

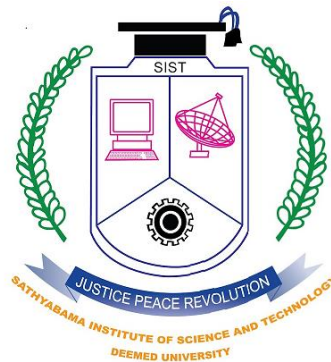
Buckling Behaviour of Cold Formed Steel Closed Compound Columns Using Channel, Zed and Angle Sections

Submitted in partial fulfillment of the requirements of the award of

Master of Engineering Degree in Structural Engineering

by

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**DEPARTMENT OF CIVIL ENGINEERING
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**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

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MAY 2023



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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of HARI KRISHNAN V (41380006) who carried out the project entitled "BUCKLING BEHAVIOUR OF COLD FORMED STEEL CLOSED COMPOUND COLUMNS USING CHANNEL, ZED, AND ANGLE SECTIONS" under my supervision from December 2022 to May 2023.

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05/05/2023

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DECLARATION

I, HARI KRISHNAN V (41380006), hereby declare that the Project Report entitled “BUCKLING BEHAVIOUR OF COLD FORMED STEEL CLOSED COMPOUND COLUMNS USING CHANNELS, ZED AND ANGLE SECTIONS” done by me under the guidance of Dr. C. Manoj Kumaar at SATHYABAMA INSTITUTE OF SCIENCE AND TECHNOLOGY is submitted in partial fulfillment of the requirements for the award of Master of Engineering in Structural Engineering

DATE : 05-05-2023

PLACE: CHENNAI



SIGNATURE OF THE CANDIDATE

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ABSTRACT

Cold-formed steel plays a vital role in today's construction industry for its lightweight properties, CFS saves a lot of cost as its about 570% lighter than conventional construction and also lighter than hot rolled steel and has a better weight-to-strength ratio in load-carrying applications on prefabricated structures at a low cost compared to regular hot rolled steel sections. CFS available in thickness varying from 0.1mm to 7.9mm, can be selected as per structural load-bearing requirements and aesthetics. It can be easily shaped either by cold rolling at normal room temperature or by press braking to form unique shapes like zeta, lipped z, and Sigma. The material to be fabricated is tested for elongation and yield strength using a steel tensile coupon testing machine. The study is conducted on a 2mm thick Cold formed steel sheet bent as 100mm x 50mm x 8mm c-lipped channel of 2 numbers combined into a box column connected using welding face to face in which 4 different shapes are placed inside the box column as multiple compound sections, other sections are Zed section, rectangular, channel and L angle combined in total 3 samples which are placed inside and bolted using a self-tapping screw. The goal of this research is to survey the maximum load-carrying ability among these 4 compound steel columns and the buckling acting of these 2 layered steel column sections validated from the result of design and analysis using ABAQUS finite element software. Comparing with the results from the experimental method conducted using column axial load testing machine and studying the buckling behavior using LVDT and determining the best compound section among 4 different compound models in comparison with buckling and axial load carrying capacity.

Keywords: Abaqus, Buckling, Compressive strength, Compound Section, TIG Welding.

TABLE OF CONTENTS

CHAPTER No.	TITLE	PAGE No.
	ABSTRACT	iv
	LIST OF FIGURES	x
	LIST OF TABLES	xiii
	LIST OF ABBREVIATIONS	xiv
1	INTRODUCTION	1
	1.1 GENERAL	1
	1.2 APPLICATION OF COLD-FORMED STEEL	4
	1.3 HISTORY OF COLD ROLLED STEEL	5
	1.4 HOT ROLLED STEEL	6
	1.5 OBJECTIVES	7
	1.6 NEED FOR STUDY	7
2	LITERATURE REVIEW	8
	2.1 LITERATURE	8
	2.2 SUMMARY	10
3	METHODOLOGY	12
	3.1 FLOW CHART	12
	3.2 MATERIALS	13

3.2.1	Cold-formed steel	13
3.2.2	Cold Roll Forming	14
3.2.3	Properties of The CFS steel (Mechanical)	16
3.2.4	Brake Pressing	17
3.2.5	Bolted Connection	17
3.3	PROPERTIES TO BE TESTED	18
3.3.1	Coupon Testing Procedure	19
3.4	SPECIFICATIONS OF THE BUILT-UP COLUMN	21
4	ANALYTICAL INVESTIGATION	
4.1	ABAQUS	24
4.1.1	Advantages Of Abaqus	24
4.1.2	Disadvantages Of Abaqus	25
4.1.3	Finite Element Analysis	25
4.1.4	Advantages of Finite Element Analysis	25
4.1.5	Disadvantages of Finite Element Analysis	26
4.2	STEPS FOR MODELLING THE COLUMN	26
4.2.1	File Definition	26
4.2.2	Geometry of the Models	26
4.2.3	Material Definition	27

	4.2.4	Model Specifications	28
	4.2.5	Properties Application	29
	4.2.6	Creation Of Interactions	30
	4.2.7	Assigning the Bolt Holes	30
	4.2.8	Analysis Part	31
5		EXPERIMENTAL INVESTIGATION	33
	5.1	EXPERIMENTAL SETUP	33
	5.1.1	Experimental Test Procedure	34
	5.1.2	Purchasing Of CR Sheets	34
	5.1.3	Laser Cutting Of CR Sheet	35
	5.1.4	Folding Of CR Sheets	35
	5.1.5	Welding And Fasteners	36
	5.1.7	Experimental Results	37
6		RESULTS AND DISCUSSION	39
	6.1	RESULTS AND DISCUSSION	39
	6.1.1	Axial Load Carrying Capacity Comparison	39
	6.1.2	Analytical Results	40
	6.1.3	Experimental Results	41
	6.1.4	Comparison of Analytical and	41

	Experimental Results	
	6.1.5 Weight to Strength Ratio	42
7	CONCLUSION AND RECOMMENDATION	43
	REFERENCES	44

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE NO.
1.1	Cold Formed Steel Building	2
1.2	Cold- Formed Steel Structure	4
1.3	Various Forms of Cold Formed Sections	6
1.4	Hot Rolled Steel Sections	7
3.1	Flow Chart of the Research	12
3.2	Cold Formed Sheet Roll	14
3.3	Cold Roll Forming Process	17
3.4	Structure of Cold Formed Steel	16
3.5	Different shapes of CFS	16
3.6	Brake Pressing	17
3.7	Self Tapping Screws	18
3.8	Coupon Testing Machine	19
3.9	Dimensions of Coupon Testing Sample	20
3.10	Cross Section of Built-Up Column Model DCTT	22
3.11	Cross Section of Built-Up Column Model CTTZ	25
3.12	Cross Section of Built-Up Column Model	25

	CTTCA	
3.13	Cross Section of Built-Up Column Model	26
	CTCB	
4.1	Defining The Geometry	27
4.2	Material selection tab	27
4.3	Edit Material Form – Elastic Material	28
	Definition	
4.4	Outline of Built-up column Model DCTT	27
4.5	Properties Application of Built-up Column Model DCTT	29
4.6	Interaction of Built-up Column Model DCTT	30
4.7	Creation of assembly in Abaqus Model DCTT	31
4.8	Buckling Shape of Model DCTT	31
4.9	Buckled shapes of all 4 models	32
5.1	Purchase of CR sheet	35
5.2	Laser Cutting of CR Sheet	35
5.3	Brake Pressing Machine	36
5.4	Welding and Fasteners	36
5.5	Experimental Buckling Shapes of Model DCTT & Model CTTZ	37

5.6	Experimental Buckling Shapes of Model CTTCA & Model CTCB	38
6.1	Axial Load Carrying Capacity of Experimental and Analytical Results	40
6.2	Load vs Deflection curve for Model DCTT,CTTCA,CTTCA and CTCB – Analytical Values	40
6.3	Load vs Deflection curve for Model DCTT,CTTCA,CTTCA and CTCB – Experimental Values	41
6.4	Load vs Deflection Comparision of Both Analytical and Experimental Results	42

