resistance and vibration, and high strength properties, FRP composites are becoming a feasible alternative to concrete and in the construction of buildings and bridges. FRP composites can also be used in the production of floor beams.

Automotive: The application of FRP composites can be divided into three categories. The body, frame, and engine all have components. The first two parts were more well-liked than the third one (Mallick, 2007).The vehicle body is designed to reduce total vehicle weight

when making seats, resulting in more energy-efficient vehicles. Structural panels and Fuel water tanks for the floor and exterior, spoilers, axle shafts, helmets, gears, bumpers, body panels, and bearings are just a few of the applications for FRP composite (Mallick, 2007).

Defense: Military applications of FRP composites can be traced back to the early Second World War. This was the product of widespread industrial exploitation. Moreover, it encourages the reduction of repair and maintenance costs due to the possibility of improved fatigue and corrosion resistance, and through good fiber design, it allows aircraft flexibility, aero-dynamism, and aero-elasticity, especially in their aerofoil, tails, and wings(Mallick, 2007).

Aerospace: This sector used FRP composites for structural applications rather than other sectors in the current period. Through the use of FRP composites, the weight is reduced, resulting in increased speed and payload. The A310 aircraft, designed by Airbus in 1987, made extensive use of composite materials. In the meantime, both aircraft's composite tails were made by Airbus A320 in the same year (Mallick, 2007). FRP composites are used to make aircraft wings, stabilizers, seats, floors, helicopter blades, fuselage, landing gears, fuel tanks, and tail plans, among other things (Adams, 1987). In addition, truss structures, payload bay doors, manipulator arms, and remote pressure vessels are all built with FRP composites (Mallick, 2007).

Marine: FRP composites could also be used to make warships, ship hulls, and due to their excellent corrosion resistance characteristics. Many such marine vehicles also have the advantage of being smaller, which aids in acceleration (higher cruising speed). In addition, the fuel economy and maneuverability of marine vessels have been improved. Approximately 90% of all recreational vessels are currently made from composites of glass fiber/polyester or vinyl ester resin (Mallick, 2007).

Domestic: Desks, chairs, railings, toilet panels, internal and external construction products, and furniture springs are only a few of the household items manufactured from FRP composites (Adams, 1987)

Sports, leisure, and recreation: This application is focused on the main issues of weight reduction, design flexibility, and vibration absorption. pole-vaulting and Fish caching sticks, bicycle fasteners, swimming panels, sports shoes, baseball bats for archery bows, skis, golf course shafts, tennis and outdoor tennis rackets, surfing, and skate boards all use specialized materials. FRP composite applications in leisure, recreation, and sports are possible due to their versatility in design (FRP composites), vibration damping, and commonly known reducing weight properties (Adams, 1987)

Electrical and electronics: FRP composites are involved in the manufacturing of electrical equipment such as frames, cables, insulators, transformer housing, and other similar products (Adams, 1987)

Medical Science: FRP composites are used to make bone plates. These plates are used for implantable devices, fracture fixation, and prosthetics, among other things.

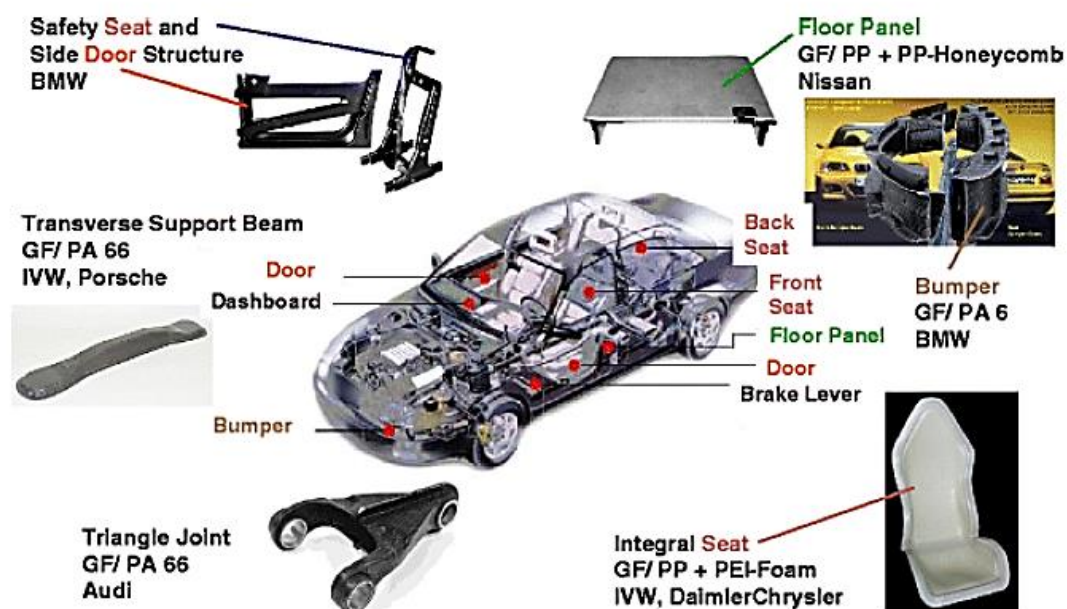


Figure 2. 3 Automotive Applications of Composite Materials (Friedrich & Almajid, 2013)

Most of the previous studies focused at the effect of normal-modulus CFRP composites configurations and material properties on the flexural and shear strength of the steel beams. Also Experimental and numerical bond characteristics and flexural behavior of ultra-high modulus CFRP strengthened steel girder bridge was studied .Therefore, there are no numerical studies conducted on static behavior of CFRP strengthened castellated steel beam .This Thesis will deal with the static behavior of ultra-high modulus (UHM) CFRP strengthened castellated steel beam numerically.

CHAPTER THREE

MATERIALS AND METHODS

The Castellated steel beams are widely used in modern construction due to their light weight design and efficient material utilization. However, the presence of web opening introduces stress concentration, leading to reduced load bearing capacity and potential failure static loads. Due to its high strength-to-weight ratio and resilience to corrosion, carbon fiber reinforced polymer (CFRP) strengthening has become a viable method for improving their structural performance. Furthermore, because experimental testing is expensive, the Finite Element (FE) method can be viewed as an effective alternative that eliminates the difficulties associated with conducting experiments. Nevertheless, the results of finite element modeling cannot be taken into account until they are verified by experimental evidence or theoretical computations. In order to assess the impact of increasing CFRP thickness or the number of CFRP layers, different opening configurations and holes dimensions the study performs a parametric investigation using Abaqus Finite Element Analysis (FEA). This research is about folded two. The finite element modeling of a castellated steel beam using the finite element analysis program ABAQUS is first validated using the experimental results. The second step was a parametric research to determine which CFRP layers, opening configurations and holes dimensions function well when loading is applied.

Therefore, in order to achieve the objective of study, the ABAQUS Software (V6.14) was used to numerically analyze the castellated steel beam and determine how these parameters affected the deflection, ultimate load, and load-deflection curve under static loading circumstances. A brief description of the specimens utilized in numerical analysis is provided in the section that follows.

3.1 Research Methodology

This study was a Parametric consisting of three Castellated steel beam with the same dimensions of specimens tested in the aforementioned study(Al-Thabhwawee, 2017)but with Open spacing and hole depth vary in addition to different opening configuration, CFRP

layers and number of openings . The deflection, ultimate load and load -deflection curve of castellated steel beam were numerically analyzed using Finite element software package ABAQUS (V6.14). Sixteen models of castellated steel beam were studied with varying CFRP layers provided at mid-span region of bottom flange, holes dimensions and opening configurations.

To determine which CFRP layers, opening configuration and holes dimensions had the maximum resistance, stiffness, and minimum failure rate to give the structures the highest level of safety, apply a concentrated load to the center of the model. To accomplish the objective of the research the Finite Element Analysis Abaqus program was used. The general processes involved in the software analysis are depicted in Figure 3.1.

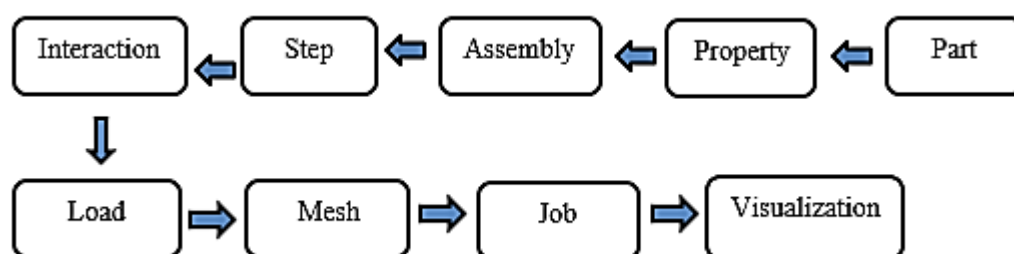


Figure 3. 1 Flow chart of FEM in Abaqus

The numerical analysis of castellated steel beam was done using ABAQUS standard program following the below steps.

- 1) Validation castellated steel beam of specimens tested in the aforementioned study were performed before parametric study of CFRP strengthened castellated steel beam
- 2) From Group 1 of the specimens tested in the aforementioned study CB-1 were used as specimen for parametric study CFRP strengthened castellated steel beam numerically for finite element analysis.
- 3) CFRP strengthened castellated steel beam with stiffeners under point load & support location, opening geometry was created part module in Abaqus

-
4. Elastic-plastic Material properties of castellated steel beam & Elastic properties of CFRP as lamina type and stiffeners were defined in FEA
 5. Section would be created as shell homogeneous for all parts created and assigned for materials defined
 6. Parts were assembled using rotation and translation
 7. In step module General static nonlinear was used in ABAQUS Standard solver
 8. Assembled part were connect by Tie constraints
 9. Load and boundary conditions were assigned with the help of reference point passing through centroid of the section
 10. For CSB, stiffeners, and CFRP sheets, a 4-node doubly curved thin or thick shell, reduced integration (S4R) element was utilized.
 11. Mesh part was made with uniform meshes
 12. In Job module nonlinear analysis of each model was done
 13. Finally, the deflection, ultimate/failure load of each model were extracted & load-deflection curve was plotted.

3.2 Materials

3.2.1 Castellated steel beam

A hot-rolled castellated beam derived from IPE140 steel of steel grade S275JR used in the experimental study was adopted that has yield strengths (f_y), ultimate strengths (f_u) and modulus of elasticity (E_s), poisons ratio through tensile tests are obtained as 279, 432 and 201000 MPa, ,0.3 respectively. The model material non-linearity was considered through a bilinear elasto-plastic response with a 4% strain hardening.

3.2.2 The CFRP Laminate

FRP composites are made of two different components. The ingredients are not soluble in one another and are mixed together at a macroscopic level. One constituent is the reinforcement fiber, which is embedded in the second constituent, a continuous polymer called the matrix (Silwal et al., 2024). Usually stronger and stiffer than the matrix, the reinforcing fibers make up as much as 70% of the compound volume. Three mutually orthogonal planes of material properties make up the unidirectional lamina, with the x direction parallel to the fibers and the y and z directions perpendicular to the x direction. It is therefore regarded as an orthotropic substance. Additionally, this orthotropic material is transversely isotropic, meaning that the FRP composites' characteristics are essentially the same in any direction perpendicular to the fibers. The characteristics in the y and z directions are therefore identical. Thus, this material is so-called a especially orthotropic material (Teng et al., 2015). Researchers adopted various methods to create a bond between the steel and CFRP. The bond can be created by using spring elements with stiffness equal to the initial Young's modulus of the adhesive (Fernando et al., 2009). Otherwise, the solid surface and CFRP surface can form a complete bond through full interaction. The "Perfect Bonding" between CFRP and steel was assumed in this investigation. that is, there is no slip (Silvestre et al., 2008). The full interaction can be assigned to steel surface and CFRP by assigning "tie constraint" where the CFRP material is assumed as isotropic. In order to establish tie constraints, the CFRP shell surface should be regarded as the slave surface and the castellated beam surface as the master surface. By tying the solid surface to the CFRP surface, a perfect connection was taken into consideration for this investigation.

The ultra-high modulus laminates ePLATE HM512, distributed by Mitsubishi Plastics Composites America, Inc. 1382mm x 73mm CFRP laminate of cross sectional area 60mm² were used. In this study as an external strengthening material for the CFRP laminate material properties are given in Table 3.1

Table 3. 1 CFRP Material Properties (Peiris, 2011)

Laminate category	Tensile Modulus(GPa)	Tensile Strength(MPa)	Ultimate Tensile strain
Ultra High Modulus	514	1923	0.00332

3.2.3 Stiffeners

The 8mm thick stiffeners provided at left right support & at mid span under point of load application and its linear elastic properties of is $E= 201000\text{MPa}$, $V=0.3$ will be used.

3.3 Previous Experimental Test Details

The experimental results obtained by (Al-Thabhawee, 2017) is used here as a reference to verify the FE models. Table 1 shows the specimens tested in the aforementioned study. Hot-rolled standard section IPE 140 was chosen as the original section for constructing six specimens of castellated steel beams (CSBs) as well as control beam as seventh specimen. The castellated steel beams (CSB) were fabricated such that three different depth of beams were (218mm), (194mm) and (181mm). Flange thickness was (6.9mm), web thickness was (4.7mm) and span length was (1600mm). The castellation dimensions and notations are shown in Fig. 2. The geometric details and material properties of the parent beam and six castellated beams are summarized in Table (1). Plasma machine is used to cut standard section along its web and re-joint the two pieces by using electrode welding to fabricate a castellated steel beam. The material properties were obtained from tension tests on flat tensile specimens according to (ASTM & others, 2001).