LIST OF TABLES

TABLE NO.	TITLE	PAGE NO.
3.1	Results obtained from coupon test	21
4.1	Analytical Results	32
5.1	Maximum Load In Axial Direction Set 1	37
5.2	Maximum Load In Axial Direction Set 2	38
6.1	Strength To Weight Comparison	42

LIST OF ABBREVIATIONS

FEM	Finite Element Method
CFS	Cold-Formed Steel
DCTT	Double Channel Toe-to-Toe
CTTZ	Channel Toe-to-Toe with Zed
CTTCA	Channel Toe-to-Toe with channel Angle
CTCB	Channel Toe-to-Toe with Channel Back-to-Back

CHAPTER 1

INTRODUCTION

1.1 GENERAL

CFS is Extensively used in the construction industry due to its lightweight properties, making it a cost-effective alternative to conventional construction methods. With a weight that is approximately 570% lighter than regular steel, and a better weight-to-strength ratio, it is mostly preferred in load-bearing applications on prefabricated structures. CFS is available in different thicknesses, ranging from 0.1mm to 7.9mm, allowing it to be selected according to specific structural requirements and aesthetic preferences. The material can be easily shaped either by cold rolling or press braking, to form unique shapes such as zeta, lipped z, and Sigma. In this study, a 2mm thick cold-formed steel sheet was bent into a 100mm x 50mm x 8mm c-lipped channel, which was then combined into a box column using welding face to face. The box column was then fitted with three different shapes, namely Zed section, rectangular, channel and L angle, to form three different compound sections.

The aim of the research was to determine the maximum load-carrying ability of these four compound steel columns and their buckling behavior. This was achieved by designing and analyzing the different compound sections using ABAQUS finite element software. The results were then compared with the findings from the experimental method conducted using a column axial load testing machine, where the buckling behavior was studied using LVDT.

Through this study, the best compound section among the three different models was identified by comparing their buckling and axial load-carrying capacities. Overall, cold-formed steel is an effective and versatile material for construction projects, offering a range of benefits, including lightweight properties, cost-effectiveness, and ease of shaping.



Fig. 1.1 Cold Formed Steel Building

Cold-formed steels are lightweight materials used for various small-scale/low-rise buildings for load applications. Cold-formed steels are brake-pressed or bending flat sheets at room temperature Cold-formed steel is about 575% lighter than conventional RCC construction using and 59% lesser than structural steel. They are used in vehicles, agriculture, electrical equipment, etc. The yield strength of the CFS sheet comes to around 280 N/mm². CFS is used in prefabricated structures as truss elements. Cold-formed steels are being tested in various structural members for load-carrying capacity with less cost. The following cold-formed built columns shall be used in construction applications with providing appearance as well as load-carrying properties at less cost.

When designing a building or structure, the focus is on achieving strength at a lower cost, durability, and a good return on investment. In such cases, steel is often the material of choice. Cold-formed steel, in particular, offers several advantages over hot-rolled steel. It can be easily bent and structured at room temperature, resulting in significant time and cost savings. In many developed countries, cold-formed steel is used even for constructing buildings with more than four stories, and some structures can go up to 10 stories. Further research on these materials reveals that they are widely used in other countries, and we are only beginning to adopt them as a developing technology.

Built-up columns are done by cutting the beam using a laser as per the dimensions used for fabricating the column using laser cut. Manufacturing the built-up column by bending the CFR sheets as in the model given below and welding it and bolting it to make it a single column. The high-strength columns resulting in analytical are fabricated as compound sections with the outer core as a square face-to-face-lipped column and are analyzed, to study the buckling behavior. Compared to HRS these CFS can perform equally with a very lesser dead load to the structure. When we have regular construction techniques using wood or concrete, One of the main reasons why cold-formed steel (CFS) is preferred over other conventional materials is due to its excellent elastic and plastic limits. This makes it an ideal choice when designing a frame that needs to withstand buckling. Using CFS sections can result in significant cost savings during construction as compared to hot-rolled steel, which would require a crane for erection. Moreover, CFS can be easily handled and transported due to its less weight nature, further reducing transportation costs. In short, the superior strength-to-weight ratio and other favorable mechanical properties of CFS make it a top pick for various construction applications, from small-scale residential projects to larger commercial and industrial structure

One of the key advantages of cold-formed steel is its lightweight nature, which leads to lower transportation costs. This reduced weight also means that the self-weight of the structure is lower, resulting in significant cost savings during the design phase. Many CFS frames are prefabricated in factories, which can be directly transported to the construction site with minimal machinery and manpower due to

their lightweight. This reduces the need for heavy equipment and labor-intensive construction processes, further lowering the overall cost of construction. The use of CFS is an increasingly top picker in construction for its economic viability, environmental friendliness, and user-friendliness.

Cold-formed steel (CFS) panels offer several advantages in terms of ease of installation for plumbing and electrical points. This is due to the predefined holes and chases that can be designed into the panels without requiring any changes during installation. Although CFS has been around for over 300 years, its benefits and uses are only gradually becoming apparent to users in the real world. CFS also comes with pre-punched holes that are useful for electrical and plumbing work, making installation faster and more efficient. In the United States and many other developed countries, CFS is extensively used due to its numerous advantages, including cost-effectiveness, sustainability, and flexibility in design.



Fig. 1.2 Cold-Formed Steel Structure

1.2 APPLICATIONS OF COLD-FORMED STEEL

There are various applications in CFS in a field used for different types of purposes, a few among them are discussed below

- Good aesthetics with structural integrity

- CFS is can be applicable in many different areas including agriculture, transportation, domestic water supply, and structural pipelines
- CFS can be used for constructing gas pipes and water lines.
- Best suited for house equipment and for the best corrosion resistance
- Cold-rolled steel is suitable for good floor finish and high-strength areas.
- As the thickness is lesser accuracy can be achieved at top notch.
- The metal withstand high abrasion which is suitable for furniture and other household material which are frequently moved.
- All types of lockers and other high-security hardware are made of this CFS
- CF Steel is the top picker for people who need a sleek appearance with lesser thickness.
- Widely used in airports, sheds, telecommunication and various other sectors.
- Aesthetical improvement without compromise in strength
- Used in high-pressure vessels where the thickness of the material is not to be compromised.
- Most preferably used in petroleum industries and other high-flammable chemical industries.
- Cold-rolled steel is used in pressure vessels due to its elongation rate, toughness, embrittlement resistance, and fatigue strength

1.3 HISTORY OF COLD ROLLED STEEL

Hot rolled steel is heated and then cooled, cold rolled steel is heated and cooled at room temperature and then rolled after again. Only a few shapes are available cold-rolled as shown in Fig 1.4 (sheet, box, circular). An accurate shape offers good surface finishes. Cold-formed steel (CFS) is the term derived as this steel is manufactured at normal room temperature to the desired shapes such as pressing, bending, etc. Large sheets of cold-rolled steel (CRS) are generally used in manufacturing units. The terms are opposed to hot-formed steel



Fig. 1.3 Various forms of cold-formed sections.

Cold-formed steel, are extensively used in structural and non-structural applications such as beams and column in construction. Most commonly used in the US for many products.

1.4 HOT ROLLED STEEL

Compared to cold rolled steel, hot rolled steel is a more time-consuming and laborious process. The process involves heating the raw material, shaping it, and then cooling it rapidly to obtain the desired product. Hot rolled steel is commonly available in channel form, which can be used for structural applications and other purposes, whereas cold-formed steel offers a variety of shapes such as zed channels and angles for different applications. Hot-rolled steel is typically heavier than cold-formed steel. Different shapes in hot rolled steel are formed by heating the material again and molding it, whereas with cold-formed steel, we can bend and shape it to the desired form at normal room temperature. Due to the rapid heating

and cooling of the material, there is a significant amount of shrinkage loss, which can result in inaccurate dimensions of the final product. Billets are often used as the raw material source for hot-rolled steel processing.



Fig. 1.4 Hot rolled steel sections

1.5 OBJECTIVE

There are various objectives in cold-formed steel few are described below

- To determine the effectiveness of built-up (compound) column
- To understand and study the load vs deflection.
- To Examine the stress distribution of the column section.
- To determine the buckling behaviour of the CFS built-up column.
- To determine the results of analytical and experimental outcomes.

1.6 NEED FOR STUDY

There are various reasons to study cold-formed steel few of them are

- To save construction time drastically when compared to conventional construction.
- To reduce the cost of construction and make affordable houses for every people
- To use eco-friendly products in construction.
- To use sleek material with a pleasant appearance with structural integrity

CHAPTER 2

LITERATURE REVIEW

2.1 LITERATURE

Huang Y, Young B (2014), has studied in his experiment about material properties using a coupon test procedure, various steels like cold-formed carbon steel, cold-formed stainless steel and aluminum alloy are subjected to testing as to study the result and behaviour of the steel using coupon test. By this method a proper procedure for coupon testing has been arrived by the team.

Manikandan and Pradeep (2018) have studied the axial compression of the CFS and also given data about the behaviour of the column under compression. They have also plotted the graph using linear elastic buckling analysis software. columns are analysed under pin end conditions with axial compression the theoretical and numerical investigation on the ultimate strength and behaviour of pinned end new inventive stiffened CFS section.

Senthil kumar et al., (2022) studied the strength of concrete-infilled steel columns and studied the yielding of self-tapping screws under axial compression and the performance of the stiffener angle. An intensive numerical analysis was carried out by varying stiffener angles as 90°, 120°, and 141° and plain sheet columns performed lesser when compared to the columns infilled with concrete as a composite member in buckling. Self-tapping screws provide a good type of connection in CFS columns.

Liu et al., (2022) determined the results of different dimension coupon tests and the behaviour of irregular octagonal hollow section performance under axial load. As the cross-section of the materials increased or changed the strength behaviour at the corners showed increased performance obvious than the flat coupons counterpart. The material properties variations and the residual stresses distributions in cold-formed HSS. corner coupon specimens cannot meet the requirement on ductility due to the large plastic deformation experienced during press-braking fabrication. An enhancement of 5% in yield strength can be observed.

Yao et al., (2022) have studied about the stress–strain model for the stub column thin-walled ion of thin walled profile performance under axial compression and they used stub column in analysis and tested for maximum deflection of it. The Continuous Strength Method showed higher result compared to other methods. CSM curve were obtained with higher values in buckling strength. The modified curve can show even more performance of the buckling with change in thickness of the section models.

Nie et al., (2019) studied the strength of corroded cold-formed steel and also checked the corroded coupon and flat coupon performance. The modulus of elasticity is higher for corner coupon whereas when comparing with the flat coupon. The elongation is lesser in corner coupon when the flat coupon continuously increased with greater degradation in the shape. Corner coupon values where linear when compared to the corroded. This results can be used to study the properties of the corroded cfs sheets when used in project and the behaviour of the cfs to the rusting.

El Hady et al., (2022) have done a compound section model using 4 different samples combined as a column and subjected to axial compression and the coupon test results were discussed in this experiment. Experimental test results shows that the 3 different slender columns of small medium large showed failure in local buckling and flexural. This helps to understand the predefined buckling zones of the column and design the models as per the buckling zones respect to the shape of the column.

Glauz (2023), have studied the strength-based approach to the built-up column and also calculated the slenderness ratio for the column and analyzed it. As per the calculation the required values was lesser when compared with the theoretical methods. The flexural buckling stiffness provided by the strength-based end connection requirements exceed the flexural buckling stiffness used for design, in most cases by the end connections alone, and in some cases with the additional stiffness provided by intermediate connection.

Kesawan and Mahendran (2022) have studied the DSM is used to evaluate the local buckling at elevated temperatures for the hollow section. The DSM also yields higher estimates of capacity than the finite element models for advanced high-strength steel grades. The FEM is able to reproduce the experimental behavior of a SHS cold-formed column failure in buckling at temperatures ranging from 21 °C to 600 °C.. In this paper, we study about the behaviour of hollow and plan column at both normal and high temperature

Chen M, Young B (2020) have studied about the tensile performance of the cold formed steel half filled with concrete at top and bottom. The tensile result obtained where compared with the result available in hand for the tubular section. The tensile stress were increased in rectangular and square section. For circular and hollow strength was almost close for specimen obtained from tensile tubular and tensile coupon

Kesawan and Mahendran (2018) have studied the properties of the cold-formed steel section behaviour when subjected to fire. Performance of the cold-formed steel section after post fire and their life in building where studied. It is crucial to study the CFS performance on fire damage and reusability with and without strength-enhancing techniques before using it on tructures.

2.2 SUMMARY

By studying the various kinds of literature we could able to understand the behaviour of the steel built-up column under axial load and buckling behaviour and few more observations and learnings are mentioned below

- The literature review revealed that bolted connections and extended lips perform well in cold-formed built-up steel columns under axial load and buckling conditions.
- The slenderness ratio and section thickness are important considerations when designing perforated or compound sections for cold-formed steel columns.
- Calculating the pitch and edge distance is crucial for providing efficient bolt

and welded connections in the column.

- Both experimental and analytical methods should be used to arrive at detailed results when testing cold-formed steel columns.
- Cold-formed steel can be used for load-carrying purposes and aesthetic enhancement due to its availability in different shapes and thicknesses.
- Cold-formed steel offers the advantages of low-cost and quick construction.
- Researchers have studied cold-formed steel with various shapes, combinations of height and diameter, and slenderness ratios, which provide basis for developing new built-up columns under buckling loading conditions.
- Columns with concrete infill shall be used as compound sections to take tensile stresses and perform well under axial compression.