The castellated specimens were divided into two groups based on the number of hexagonal openings. Group1 included three specimens which have eight hexagonal holes, while the remaining three beam specimens which have six hexagonal holes were listed in Group2. In order to avoid any failure modes not required, a transverse stiffeners were installed at mid-span under concentrated forces and at locations of end supports, where all specimens were simply supported.

All specimens were put in test machine with adequate care taken to ensure that beams were correctly placed in the test machine and the mid-span of the beam was in line with the hydraulic jack center line as shown in Figure 3. All specimens were tested by using load machine of (1000 kN) capacity. The load- displacement histories for all specimens load located at the mid-span were obtained in the experimental tests. Such results can be used for the verification of FE models.

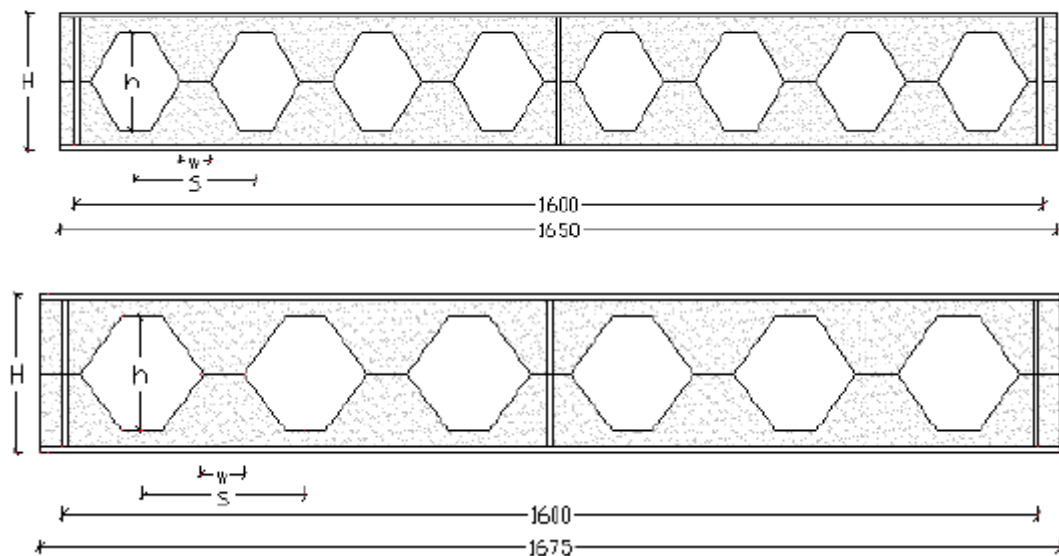


Figure 1 Dimensions and notation of castellated steel beams specimens



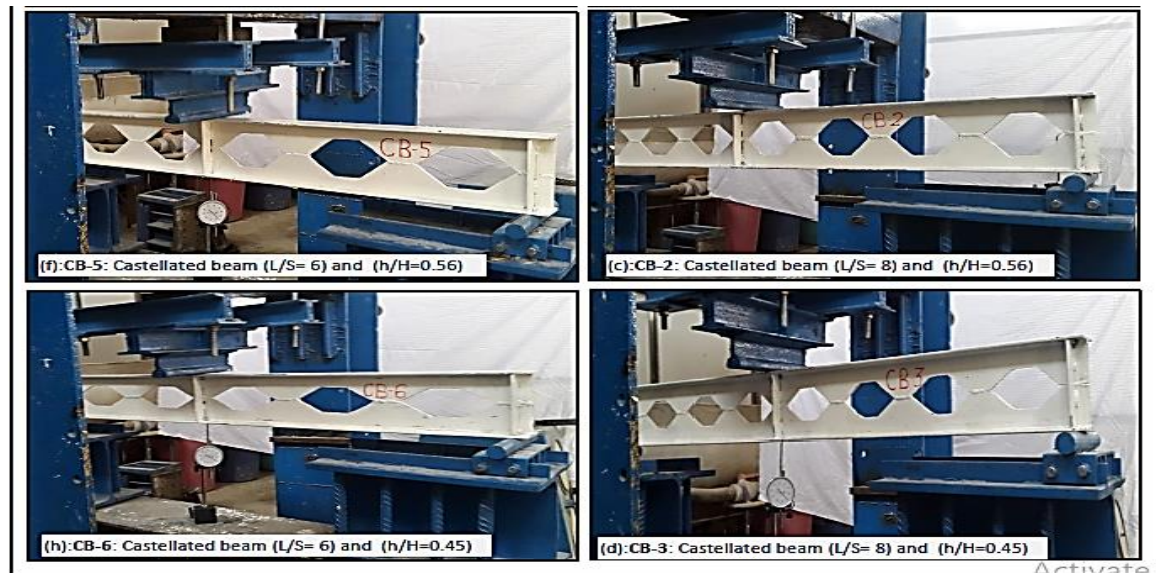


Figure 2 Test setup

Table 1 Dimensional and Material Properties of Specimens

Groups	Specimens	Dimensions(mm)				Material Properties(MPa)		
		H	h	S	w	f_y	f_u	E_s
Control	CB-0	140	----	----	----	279	432	2.01×10^5
Goup-1	CB-1	218	156	200	50	279	432	2.01×10^5
	CB-2	194	108	200	50			
	CB-3	181	82	200	50			
Goup-2	CB-1	218	156	200	50	279	432	2.01×10^5
	CB-2	194	108	200	50			
	CB-3	181	82	200	50			

3.4 Finite Element Modeling

Abaqus/static General is utilized to evaluate the behavior of simply supported castellated steel beams by nonlinear three-dimensional finite element analysis. The analysis's findings were consistent with experimental findings, and the comparison showed good accuracy. Four nodes and an isotropic material attribute define the three-dimensional shell element (S4R). Description of the element S4R can be seen from ABAQUS Analysis User's

Manual(Simulia, 2014). Every node has three degrees of freedom; all of the stiffener, CFRP, and castellated beam were modeled using translation in nodes x, y, and z. Several component instances, including the Castellated steel beam, CRP, and stiffeners used to impart load to the Castellated steel beam, were gathered to create a model of the beam. Both a global coordinate system and independent part instances were present in the assembled model. A network of castellated steel beams was used to extrude the opening. Translation and/or rotation were used to position each part instance within the assembly with respect to the global origin. By considering the surface of the castellated steel beam as the master surface and the surfaces of the stiffeners and CFRP attached to the castellated steel beam as the slave surface, tie constraint characterizes the contact between the castellated steel beam, CRP, and stiffeners. This was used to join two surfaces that are separated so that they were not moving relative to one another. The bonds between the slave and the master in the area of contact limitations were represented by the surface-to-surface interaction. Both the load and the support were then applied. The "Initial" step involves applying support with a rotation/displacement boundary condition. In "Step 1," the load is applied as a concentrated load at midpoint (RP1). The model is then divided into smaller components by choosing the element mesh size in the part instances. In other words, vital model meshing must be used in the finite element analysis. Subsequently, the job was created, allowing for the analysis. *.odb files were used to store the analysis results. The visualization module retrieves data from the output database regarding the outcomes, together with a number of model shapes, including deformed and undeformed shapes. In addition to field output requests, both of these history output requests can be accomplished at a nodal point, in elements, or else in a whole model, depending on the specific output request. The Excel utility option allows you to export data and plotting tools to Microsoft Excel, which can then be plotted in the Abaqus viewport.

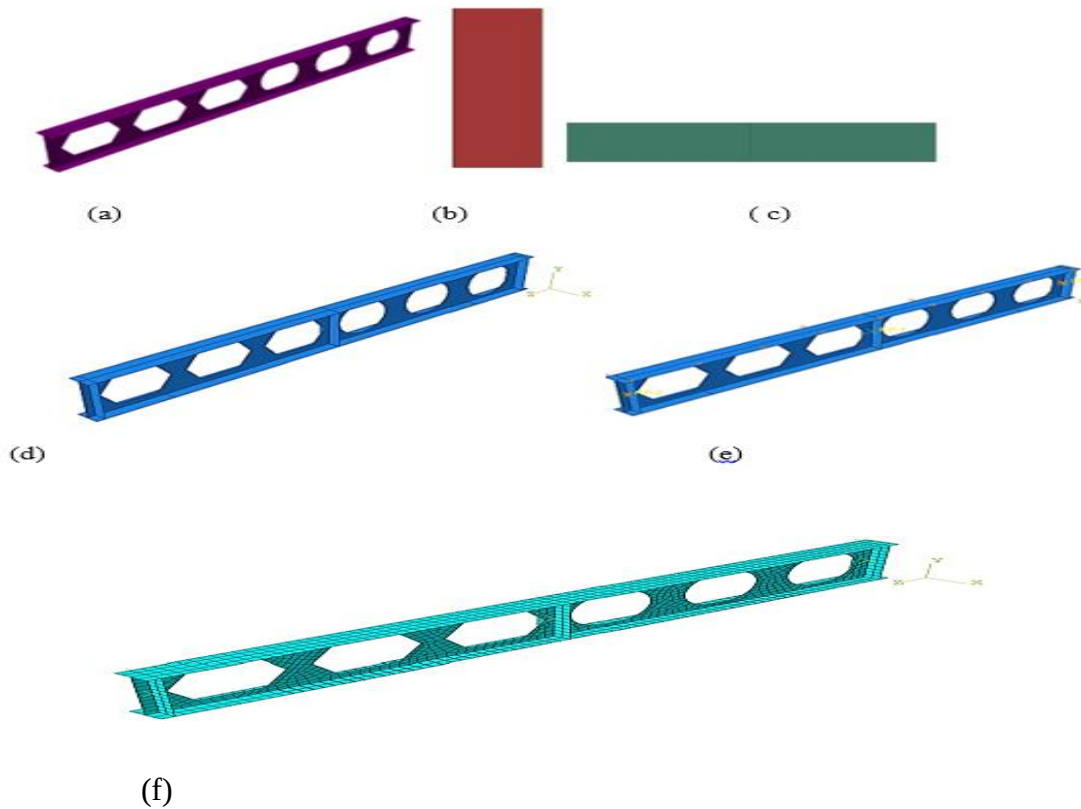


Figure 3. 2 Representation of CFRP strengthened castellated steel beams

(a) Steel beam (b) stiffeners (c) Carbon fiber (d) assembling of part instances (e) steel beams with tie constraint, load and boundary condition (f) mesh formation of castellated steel beam

3.5 Parametric Study

This research employs numerical modeling techniques to investigate the static behavior of simply supported CFRP-strengthened castellated steel beams through finite element analysis using ABAQUS software. Using the ABAQUS (V6.14) computer program, the validated FE model previously presented was used to perform parametric studies on three castellated steel beams with 16 models to examine the effects of the number of CFRP layers, holes dimensions and the opening configuration on the failure load value and mid-span deflection of castellated steel beams under static loading by displacement control method.

The typical hexagon-shaped castellated steel beam from Group 1 (i.e., CB-1) used in this study was seen in Figure 2. A parametric studies was conducted using three specimens (CSB-1, CSB-2, and CSB-3) based on the dimensions previously investigated by (Al-Thabhwah, 2017). As shown in Table 1, the beams all have the cross-sectional dimensions, flange width ($b_f = 73$ mm), flange thickness ($t_f = 6.9$ mm), web thickness ($t_w = 4.7$ mm), width of the web post ($e = 50$ mm), gross depth ($d_g = 218$ mm) and beam span ($L = 1600$ mm). However, as Table 1 shows the hole depth (h_o) and center to center opening distance(s) of castellated beam vary. Because failure by elastic and inelastic local buckling of a single member would not be acceptable in analyzing the global behavior of the examined beams, it is necessary to highlight that the selected beam sections that were analyzed be compact in order to avoid being prone to local buckling. In this study, CFRP Composite placed at the bottom flange in mid-span region of CSBs.

The behavior of structural castellated steel beams were found to be predicted by the finite element model created in section 3.6 above. The cellular-hexagonal castellated steel beams with the circular opening & hexagonal opening size of across corner distance (I),(II) = 184 mm and (III),(IV) = 150 mm (diameter circle) was investigated as shown in Table 3.1 below. In this section 3.5 a detailed parametric study on CFRP strengthened castellated steel beam using the developed finite element model. The parametric study deals with effect CFRP Layers or thickness, opening configuration, holes dimensions.

3.6.1 Mesh and Boundary Conditions

In this study, the approximate global size of 20 mm was used to mesh the considered beam. The boundary conditions are pin-pin with lateral bracing. The beam was assumed to be subjected displacement of 36 mm as point load. To determine the boundary conditions in ABAQUS, linear and rotational at both ends of the beam allowed but displacements were restricted.

3.6.2 Effect of Layers/thickness

For CFRP-strengthened castellated steel beams subjected to mid span point load, the final strength was greatly influenced by the thickness and number of CFRP layers. In this study, CFRP configurations were investigated: 1.2mm (single layer), 2.4 mm (double layer), 3.6mm (triple layer) & 4.8mm (quadruple layer). For investigating the effect of Layers/thickness CSB with various cellular-hexagonal opening configuration was selected & load deflection response were investigated.

3.6.3 Effect of opening configuration

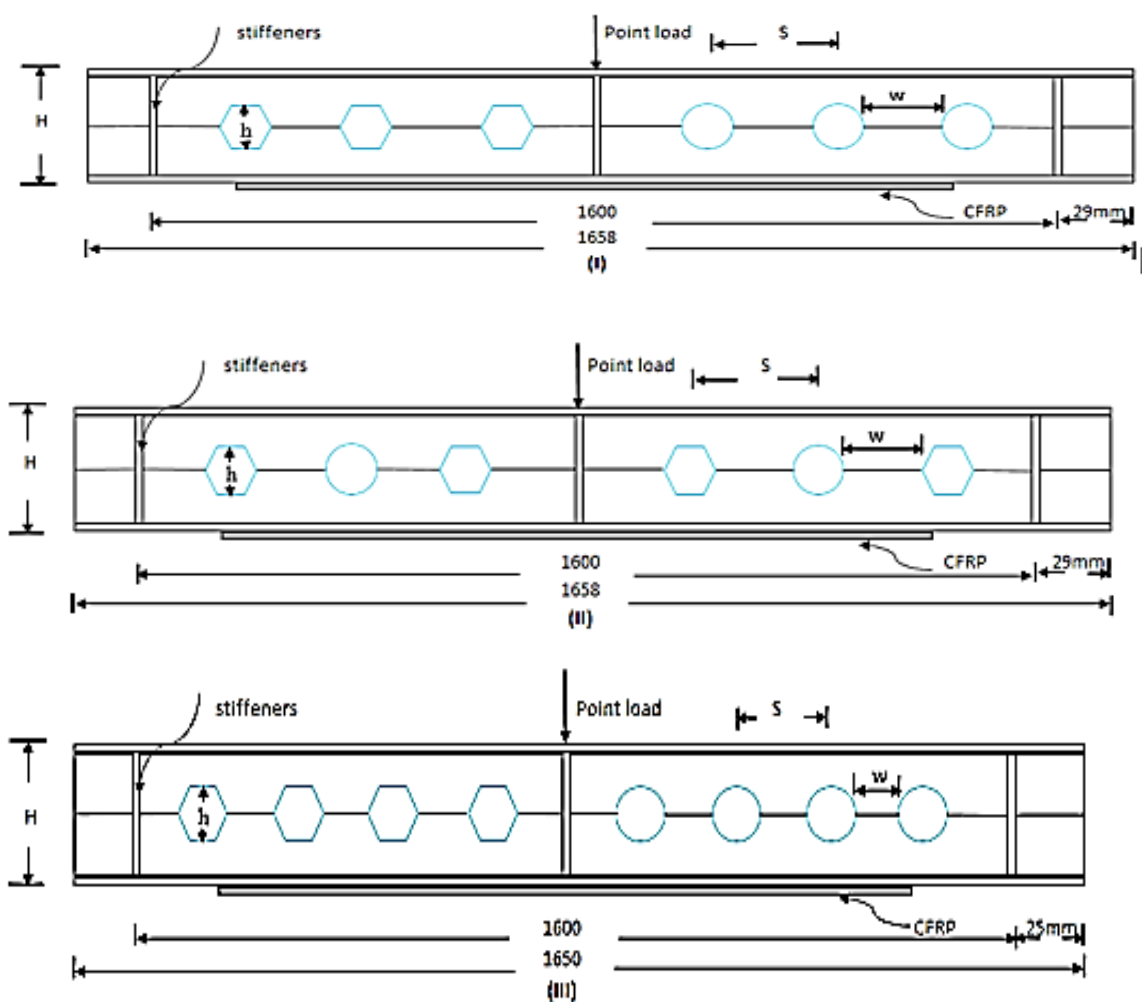
The shape, arrangement, and combination of cellular hexagonal holes have a significant impact on the structural performance of CFRP-strengthened castellated steel beams (CSBs). This study involves four distinct opening configuration-Type I to Type IV under point load at mid span with perfect bond between CFRP and bottom flange of CSB. This hybrid configuration introduces asymmetrical stiffness distribution due to the differing stress concentration around circular and hexagonal openings. The hexagonal holes provide better shear resistance & delayed buckling compared to the circular holes which induce higher localized stresses. However, the CFRP compensates the reduction strength by enhancing the tensile resistance along the bottom flange.

3.6.4 Effect of holes dimensions

The load-deflection response of a CFRP-strengthened castellated steel beam is significantly influenced by holes dimensions. CFRP externally bonded to bottom flange ensures full composite action, allowing it to effectively resist tensile stresses and enhance stiffness. The hole height to depth ratio influences flexural stiffness and deflection while variation cross section area moment of inertia and shear capacity which in turn affects the deflection behavior. Closely spaced holes i.e. smaller ratio of L/S increases the number of stress concentration zones, potentially reducing ductility but wider spacing reduces interaction between holes which leads to global flexural failure.

Table 3.2 Geometric properties of web openings

Opening configuration	Case	Center to center distance(mm)	Hole depth (mm)	Ratio of h/H	Span to center-center spacing(L/S)	Area of opening (mm ²)
Cellular -Hexagonal	(I)	268	156	0.71	6	26982.54
	(II)	268	108	0.49	6	20177.1
	(III)	200	82	0.38	8	10359.06
	(IV)	200	108	0.49	8	17566.2



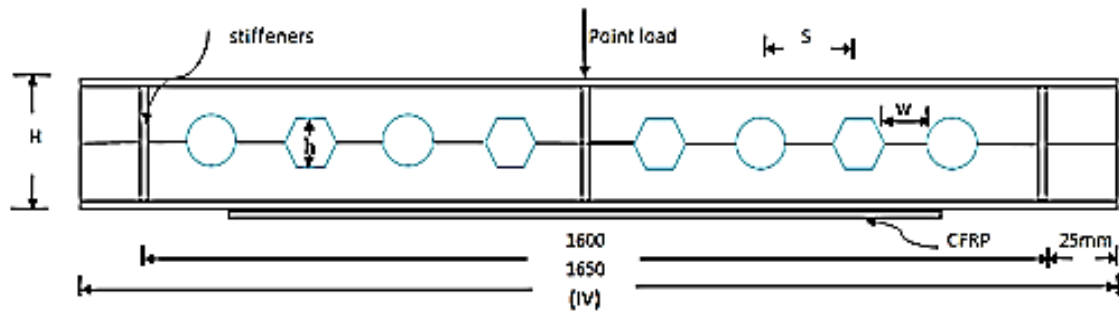


Figure 3. 3 Type of opening configuration for castellated beam; Cellular- hexagonal web opening Type I, II, III & IV

Table 3. 3 Parametric castellated steel beam specimens' details

No	Beam Code	Opening configuration case	Thickness of CFRP(mm)	Number of layers	Location of CFRP
1	CSB-1	(I)	1.2	One layer	Tension side mid-span region
		(I)	2.4	Two layers	Tension side mid-span region
		(I)	3.6	Three layers	Tension side mid-span region
		(I)	4.8	Four layers	Tension side mid-span region
2	CSB-2	(II), (IV)	1.2	One layer	Tension side mid-span region
		(II), (IV)	2.4	Two layers	Tension side mid-span region
		(II), (IV)	3.6	Three layers	Tension side mid-span region
		(II), (IV)	4.8	Four layers	Tension side mid-span region
3	CSB-3	(III)	1.2	One layer	Tension side mid-span region
		(III)	2.4	Two layers	Tension side mid-span region
		(III)	3.6	Three layers	Tension side mid-span region
		(III)	4.8	Four layers	Tension side mid-span region

CHAPTER FOUR

RESULT AND DISCUSSION

This chapter presents the findings from the finite element analysis (FEA) of CFRP-strengthened castellated steel beams, focusing on validation and parametric investigations. The numerical model is first validated against experimental or analytical data to ensure accuracy in predicting structural behavior. A parametric study is then conducted on 16 models to examine the influence of critical variables, including CFRP thickness, opening configuration and holes dimensions. Subsequently, the results are discussed in detail with respect to deflection, ultimate load and load-deflection curve.

4.1 Validation of Castellated Steel Beams

In order to conduct a parametric study, the FE models were verified first against the experimental tests presented by (Al-Thabhwawee, 2017). The Abaqus program was also used to show how variations in vertical deflection at mid-span vs the applied load for all beams until failure were affected by altering the parameters L/S , h/H , and S/H as the depth of the castellated steel beam increases. Furthermore, the outcomes of the FE analysis of the models align with the failure modes of the composite walls identified by the experiment, which were caused by welded joint rupture, local steel beam buckling, and flexural processes.

4.1.1 Load-Deformation Behavior and Deflected Shapes

Figures (4.1) to (4.7) present a comparison between the numerical and experimental load-deformation relationships in which the deformation were measured vertically at the middle web all tested specimens. The comparison revealed the validity of the numerical results obtained from the ABAQUS program by display a reasonable convergence with the experimental outcomes that were already mentioned in Table 3 of (Al-Thabhwawee, 2017) display the experimental and numerical deflected shape for the tested Castellated steel beams until failure load.

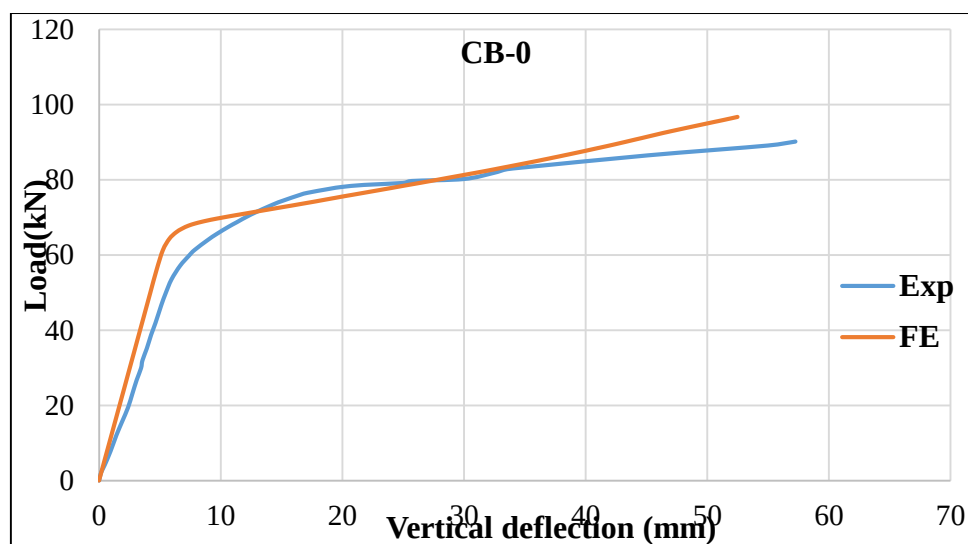
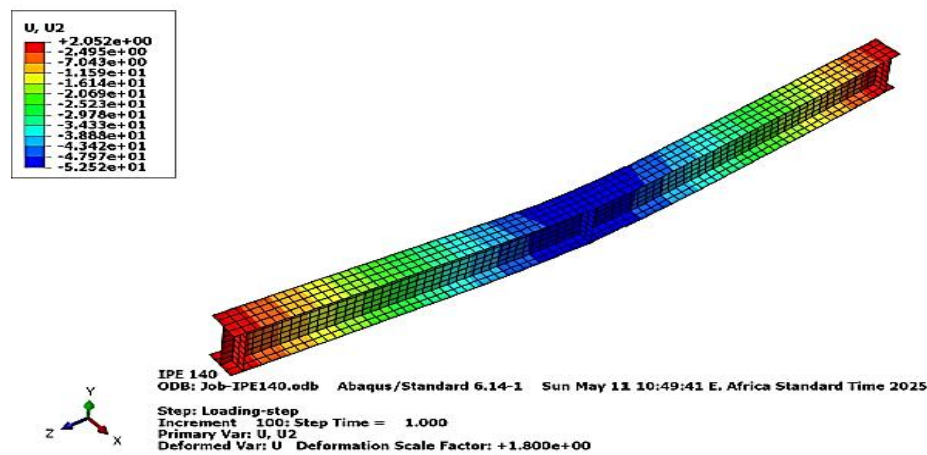
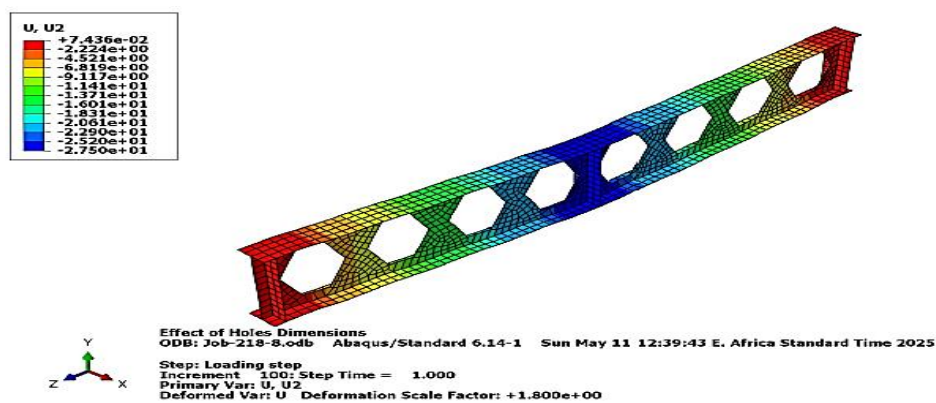