CHAPTER 3

METHODOLOGY

3.1 FLOW CHART

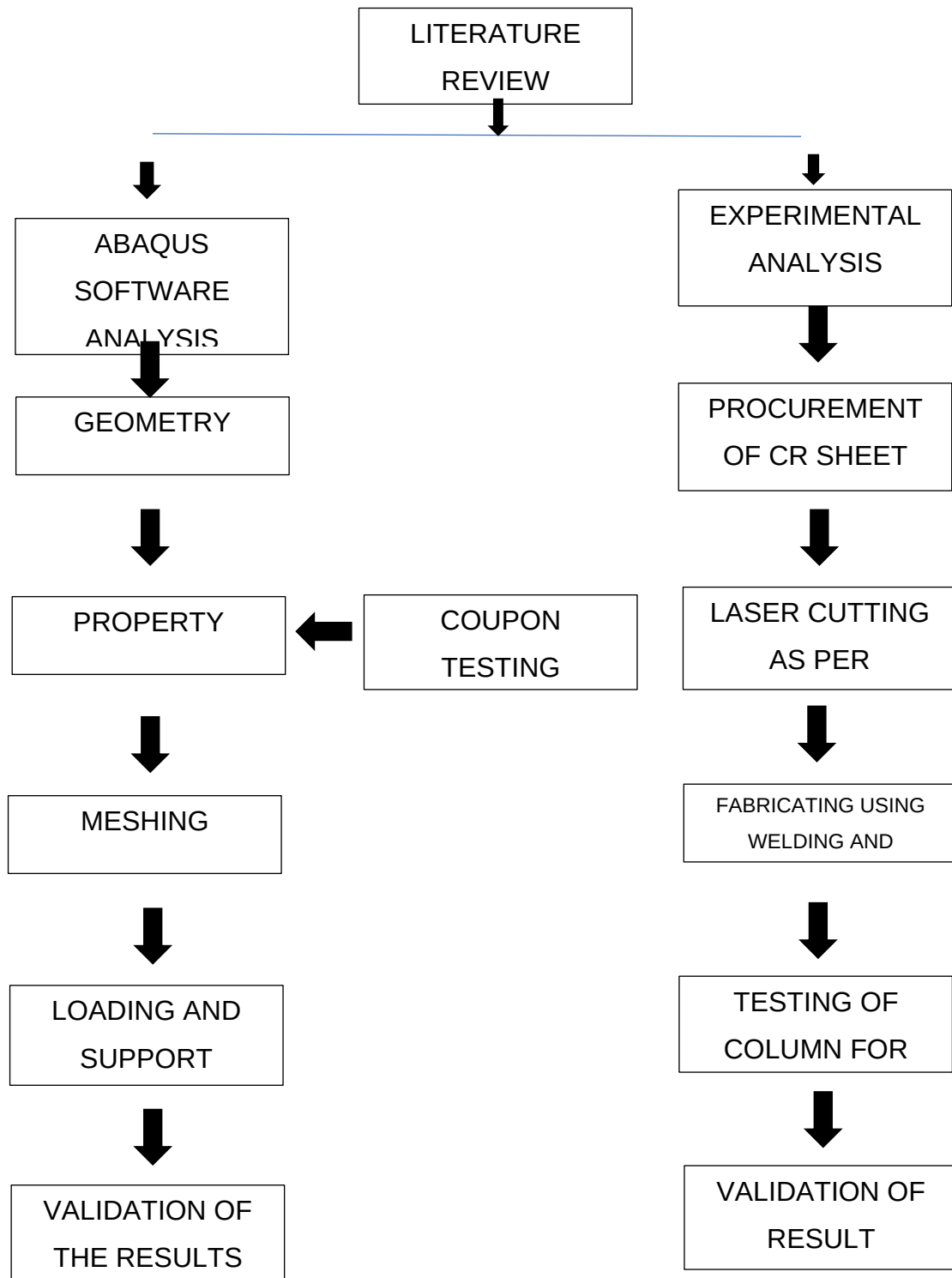


Fig. 3.1 Flow chart of the research

The flow chart methods are explained below

- The flow chart starts with a literature review on material properties and behavior of the built-up compound column.
- The project is divided into two phases: analytical and experimental.
- In the analytical phase, the shape is modeled in Abaqus, and properties are applied using coupon testing results. The entire column is meshed. load and support conditions will be applied. Linear and non-linear analyses are run to validate the results.
- In the experimental phase, cold-rolled (CR) sheets are procured, laser-cut as per specifications in Fig. 3.9 and 3.10, and fabricated using welding and self-tapping screws as shown in the figures.
- After fabrication, the built-up steel column is tested for buckling behavior and stress distribution using LVDT.
- Finally, the results gained from the analytical and experimental procedures are compared for similarity.

3.2 MATERIALS

3.2.1 Cold-Formed Steel

Cold-formed steel (CFS), as shown in Figure 3.2, refers to the process of cold-working steel near room temperature using methods such as rolling, pressing, stamping, and bending. Cold-rolled steel (CRS) bars and sheets are widely used in various manufacturing industries. Cold-formed steel, especially thin gauge sheets, is frequently utilized in construction for structural or non-structural elements such as columns and beams in regular residential-type construction. Whereas when we design the industry type building used as strut bracing or purlins etc.



Fig. 3.2 Cold Formed Sheet roll

3.2.2 Cold Roll Forming

The cold roll forming technique is extensively utilized for manufacturing building components, including individual structural members in Fig. 3.3, are used in roof or for panel works or as designer steels with holes and punches in it. Fig. 3.4). shows the model of the house. Additionally, it is employed for creating partitions, window and door frames, gutters, downspouts, pipes, agricultural machinery, trucks, trailers, containers, railway cars, household appliances, and other items. The most cost-effective production of sections from strips up to 36 in. (915 mm) wide and coils exceeding 3000 ft (915 m) in length is achieved through this method.

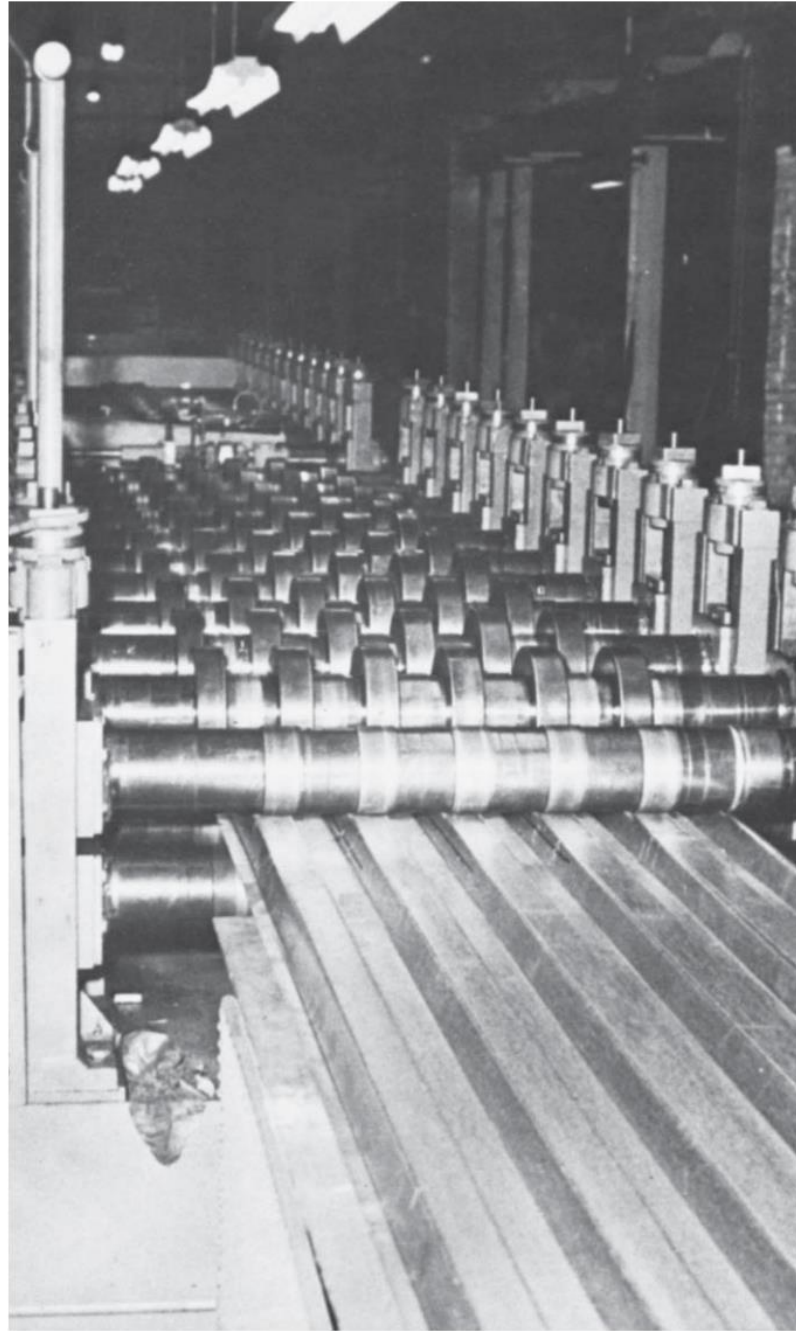


Fig. 3.3 Cold roll forming process

The cold roll forming machine utilizes pairs of rolls, as depicted in Fig. 3.3, to gradually shape strips into the desired final form. A basic section can be achieved with as few as six roll pairs, but a more intricate shape may necessitate up to 15 sets of rolls. It may take several days to prepare the rolls for use



Fig. 3.4 Structure of cold-formed steel

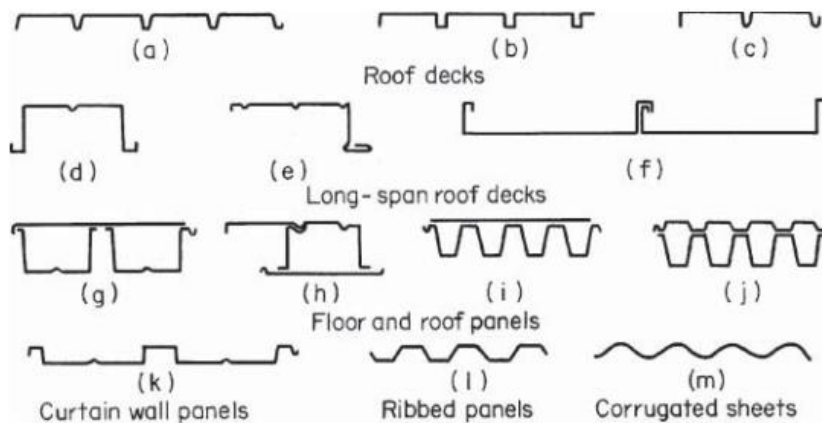


Fig. 3.5 Different shapes of CFS

3.2.3 Properties Of The Cfs Steel (Mechanical)

The mechanical properties of cold-formed steel sections can differ significantly from those of the original steel sheet or bar due to the cold-forming process, which increases the yield stress and tensile strength while reducing ductility. Although the spike in tensile strength is much smaller than the increase in yield stress, this results in a significant reduction in the spread between yield stress and tensile strength. In addition, the mechanical properties of different parts of the cross-section vary due to the uneven degree of cold working in different areas, with the corners typically having higher levels of cold work. As a result, the flat portion of a section usually yields or buckles first with respect to poor yield stress, and any additional load applied to the section is then transferred to the corners.

3.2.4 Brake Pressing

The press brake is suitable for simple shapes and folding like rectangular or square and angle which can be easily bent using the brake pressing flat bed which very quick output even 10mm thick plates can be easily brake pressured in seconds, as in fig 3.6

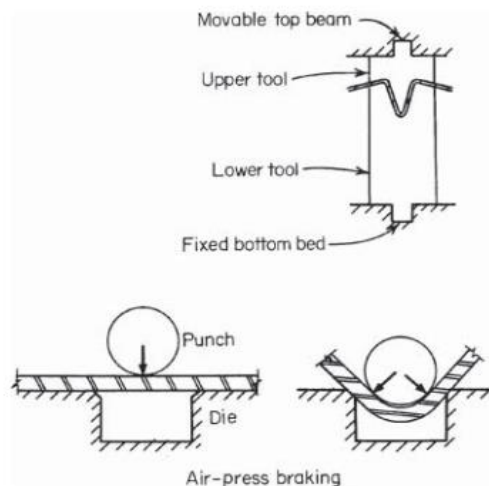


Fig. 3.6 Brake Pressing

3.2.5 Bolted Connection

Self-tapping screws are the easiest way of joining the steel sheets or members quickly at any angle with proper strength and can be easily removed for porting the sheets whenever required. Fig. 3.7 illustrates several types of self-tapping screws that are typically used in building construction. The Cold-Formed Steel Institute provides a list of screw selection methods based on the sheet

thickness

Kind of material	Thread-forming								Thread-cutting			Self-drilling	
	Type A	Type B	Type AB	Hex head B	Swage form	Swage form B	Type U	Type 21	Type F	Type L	Type B-F	Drill Kwick	Tapits
Sheet metal 0.015" to 0.050" (steel, brass, alum, monel, etc.)													
Sheet stainless steel 0.015" to 0.050"													
Sheet metal 0.050" to 0.200" (steel, brass, alum, etc.)													
Structural steel 0.200" to 1/2" thick													

Fig. 3.7 Self-Tapping Screws

3.3 Properties To Be Tested

To proceed with the feeding properties in Abaqus software we need to evaluate the following results from coupon testing

- The yield strength of the CFS material
- The percentage elongation in length
- The Young's modulus of the material
- Reduction in the area of material
- The breaking stress
- The ultimate tensile strength

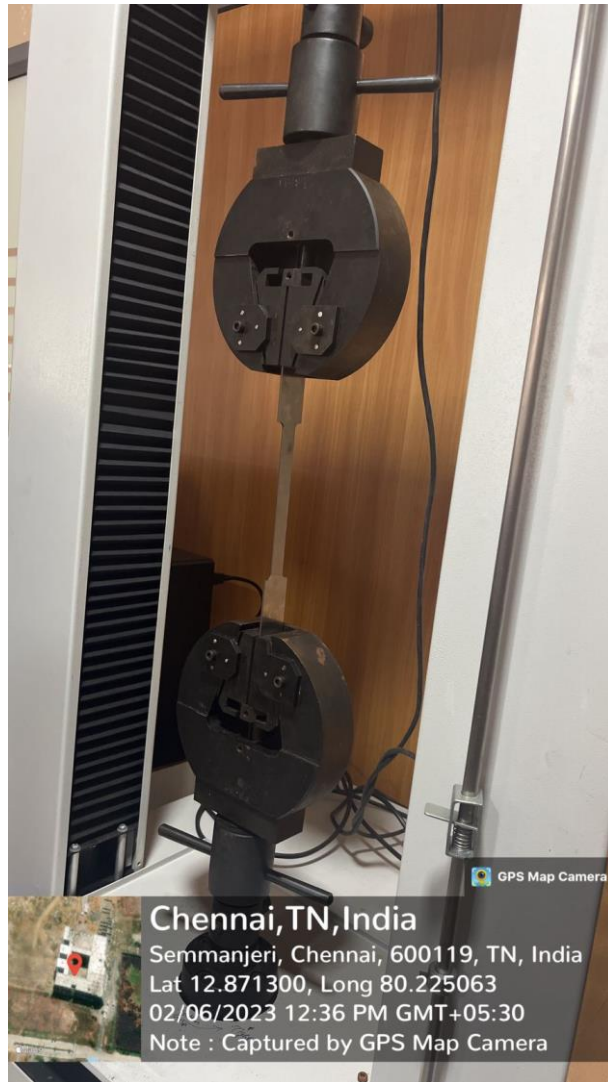


Fig. 3.8 Coupon Testing Machine

3.3.1 Coupon Testing Procedure

The coupon testing procedure is a crucial step in determining the properties of steel samples for fabrication. The methodology flow chart shown in Figure 3.8 outlines the following steps:

- A loading machine controlled by displacement stroke was used during the tensile coupon tests.
- The experimental loading can be split up into four stages: elastic range, yielding range, strain hardening range, and post-ultimate range.
- Coupon specimen is placed into the grip which holds the sample in position without any movement, once it is stable the uniform load application as in 4 stages is done.

- A higher loading rate can be applied after the elastic state to avoid prolonged time for testing, also the major strain difference will occur during those phase.
- The loading rates are classified into four types slow, research lower-bound and upper-bound
- The coupon testing make take up to 60 minutes with a gradual load applied to the specimen.
- The average strain reading are noted down for each strokes and for change in length respectively.

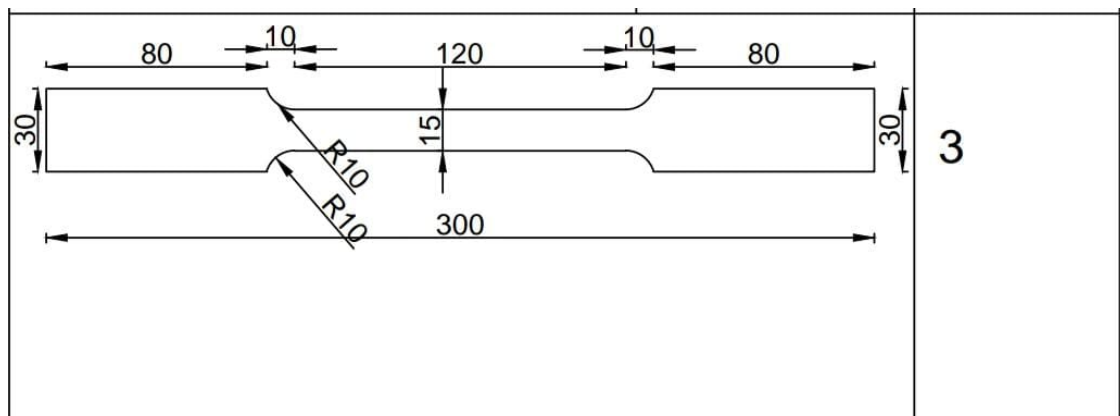


Fig. 3.9 Dimension of Coupon Testing Sample

- Coupon test is the only step to obtain the properties of the sheet which is dedicated to be used for fabrication.
- The coupons used in the test were cut from the steel profiles used in the study, following the dimensions shown in Fig 3.9 and the test procedure shown in Fig 3.8.
- Coupons were extracted from both the flat plates and corner regions of the profiles to accurately assess the impact of cold-formed steel.
- The tests aimed to determine important mechanical properties such as the Tensile Strength, yield strength and ultimate strength and to determine the poisons ratio with the tensile strength