Figure 4. 1 Load versus deflection for model CB-0 without opening



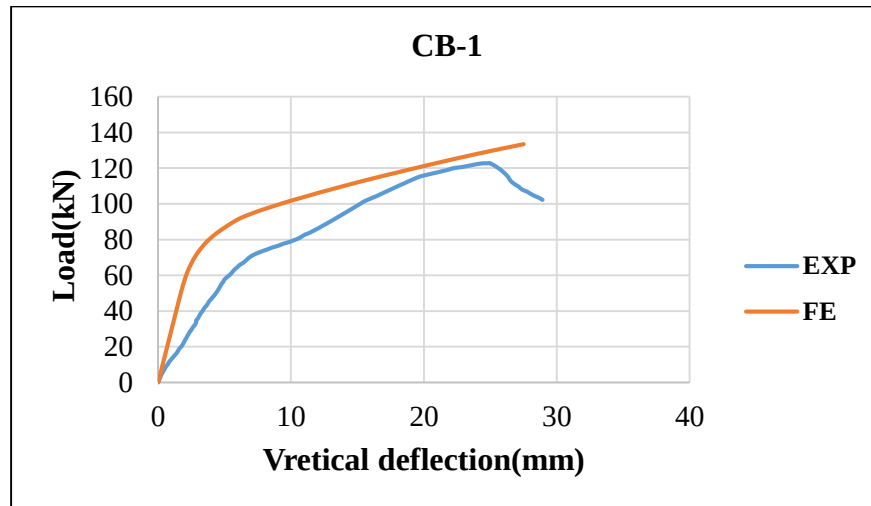


Figure 4.2 Load versus deflection for model CB-1

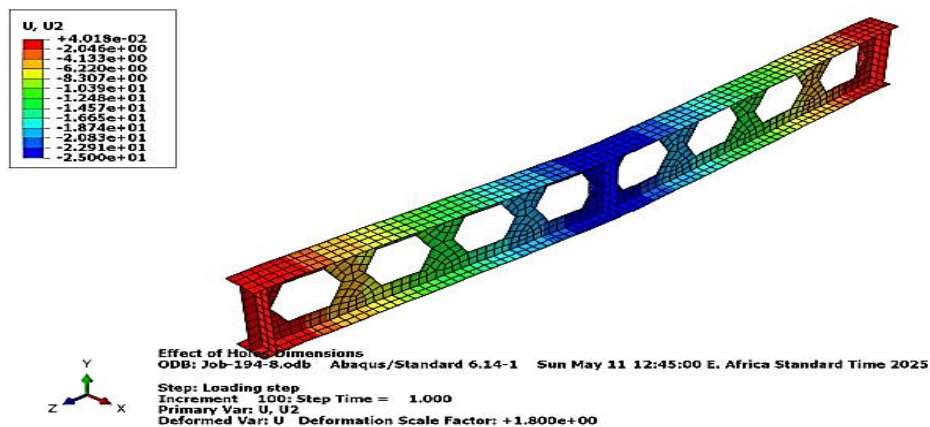


Figure 4.3 Load versus deflection for model CB-2

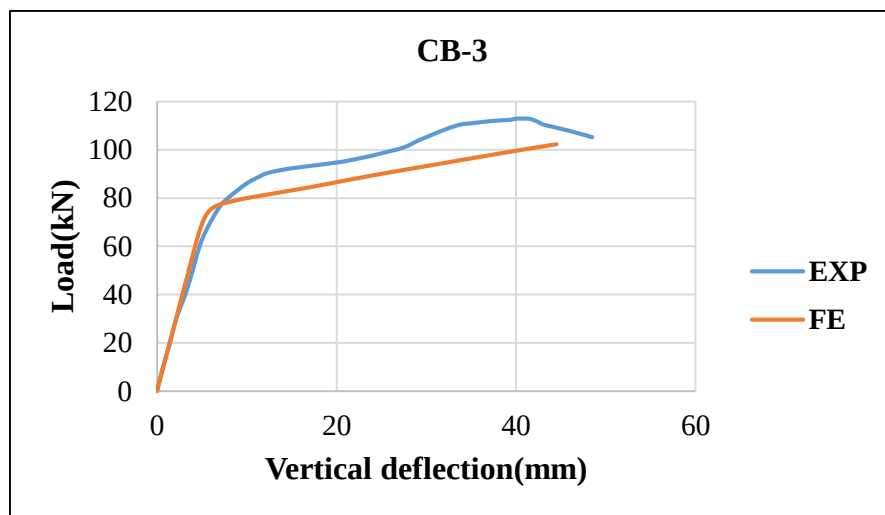
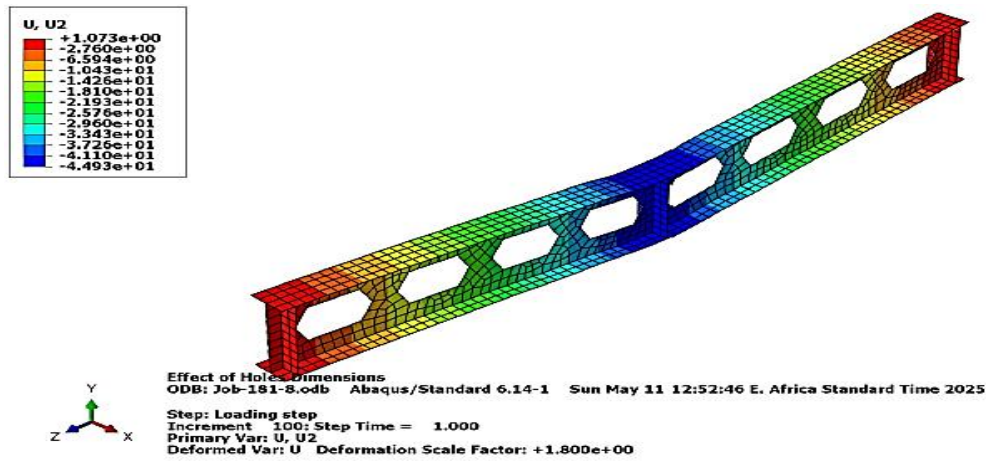
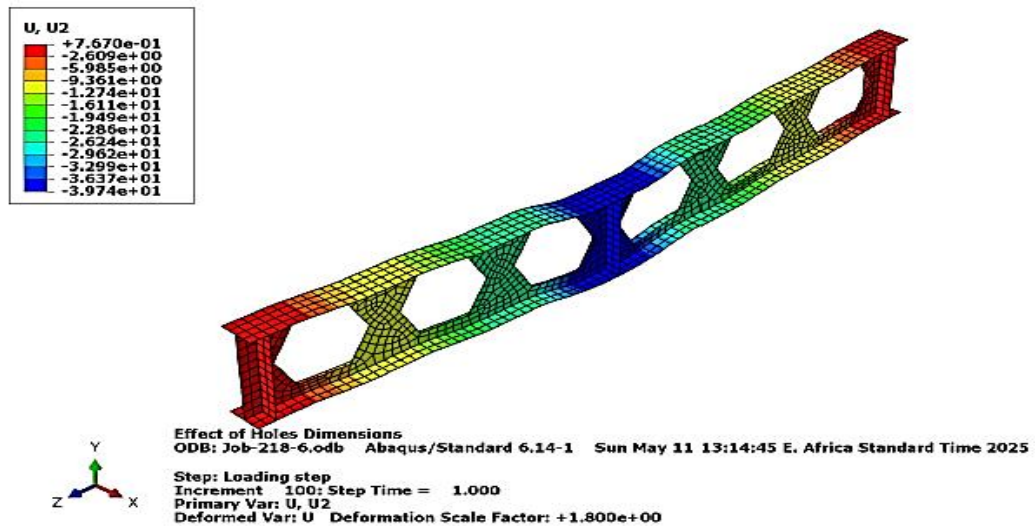


Figure 4. 4 Load versus deflection for model CB-3



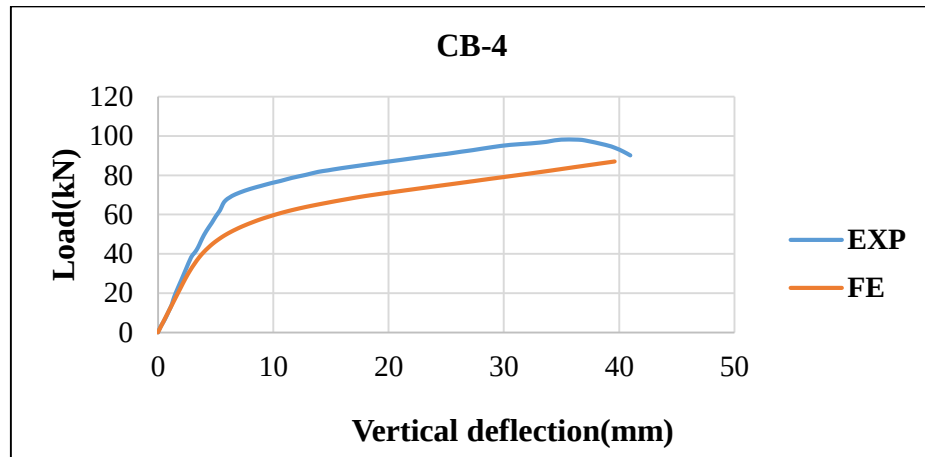


Figure 4. 5 Load versus deflection for model CB-4

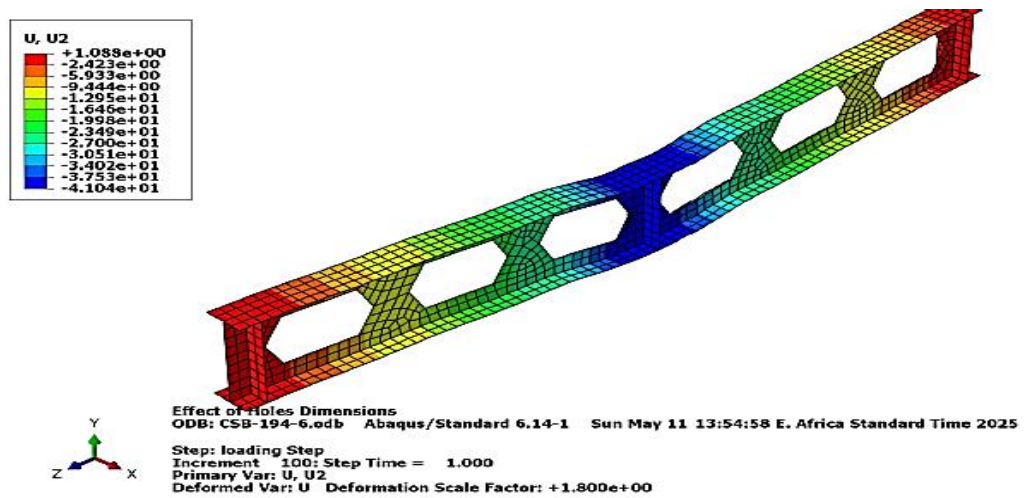


Figure 4. 6 Load versus deflection for model CB-5

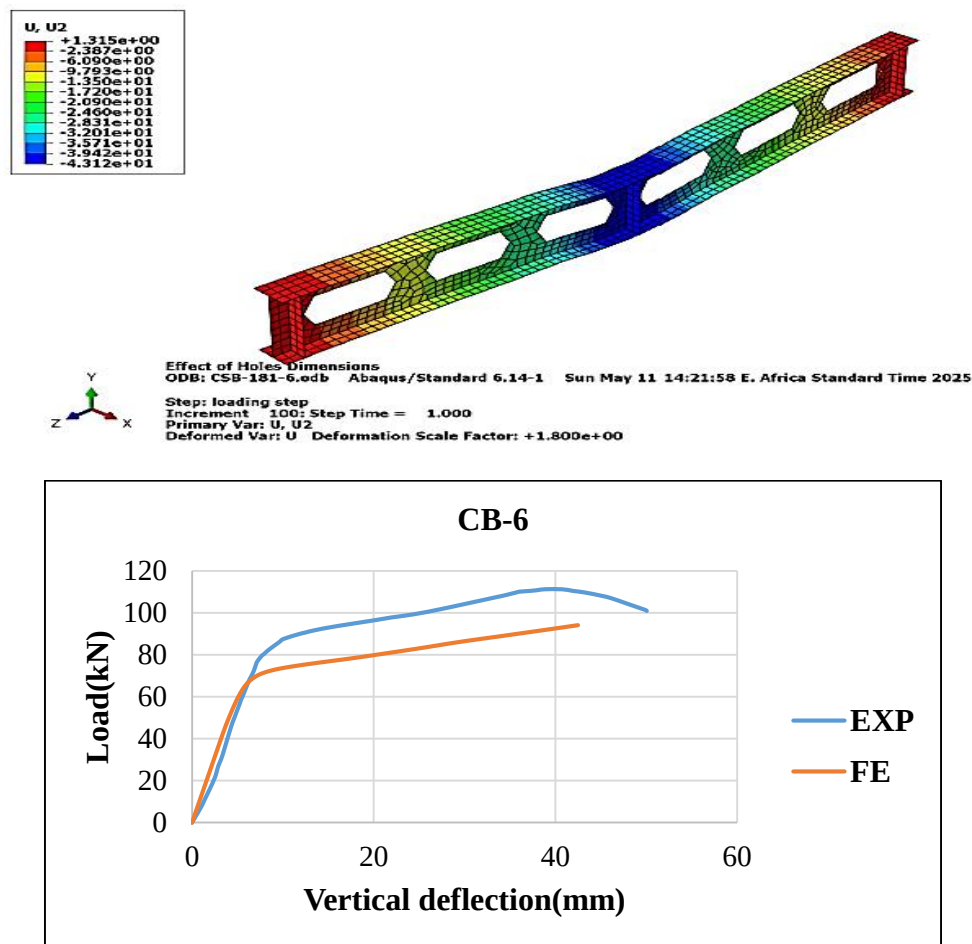


Figure 4. 7 Load versus deflection for model CB-6

4.1.2 Maximum Deformation and Failure Loads

A comparison was made between the numerical values of the ultimate load capacity and maximum deformations that resulted from ABAQUS program, with those obtained experimentally, as given in Table 3 (Al-Thabthawee, 2017). It can be observed that a reasonable agreement was obtained between the numerical and experimental results with slight difference. Thus, several variables that may affect the behavior of castellated steel beam was investigated.

Table 4. 1 Comprehensive experimental & numerical results of all castellated steel beams

Specimens	Experimental output		Numerical output		Error%	
Name	ultimate load	Vertical	ultimate load	Vertical	ultimate load	Vertical
	(kN)	deflection (mm)	(kN)	deflection (mm)	(kN)	deflection (mm)
CB-0	90.5	57.26	96.68	52.5	6.83	8.94
CB-1	122.5	25	133.46	27.5	8.31	10
CB-2	135	23	127.91	25	5.25	8.69
CB-3	112.5	41.39	102.26	44.5	9.10	7.51
CB-4	98	36.28	87	39.59	11	9.12
CB-5	97	38.80	92.37	40.5	4.77	4.38
CB-6	111	40.71	94.127	42.5	15	4.39

4.3 Effect of Layers/thickness

All three specimens were with same mesh size, web thickness, flange thickness, and boundary condition. They also have the same loading condition, which was a displacement-controlled loading condition of 36 mm. The load displacement of the specimens was compared.

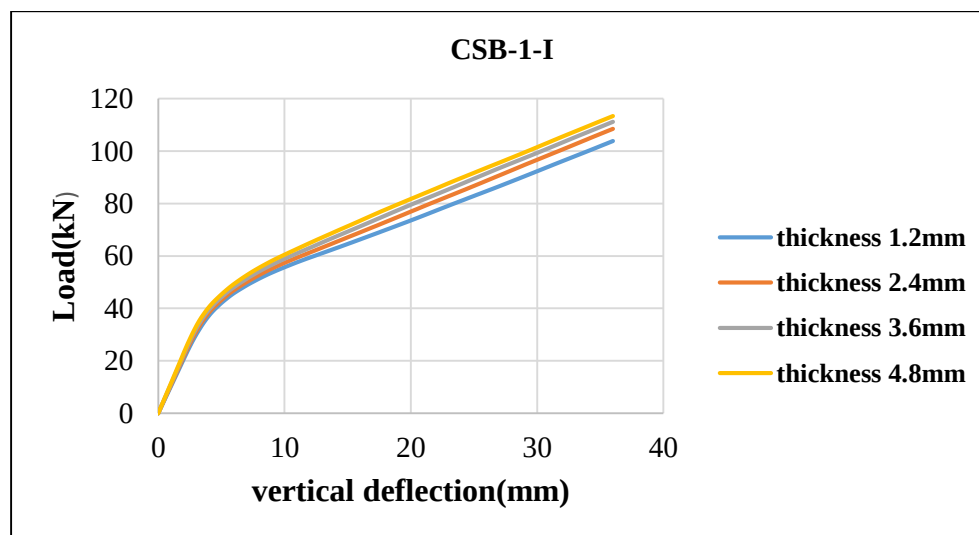


Figure 4. 8 Load versus deflection CSB-1 with different CRFP layer

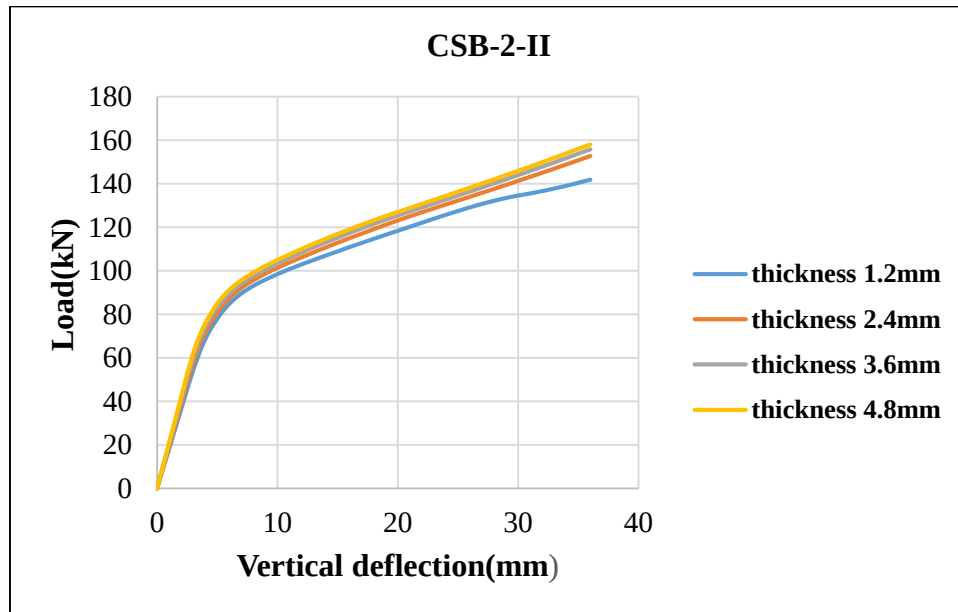


Figure 4. 9 Load versus deflection CSB-2 case type II with different CRFP layer

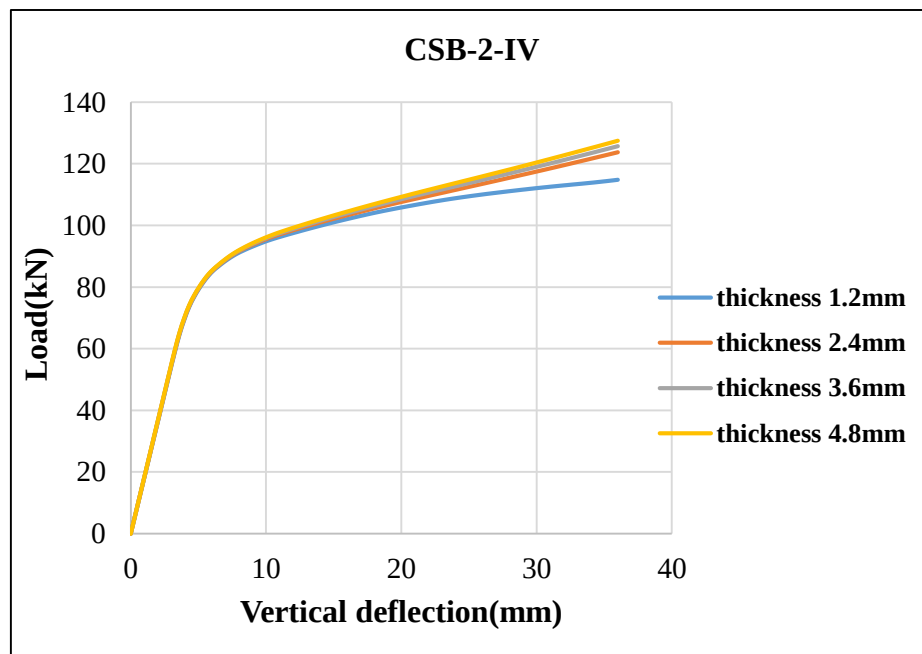


Figure 4. 10 Load versus deflection CSB-2 case type IV with different CRFP layer

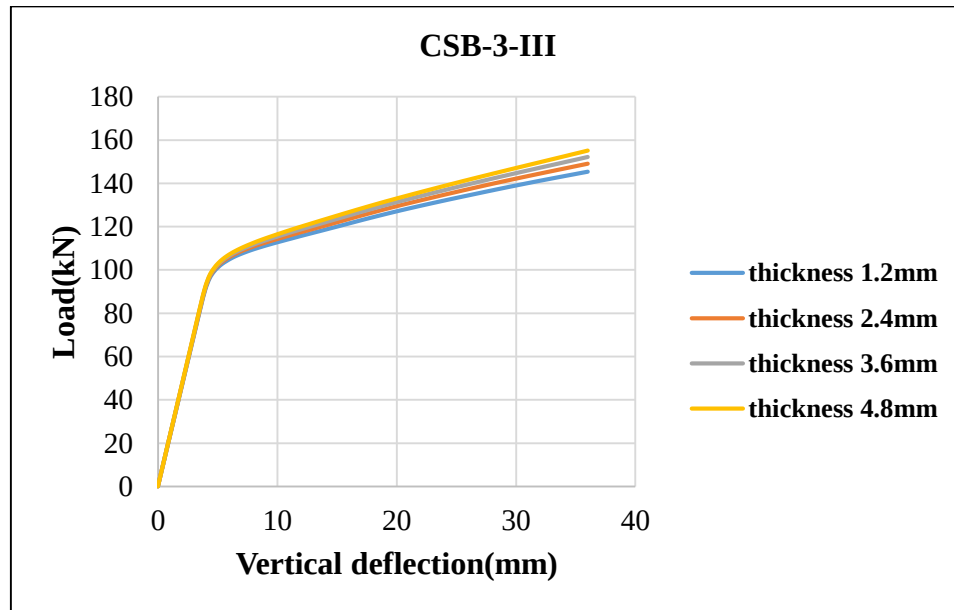


Figure 4. 11 Load versus deflection CSB-3 with different CRFP layer

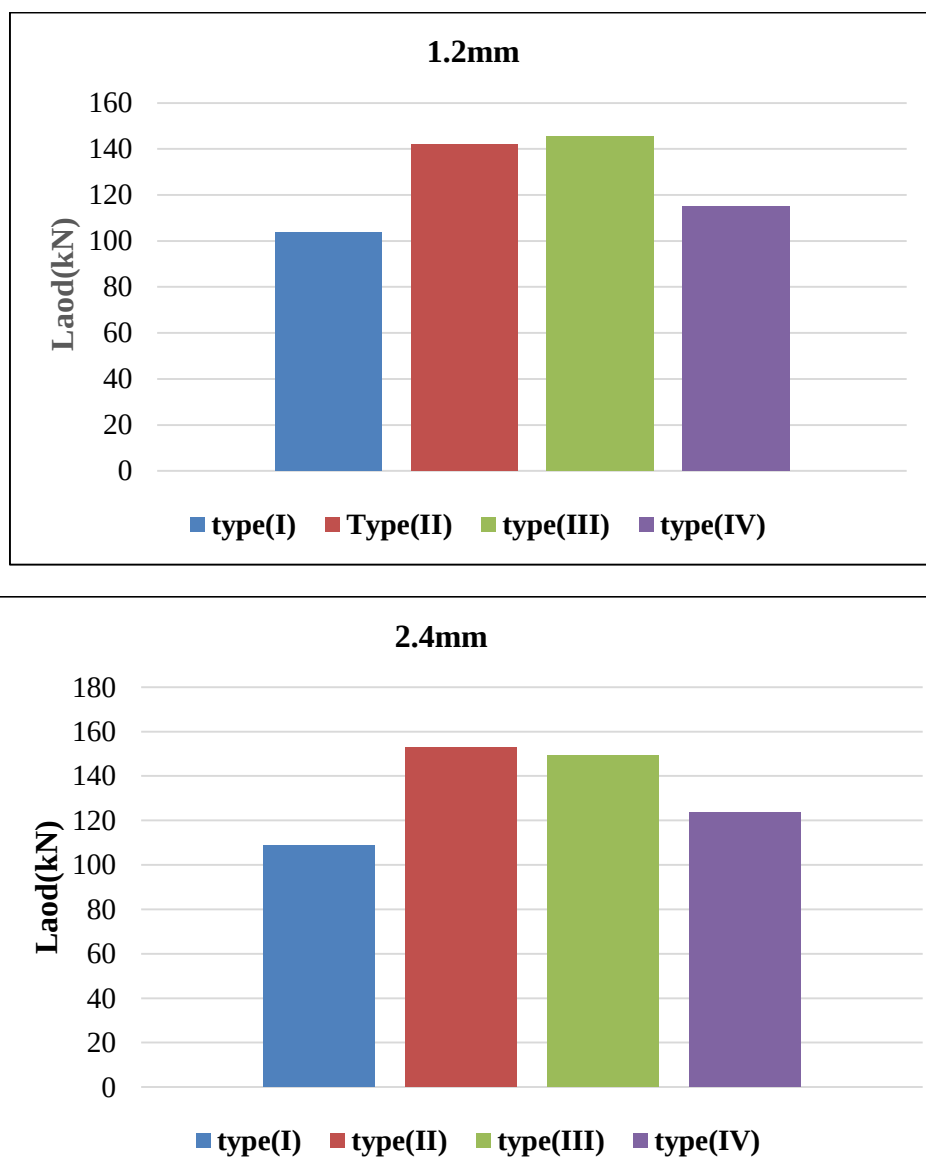
As seen in Figures 4.8–4.11, all specimens exhibit a similar load deflection response; however, there is some variation in their load carrying capacity, particularly between CSB-1–I, CSB-2–II, CSB-2–IV, and CSB-3–III for each one layer of CFRP (which is 8%, 10%, 9.95%, and 6.2% variation with respect to each four layers CFRP strips, respectively). This result shows CSB-1–I , CSB-2–II ,CSB-2-IV and CSB-3–III of each four layer CFRP resists more load than each one layer of CFRP.