Table. 3.1 Result obtained from coupon test

S.NO.	VALUES	MEAN LOAD	UNIT
1	Load at Peak	10.384	kN
2	Tensile Strength	346.117	N/mm ²
3	Load at Break	8.658	kN
4	Elongation at Break	42.533	mm
5	Breaking Strength	288.583	N/mm ²
6	Load at Yield	6.155	kN
7	Yield Stress	205.150	N/mm ²
8	Percentage Elongation	32.94	%
9	Reduction in Area	35.20	%

3.4 Specifications Details Of Built-Up Columns

The connection between the lipped C channels involves welding them together at the outer face where they join, forming a perpendicular angle with the outer square column. This is illustrated in Figure 3.10. The secondary lipped C rectangular channel is fastened to the vertical axis of the outer square column using self-tapping screws placed at the specified spacing as shown in section B-B of Figure 3.10. In the model CTTC the outer core is constant as for other models with internal layer of zed shape screwed on both side as in Fig 3.11 whereas in model CTTCA internal section is of two L angle with channel connected back to back and placed inside the common outer channel. Final model CTCB opposite to the Model DCTT internal channel are connect back to back with the common outer core section

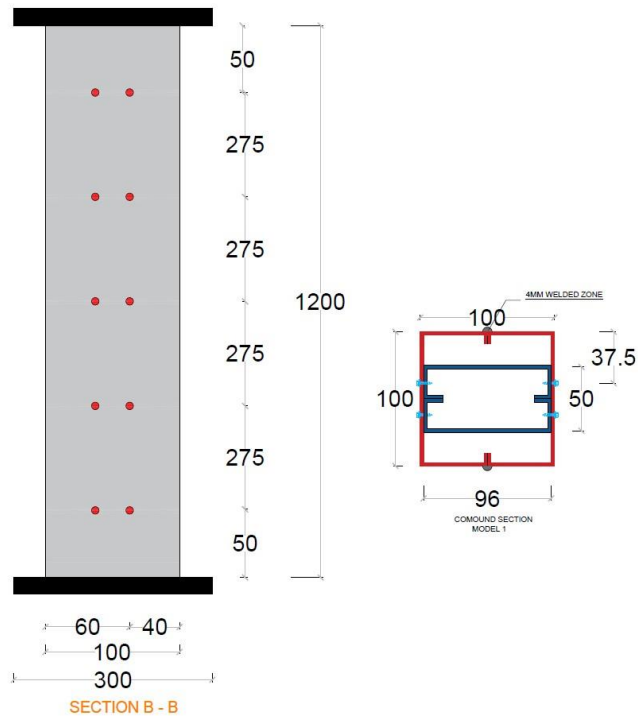


Fig. 3.10 Cross section of Built-up column Model DCTT

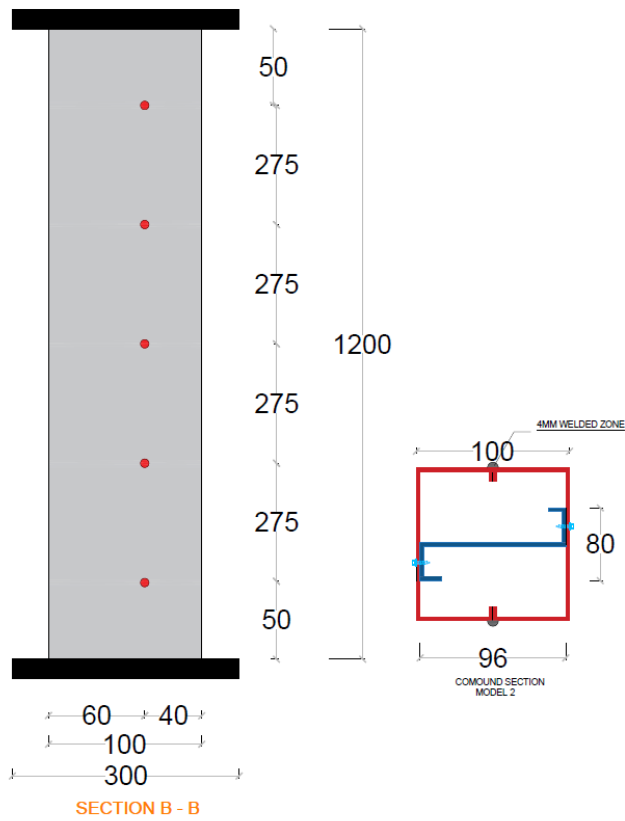


Fig. 3.11 Cross section of Built-up Column Model CTTZ

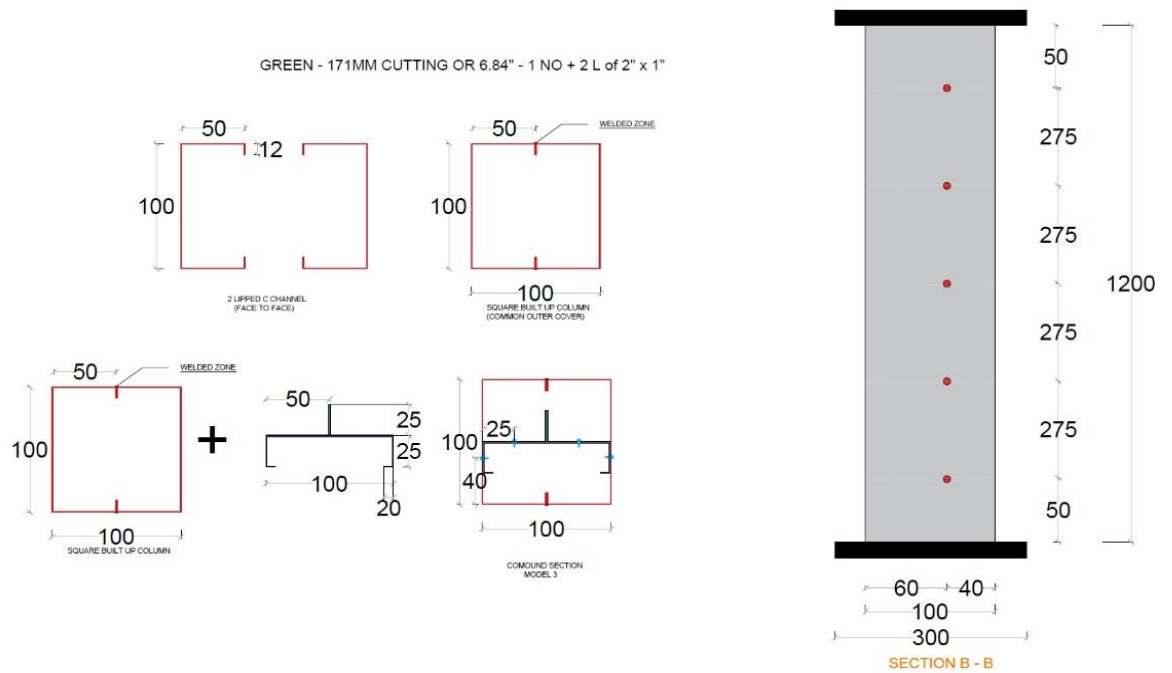


Fig. 3.12 Cross section of Built-up Column Model CTTCA

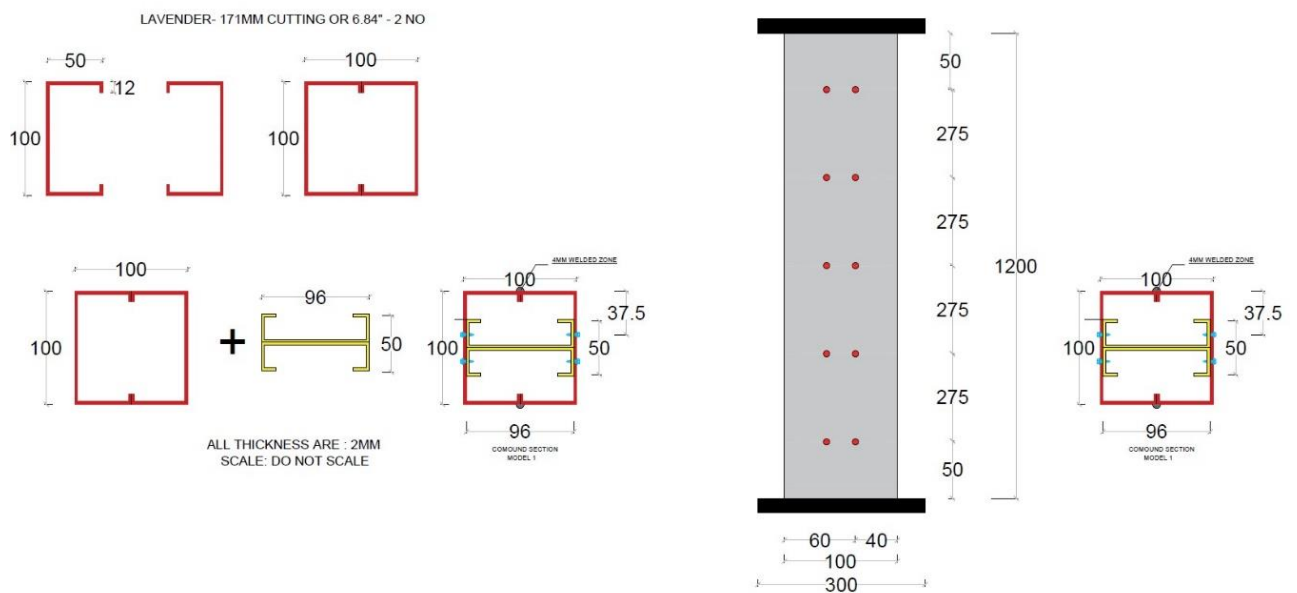


Fig. 3.13 Cross section of Built-up Column Model CTCB

CHAPTER 4

ANALYTICAL INVESTIGATION

4.1 ABAQUS

Abaqus is a widely used software package across various industries for conducting critical engineering processes such as powertrain engineering, electronic drop simulation, composite wing structure performance, sealing design, and many more. As a general-purpose finite element-based software package, it is designed to exploit the true generality of the Finite Element Analysis (FEA) method, thereby bridging the gap between its theoretical potential and the limitations imposed by other software packages.

With an extensive library of element types, Abaqus can model nearly any geometry, and its equally extensive library of material models can simulate stress and deformation in various materials, including isotropic and anisotropic metals at different temperatures, strain rates, and strains, polymers, reinforced concrete, glass, ceramics, foam, and geotechnical materials like soils and rock. Additionally, abaqus provides more information beyond the stress-strain, like the heat transfer zones with the color indication in the chart and diffusion of the material due to the load acting upon it compared to real-time.

What makes Abaqus uniquely powerful is its modularity, allowing users to model any physically reasonable combination of elements, materials, procedures, and loading sequences. Any material can be used with any element, forming a part of a model subjected to any sequence of static or dynamic loading histories. Moreover, Abaqus can be used to solve complicated problems which can not be done with manual calculations and is act as a great tool for the rts to work in detail

4.1.1. Advantages Of Abaqus

Abaqus is the simplest software for studying engineering properties with a simple user interface for designing and evaluating the results, few advantages of Abaqus are mentioned below

- Abaqus comes with two solvers (Standard and Explicit) which shall be used to run a variety of simulations. Abaqus is a user-friendly software for studying

engineering properties and evaluating results.

- Abaqus comes with two solvers, Standard and Explicit, which is recommended for use to run a variety of simulations.
- Simulations in Abaqus are set up using keywords that define the functioning of the simulation, providing a high level of control over the simulation.
- Abaqus allows users to configure materials using a variety of models, although it does not offer support for any particular materials.
- The user has fine control over meshing and element types used in the model.
- Abaqus is command-line accessible and supports scripting functionality.

4.1.2. Disadvantages Of Abaqus

- Learning how to use the software can be challenging due to its open-ended nature.
- The process of setting up simulations using the software is time-consuming since the user has to manually configure several simulation parameters

4.1.3. Finite Element Analysis

FEA, finite element method (FEM), is based on dividing the entire model into various segments very fine division to work in detail about the behaviour with respect to the loading condition by connecting the points as node. FEM has a set of formulas methods which can be used by engineers or users to run the analysis part as per their requirement. Partial differential equations (PDEs) are often used to describe the physical behavior of a product, such as its thermal transport, fluid or structural behavior. FEA was developed to enable computers to solve both linear and nonlinear PDEs. However, it is important to note that FEA provided results as nearest comparison with the real time model it cannot be considered as the accurate value results.

4.1.4. Advantages Of Finite Element Method

- FEM can handle complex geometries and irregular shapes easily as a variety of finite elements are available for the discretization of the domain.
- Boundary conditions can be easily incorporated into the FEM model.
- Different types of material properties can be accommodated in modeling from

element to element or even within an element, allowing for more accurate simulations.

- Higher-order elements can be implemented for increased accuracy.
- FEM is a simple, compact, and result-oriented method, making it popular among the engineering community.
- There are various applications and research papers available for FEM, making it an excellent tool for calculation studies based on FEM

4.1.5. Disadvantages Of The Finite Element Method

- The fine mesh in FDM requires a significant amount of input data, including nodes interaction and other problem-specific parameters.
- FDM simulations require a digital computer with significant computational power and memory.
- FDM simulations generally take longer to run compared to FEM.
- Results obtained from FDM simulations can vary significantly depending on the input data and the model setup.

4.2 STEPS FOR MODELLING THE COLUMN

4.2.1 File Definition

Start Abaqus and choose to create a new model database. Remember to save in regular time intervals throughout your session.

4.2.2 Geometry Of The Models

To create a new part in the Model Tree of the software, you can follow these steps:

- Locate the Model Tree in the software interface.
Find the "Parts" node in the Model Tree.
- Double-click on the Parts node, or right-click on Parts and select Create.
- This will open the Create Part form, where you can check the appropriate parameters depending on your structure and continue with the sketch area to draw the geometry of your model.