Also the load variation between CSB-1–I, CSB-2–II, CSB-2–IV, and CSB-3–III for each two layers of CFRP (which is 4.3%, 3.3%, 2.98%, and 3.9% variation with respect to four layer CFRP strips, respectively). This result indicates CSB-1–I , CSB-2–II ,CSB-2-IV and CSB-3–III of each four layer CFRP resists more load than each two layer of CFRP.

The difference load variation between CSB-1–I, CSB-2–II, CSB-2–IV, and CSB-3–III for each three layers of CFRP (which is 2%, 1.4%, 1.4%, and 1.9% variation with respect to four layers CFRP strips, respectively). This result reveals CSB-1–I , CSB-2–II ,CSB-2-IV and CSB-3–III of each four layer CFRP resists more load than each three layer of CFRP.

4.4 Effect of opening configuration

The load deflection response of the CFRP strengthened castellated beam was investigated under the given loading. In this section, displacement and ultimate load are obtained. The ultimate load values for type of opening configuration case (I)-(IV)) web opening were presented in Figure 4.12.



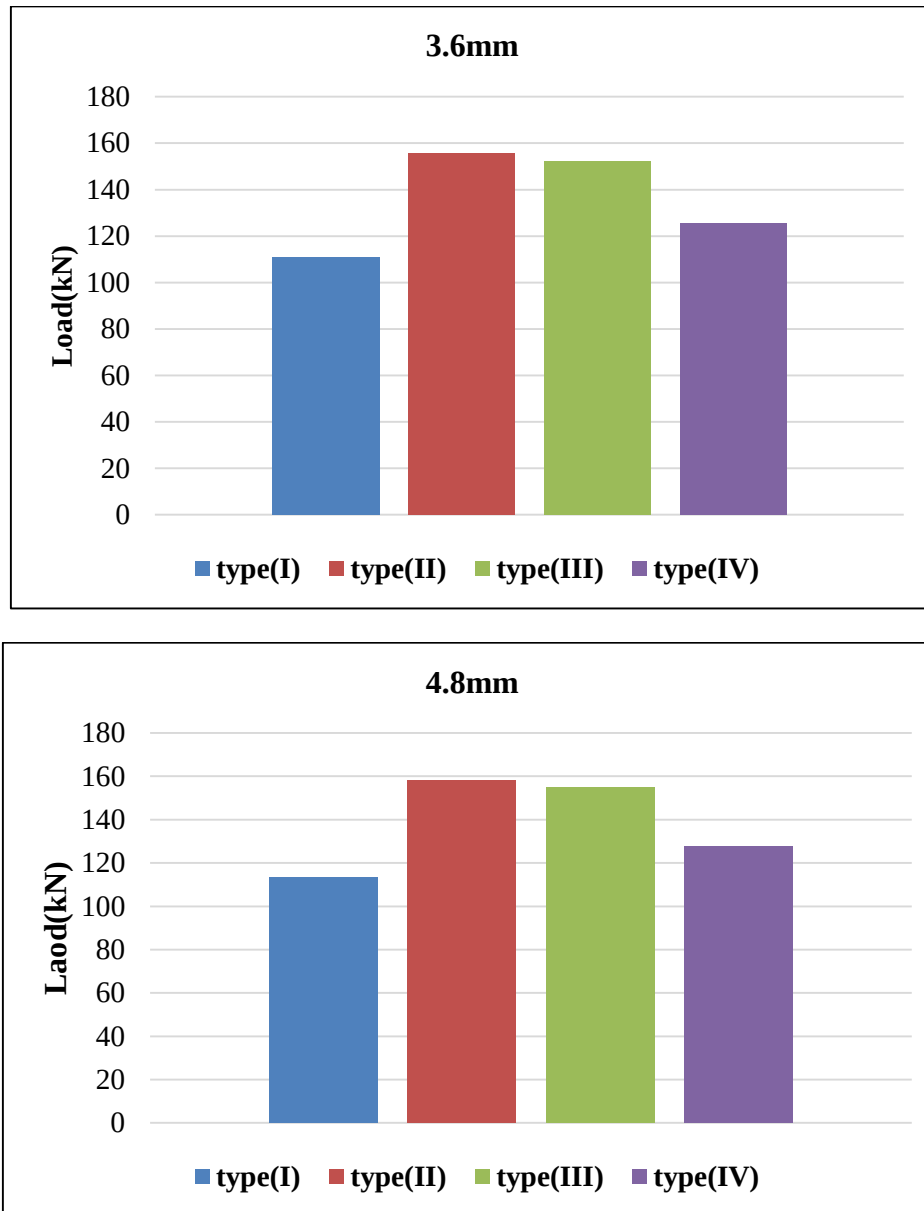


Figure 4. 12 Variation of ultimate load of all model with different opening configuration

From the comparison of the given figure 4.12, it can be clearly seen that the highest ultimate load occurs in type (II), while the lowest ultimate load occurs in type (I). The results of the type II and type III opening configurations got a variation in ultimate load 1.9%. Type II resists more than type III. The results of case type I & case type IV differs in 11% .The case

type IV carry load more than case type I. The value of ultimate load of case type III and case type IV indicates the variation of 17.78%. Case type III resists a larger load.

4.5 Effect of holes dimensions

With varying hole height to depth ratios of 0.71, 0.49, and 0.38, three castellated steel beams were modeled using ABAQUS 6.14. The only changeable hole height to depth ratio has a clear impact on the load resistance of structural castellated steel beams since all three castellated beams have the same mesh size, boundary condition, web thickness, flange thickness, and material attributes. The load versus deflection curve was shown in Figure 4.13 below

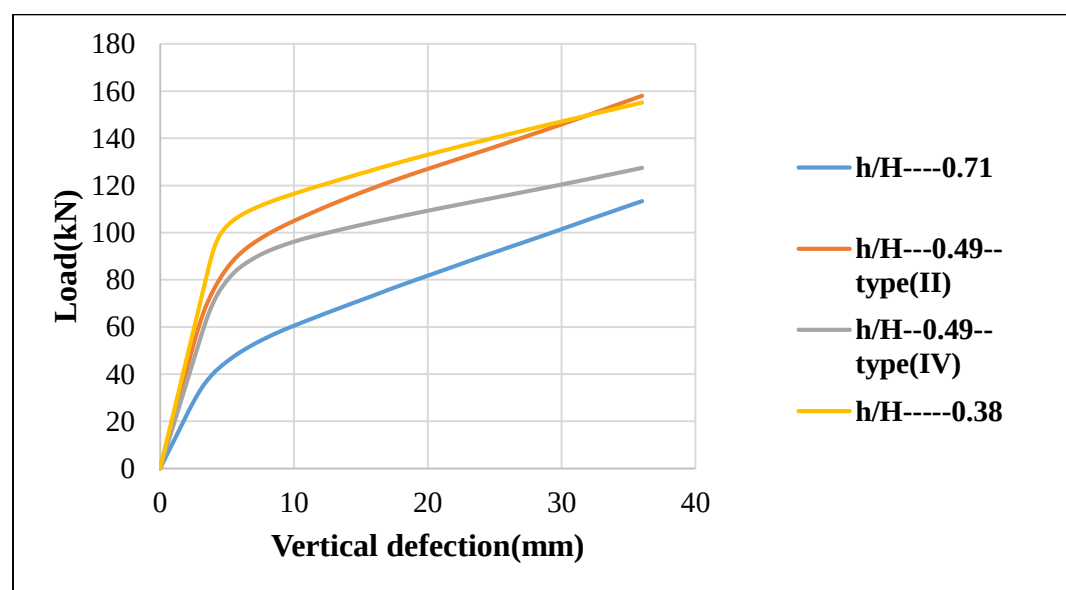


Figure 4. 13 Load versus deflection of all model of 4.8mm with different holes dimensions

Table 4.2 below illustrates the increase in ultimate load carrying capacity for various hole size.

Table 4. 2 Dimensions and FE parametric results of CFRP strengthened specimens

No	Beam Code	Opening configuration case	Thickness of CFRP(mm)	Holes height to depth ratio (h/H)	P _{UI} FE(kN)
1	CSB-1	(I)	1.2	0.71	103.79
		(I)	2.4	0.71	108.46
		(I)	3.6	0.71	111.09
		(I)	4.8	0.71	113.38
2	CSB-2	(II)	1.2	0.49	141.84
		(II)	2.4	0.49	152.79
		(II)	3.6	0.49	155.80
		(II)	4.8	0.49	158.03
		(IV)	1.2	0.49	114.82
		(IV)	2.4	0.49	123.702
		(IV)	3.6	0.49	125.73
		(IV)	4.8	0.49	127.51
3	CSB-3	(III)	1.2	0.38	145.44
		(III)	2.4	0.38	149.09
		(III)	3.6	0.38	152.22
		(III)	4.8	0.38	155.09

From the analysis, it can be concluded for cellular-hexagonal holes ($L/S=6$) as h/H changes from 71% to 49% for CSB-1 and CSB-2 case type II the ultimate load variation is (26.82%, 29%, 28.7%, 28.3%) respectively. Also for cellular-hexagonal holes ($L/S=8$) as h/H changes from 38% to 49% for each layers CFRP the ultimate load variation is (21%, 17%, 17%, 17%) respectively. This indicates that the CFRP-strengthened castellated steel beam's load-bearing capacity decreases with increasing hole height.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objective of this research was to study the numerical analysis of CFRP strengthened castellated steel beams with varying CFRP layers, holes dimensions and opening configurations. A total of sixteen distinct modeling castellated steel beams reinforced with CFRP were examined and graphed, and seven castellated beams were verified against experimental findings. The graphed results clearly depicted the behavior of CFRP strengthened castellated beam for each study variables.

In the present study following points are concluded from the results and discussions:

1. This study successfully developed and validated ABAQUS-based FEM models for CFRP-strengthened castellated steel beams, enabling effective parametric analysis to optimize their structural performance.
2. Application of ultra-high modulus CFRP strips on the bottom flange of castellated steel beams is a successful method for increasing the load capacity and its flexural behavior.
3. When one layer of ultra-high modulus CFRP strips are attached on bottom face CSB the load carrying capacity of strengthened castellated steel beam is increased up to 10% compared to four layers of CFRP
4. When two layers of ultra-high modulus CFRP strips are attached on bottom flange of CSB the load carrying capacity of strengthened castellated beam is increased up to 4.3% as compared to four layers of CFRP
5. When three layers of ultra-high modulus CFRP strips are attached on bottom face CSB the load carrying capacity of strengthened castellated steel beam is increased up to 2% compared to four layer of CFRP
6. Application of thicker ultra-high modulus CFRP strips causes significant increment in the load carrying capacity.
7. As the thickness of ultra-high modulus CFRP strips increases the ultimate load strengthened castellated beam increases as compare four layer CFRP strips.

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8. So CFRP strengthening technique is the best method compare to other conventional methods to improve the performance of castellated steel beam.
 9. The largest vertical load occur in case type II, while the lowest vertical load occur in case I.
 10. Type II resists more than type III, the case type IV carry load more than case type I and case type III resists a larger load
 11. As the hole height decreases the ultimate strength of the CSB increases

5.2 Recommendations

The present parametric study evaluated the flexural strength ultra-modulus CFRP strengthened castellated steel beam on bottom flange side. Future work should consider the following suggestions regarding the suggested model and the nonlinear finite element programs.

1. Study numerically the behavior of castellated steel beams with strengthened openings by CFRP product
2. Although the suggested model is effective for a broad range of parameters, this investigation ought to be expanded to include opening configurations other than cellular-hexagonal.
3. Investigate the behavior of various boundary conditions extended beyond hinged-hinged of castellated steel beams
4. Study numerically the behavior of castellated steel beams strengthened by normal modulus and high modulus CFRP product
5. Explore flexural behavior of castellated steel beam with and without CFRP materials

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APPENDICES

Appendix Table A 1: Other European Structural Steel Sections

Poutrelles en I à ailes parallèles (suite)

Dimensions: EN 10365: 2017

Tolerances: EN 10034: 1993

Etat de surface: conforme à EN 10163-3: 2004, classe C, sous-classe 1

Parallel flange I sections (continued)

Dimensions: EN 10365: 2017

Tolerances: EN 10034: 1993

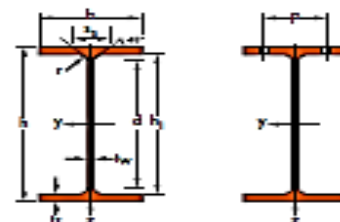
Surface condition: according to EN 10163-3: 2004, class C, subclass 1

I-Träger mit parallelen Flansflächen (Fortsetzung)

Abmessungen: EN 10365: 2017

Toleranzen: EN 10034: 1993

Oberflächenbeschaffenheit: gemäß EN 10163-3: 2004, Klasse C, Untergruppe 1



Désignation Designation Bezeichnung	Dimensions Abmessungen						Dimensions de construction Dimensions for detailing Konstruktionsmaße						Surface Oberfläche	
	G kg/m	h mm	b mm	t _f mm	t _w mm	r mm	A mm ² x10 ²	h ₁ mm	d mm	g mm	p _{max} mm	r _{max} mm	A _f m ² /m	A _w m ² /t
IPEA 240*	24,9	236,4	120	4,8	8,0	15	21,7	220,4	190,4	M 12	64	68	0,917	26,86
IPEA 240-	26,2	237	120	5,2	8,3	15	22,3	220,4	190,4	M 12	64	68	0,918	25,10
IPE 240	20,7	240	120	6,2	9,8	15	29,1	220,4	190,4	M 12	66	68	0,922	20,02
IPE-O 240*	24,2	242	122	7,0	10,8	15	42,7	220,4	190,4	M 12	66	70	0,932	27,17
IPEA 270-	30,7	267	135	5,5	8,7	15	29,2	242,6	219,6	M 16	70	72	1,027	22,75
IPE 270	26,1	270	135	6,6	10,2	15	45,9	242,6	219,6	M 16	72	72	1,041	28,86
IPE-O 270*	42,2	274	136	7,5	12,2	15	52,8	242,6	219,6	M 16	72	72	1,051	24,88
IPEA 300-	36,5	297	150	6,1	9,3	15	46,5	278,6	248,6	M 16	72	86	1,156	21,65
IPE 300	42,2	300	150	7,1	10,7	15	52,8	278,6	248,6	M 16	72	86	1,160	27,46
IPE-O 300*	49,2	304	152	8,0	12,7	15	62,8	278,6	248,6	M 16	74	88	1,174	22,81
IPEA 330-	43,0	327	160	6,5	10,0	18	54,7	307,0	271,0	M 16	78	96	1,250	29,09
IPE 330	49,1	330	160	7,5	11,5	18	62,6	307,0	271,0	M 16	78	96	1,254	25,52
IPE-O 330*	57,0	334	162	8,5	13,5	18	72,6	307,0	271,0	M 16	80	98	1,268	22,24
IPEA 360-	50,2	357,6	170	6,6	11,5	18	64,0	334,6	298,6	M 22	86	88	1,351	26,91
IPE 360	57,1	360	170	8,0	12,7	18	72,7	334,6	298,6	M 22	88	88	1,352	22,70
IPE-O 360*	66,0	364	172	9,2	14,7	18	84,1	334,6	298,6	M 22	90	90	1,367	20,69
IPEA 400-	57,4	397	180	7,0	12,0	21	72,1	372,0	321,0	M 22	94	98	1,464	25,51
IPE 400	66,2	400	180	8,6	13,5	21	84,5	372,0	321,0	M 22	96	98	1,467	22,12
IPE-O 400*	75,7	404	182	9,7	15,5	21	96,4	372,0	321,0	M 22	96	100	1,481	19,57
IPE V 400*	84	408	182	10,6	17,5	21	107,0	372,0	321,0	M 24	96	100	1,487	17,70
IPEA 450-	67,2	447	190	7,6	13,1	21	85,6	420,8	378,8	M 24	100	102	1,602	22,87
IPE 450	77,6	450	190	9,4	14,6	21	98,8	420,8	378,8	M 24	100	102	1,605	20,69
IPE-O 450*	92,4	456	192	11,0	17,6	21	117,7	420,8	378,8	M 24	102	104	1,622	17,56
IPE V 450*	107	460	194	12,4	19,6	21	132,0	420,8	378,8	M 24	102	104	1,625	15,78
IPEA 500-	79,4	497	200	8,4	14,5	21	101,1	468,0	426,0	M 24	100	112	1,741	21,94
IPE 500	90,7	500	200	10,2	16,0	21	115,5	468,0	426,0	M 24	102	112	1,744	19,23
IPE-O 500*	107	506	202	12,0	19,0	21	136,7	468,0	426,0	M 24	104	114	1,760	16,40
IPE V 500*	129	514	204	14,2	22,0	21	164,1	468,0	426,0	M 27	104	114	1,780	12,81

- Commande minimale pour S235 JR, cf. conditions de livraison page 8, pour toute autre qualité d'acier sous-entendu.
- Commande minimale 50t par profilé et qualité ou suivant accord.
- Minimum order for the S235 JR grade of delivery conditions page 8, for any other grade d'acier or upon agreement.
- Minimum order: 50t per section and grade or upon agreement.
- Minimum storage and delivery conditions upon agreement.
- Mindestbestellmenge für S235 JR gemäß Lieferbedingungen Seite 8, für jede andere Güte d'acier oder nach Vereinbarung.
- Mindestbestellmenge: 50t pro Profil und Güte oder nach Vereinbarung.
- Mindestbestellmenge und Lieferbedingungen nach Vereinbarung.

Appendix Table A 2: Performance Table

e-plate

■ High-intensity grade

	GM212	GM510	GM512	GM515	GM520	GM1012
Young's modulus (kN/mm ²)	170(156)					
Tensile strength (N/mm ²)	2,400					
Thickness (mm)	1.2	1.0	1.2	1.5	2.0	1.2
Width (mm)	25	50	50	50	50	100
CFRP cross-section area (mm ²)	30	50	60	75	100	120
Weight (g/m)	48	80	97	120	160	194

■ High-elasticity grade

	HM512	HM520	HM1020	HM1040	HM1440
Young's modulus (kN/mm ²)	450				
Tension strength (N/mm ²)	1,200				
Thickness (mm)	1.2	2.0	2.0	4.0	4.0
Width (mm)	50	50	100	100	140
CFRP cross-section area (mm ²)	60	100	200	400	560
Weight (g/m)	109	182	384	728	1,014

Appendix Table B 1: Ultimate load for the beams with various layers of CFRP

Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

In this section Ultimate load for the beams with various layers of CFRP were illustrated by Figures (B1-B16)

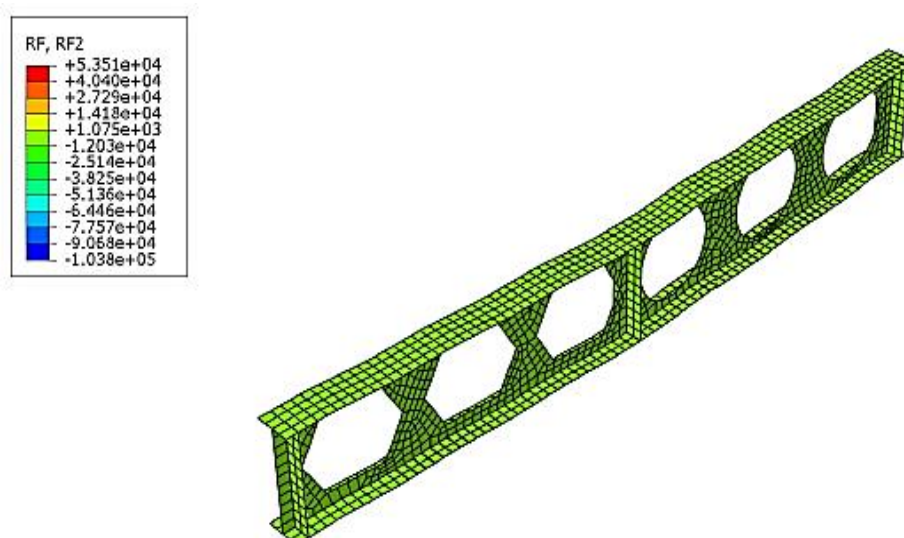


Fig. (B.1): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

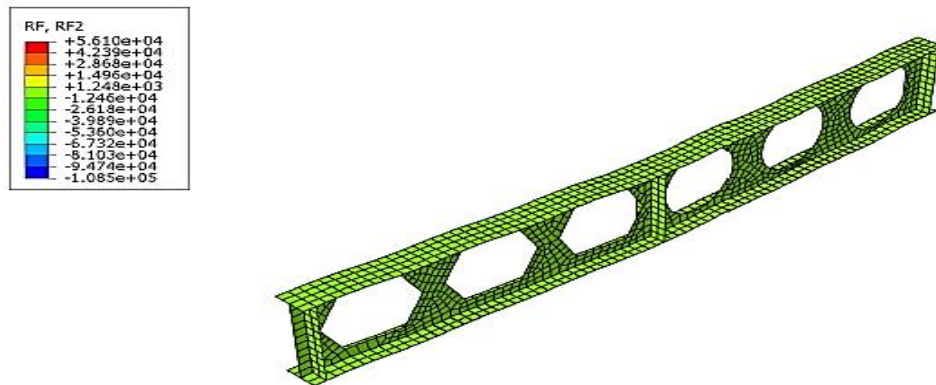


Fig. (B.2): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

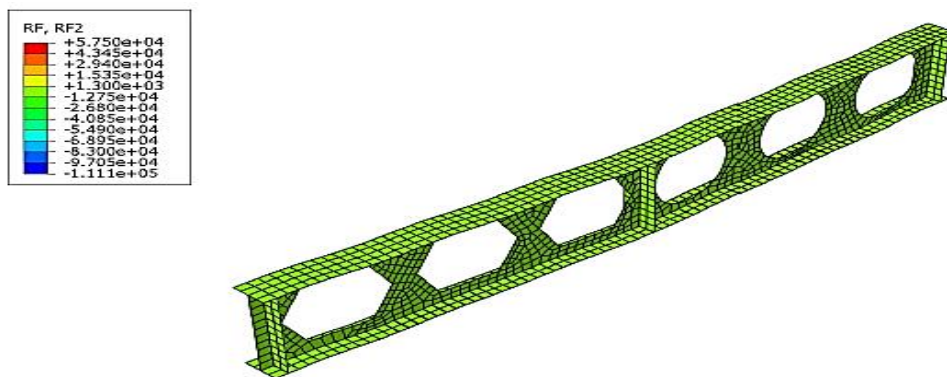


Fig. (B.3): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

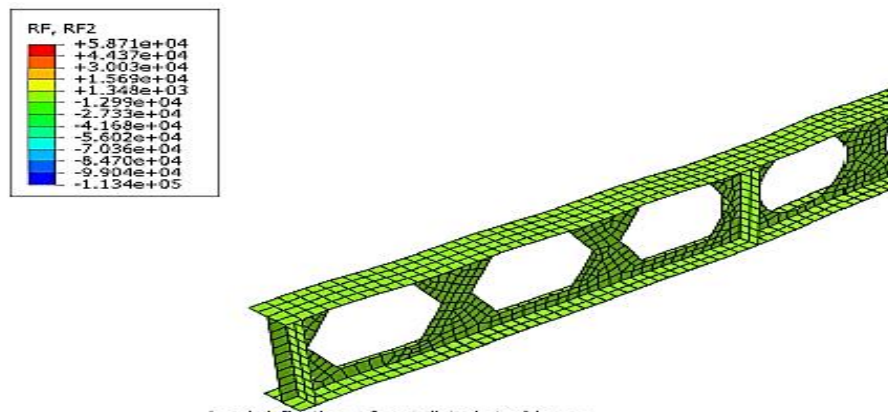


Fig. (B.4): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

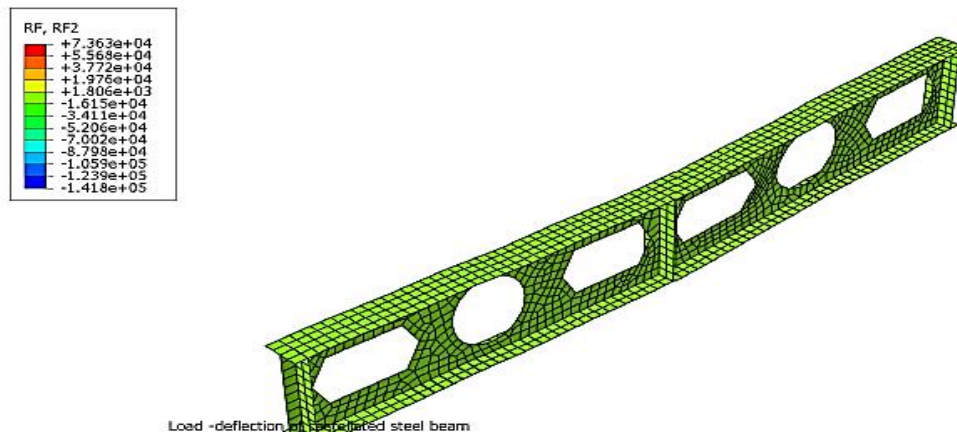


Fig. (B.5): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

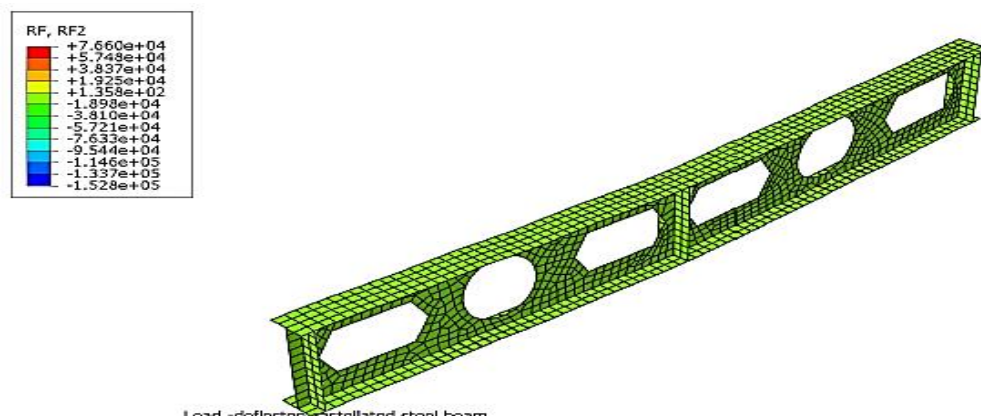


Fig. (B.6): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

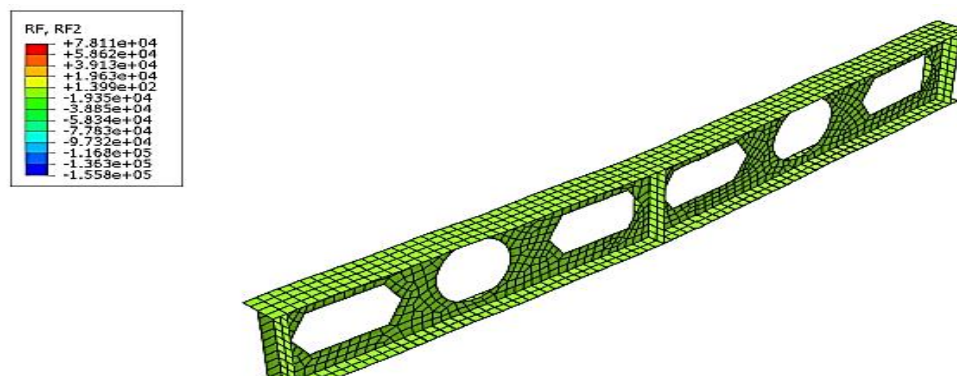


Fig. (B7): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

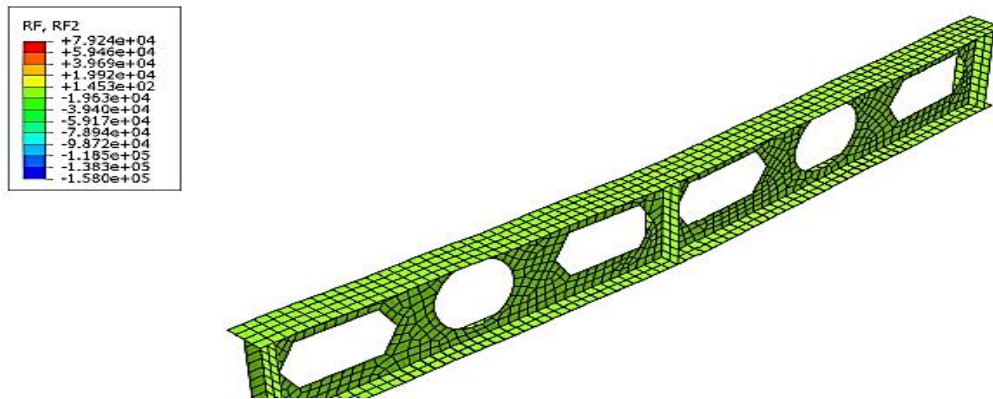


Fig. (B.8): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

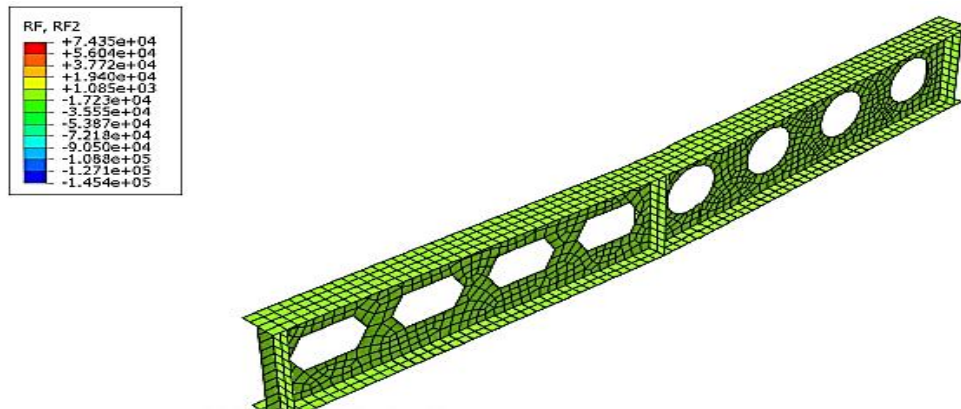


Fig. (B.9): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

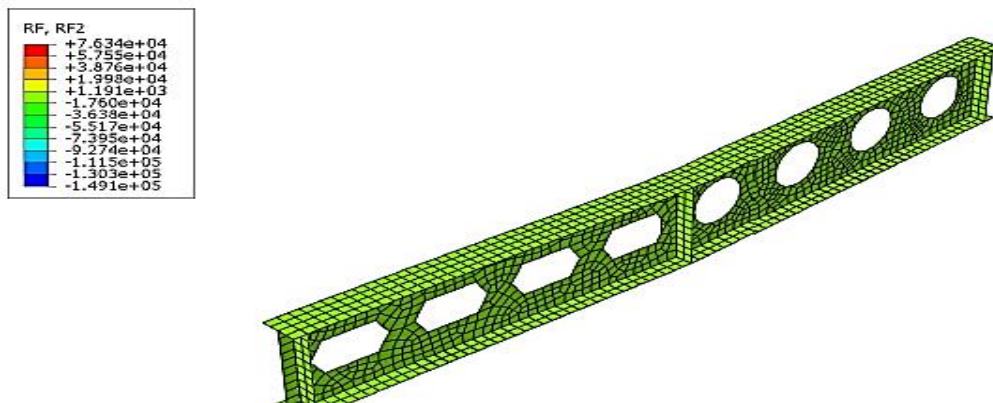


Fig. (B.10): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

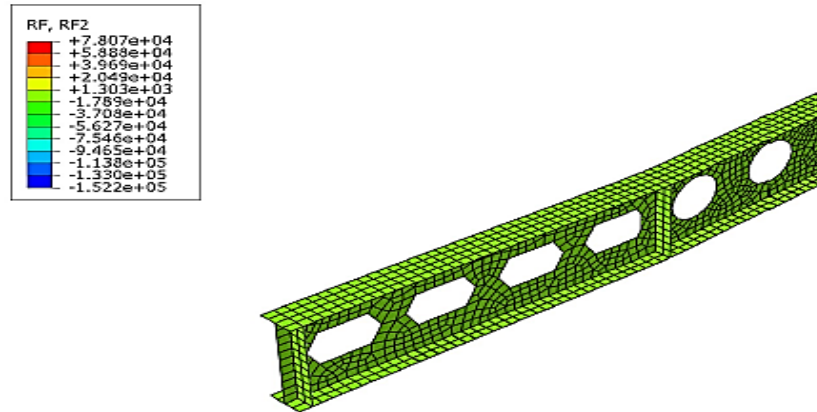


Fig. (B.11): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

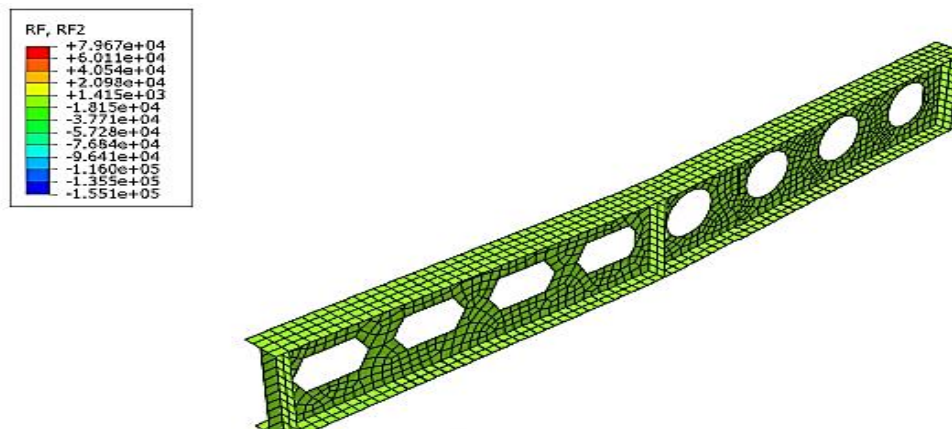


Fig. (B.12): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

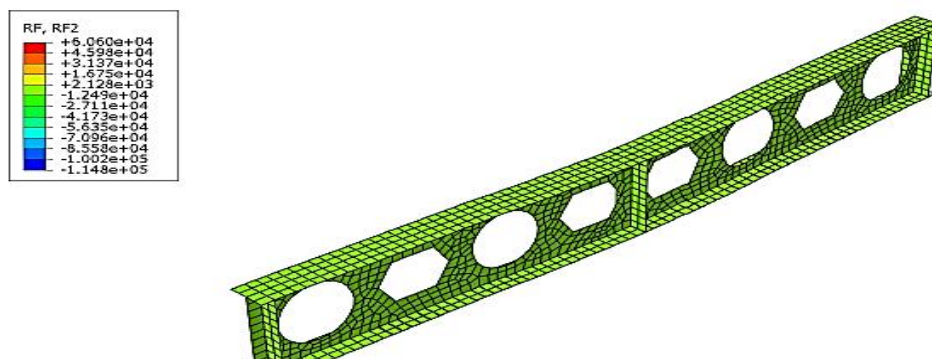


Fig. (B.13): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

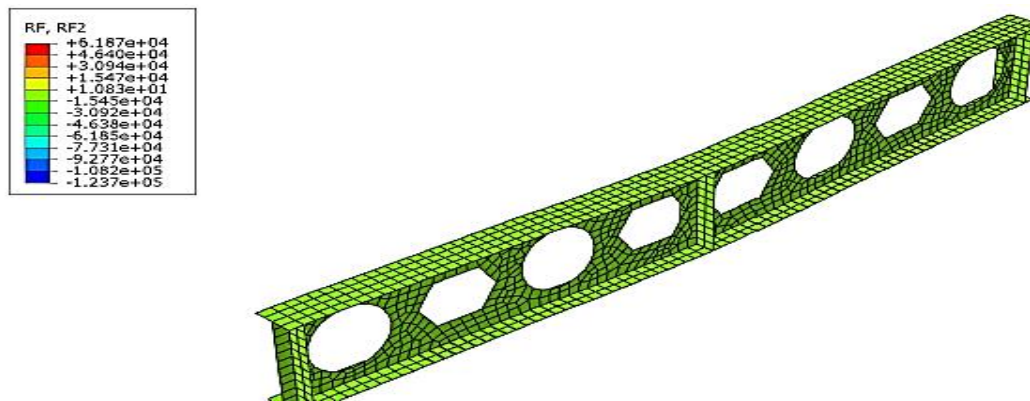


Fig. (B.14): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

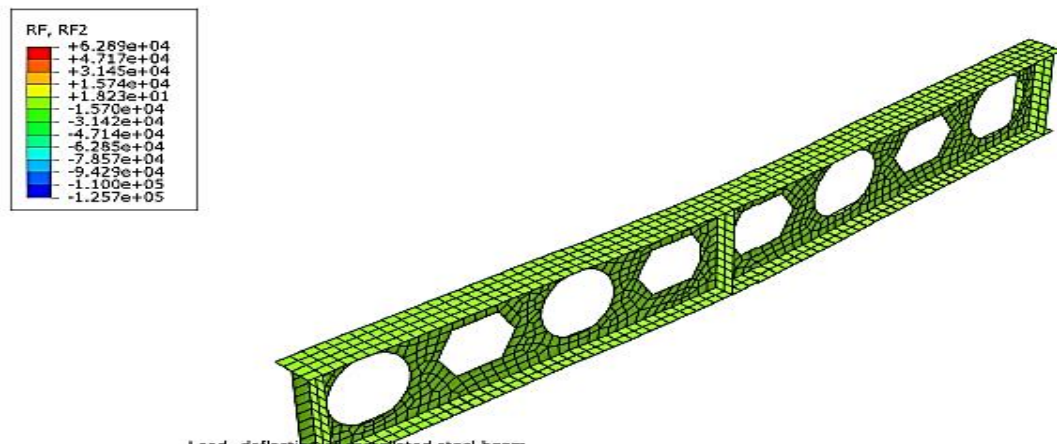


Fig. (B.15): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP

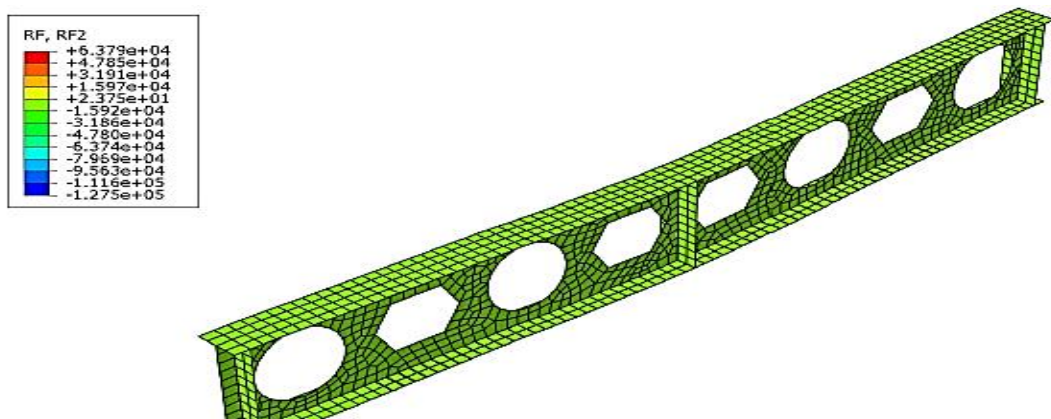


Fig. (B.16): Ultimate load for the CFRP strengthen castellated steel Beams with various layers of CFRP