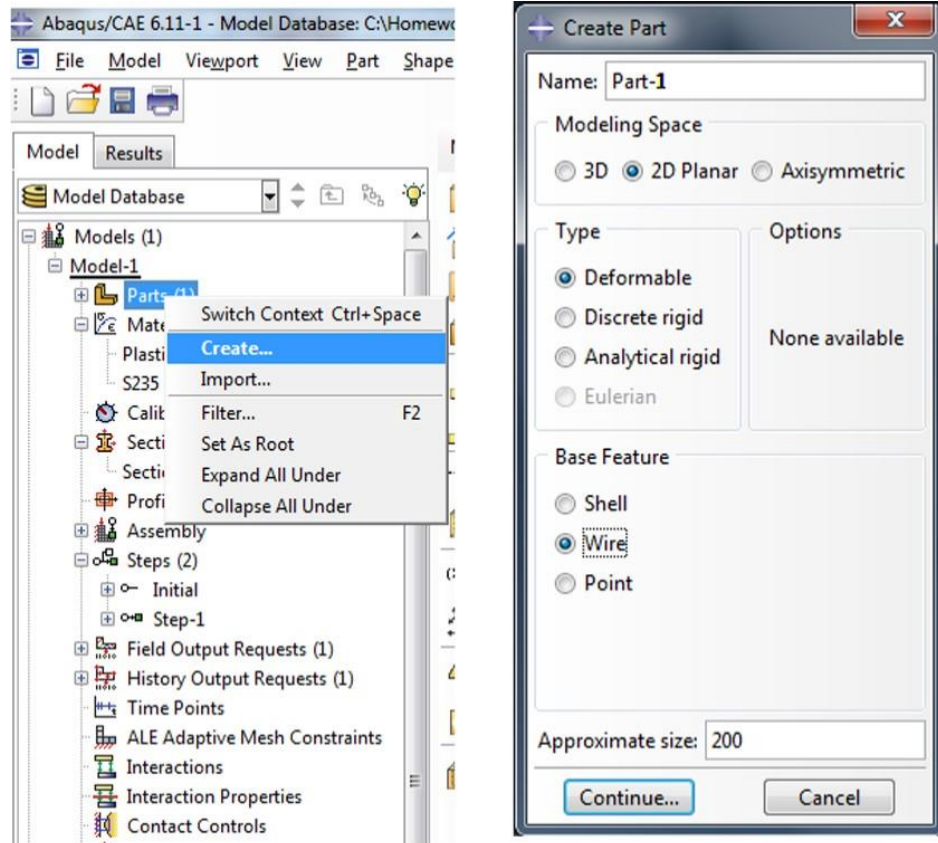


Fig. 4.1 Defining The Geometry

To begin creating a 2D wire structure in the Create Part form (as shown in Figure 4.1), select the relevant parameters based on the structure you want to create. Once you have made your selections, click on Continue to access the sketch area. This area provides you with a CAD interface where you can draw the geometry of your model.

4.2.3 Material Definition

Double-click on the Materials node in the Model Tree (Fig. 4.2)

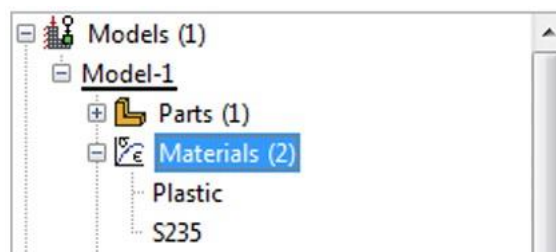


Fig. 4.2 Material selection tab

Name the new material and give it a description. To define an Elastic Material click on the Mechanical tab Elasticity Elastic and give appropriate values for the Young's Modulus and the Poisson's ratio (Fig. 4.3)

Edit Material

Name: S235
Description: I

Material Behaviors

- Elastic

General Mechanical Thermal Other

Elastic

Type: Isotropic

☐ Use temperature-dependent data

Number of field variables: 0

Moduli time scale (for viscoelasticity): Long-term

☐ No compression

☐ No tension

Data

	Young's Modulus	Poisson's Ratio
1	210000000	0.3

OK Cancel

Fig. 4.3 Edit Material Form – Elastic Material Definition

4.2.4 Model Specifications

We provide the model specification to shape the columns with length extrusion in all three axes, conforming to the dimensions required based on the modeled shape.

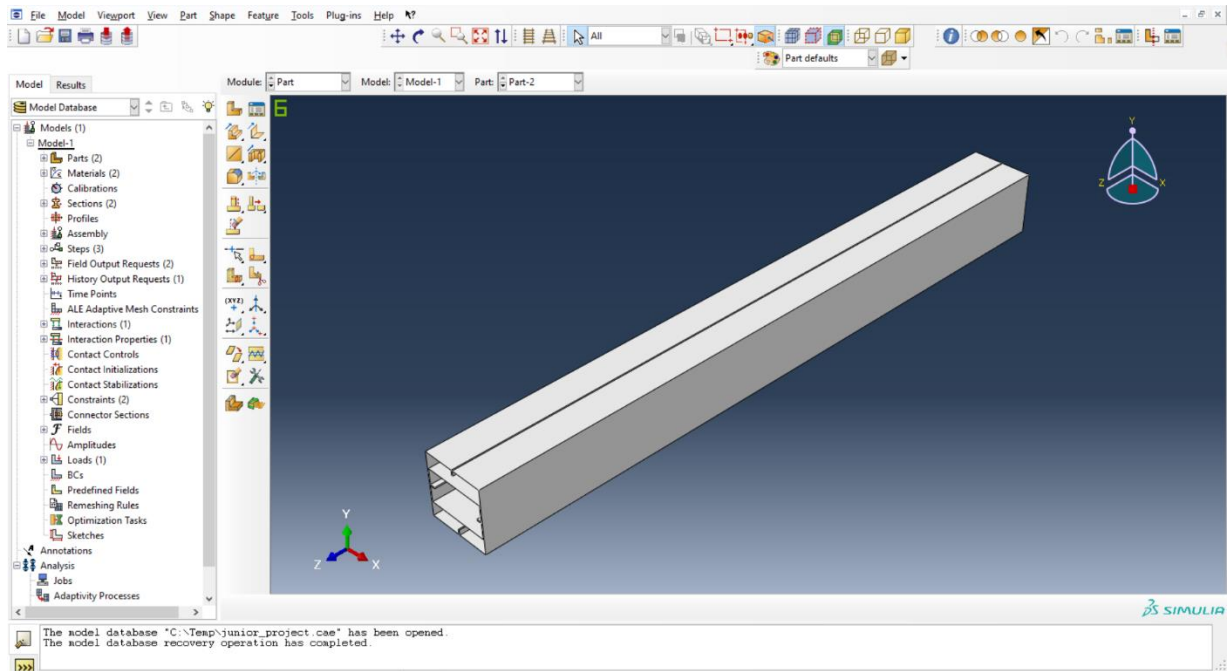


Fig. 4.4 Outline of Built-up column Model DCTT

4.2.5 Properties Application

By inputting the values obtained from coupon test results as properties in software, we can ensure that the material matches exactly with the experimental testing. Additionally, feeding the properties of the materials that will be used in the experiment allows us to expect accurate results in an analytical investigation.

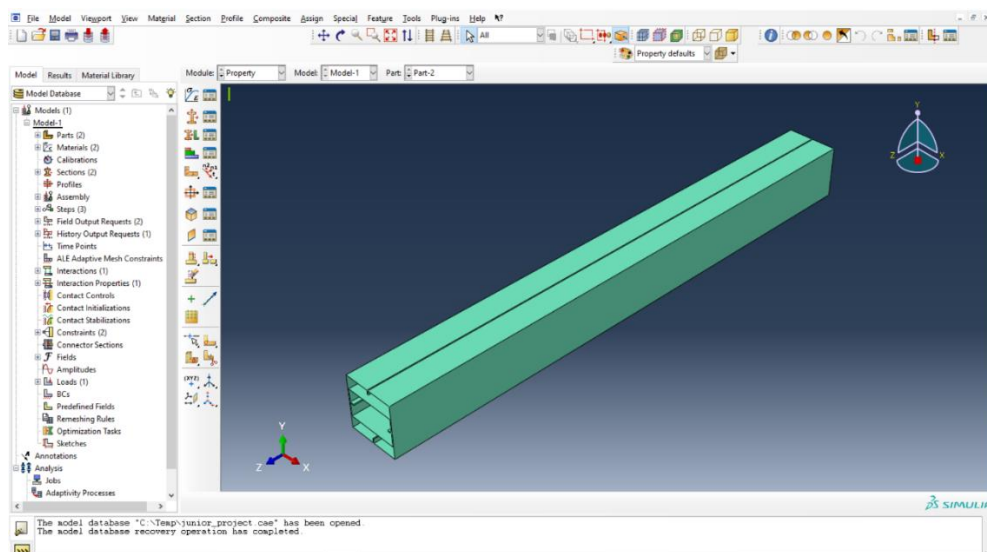


Fig. 4.5 Properties Application of Built-up Column Model DCTT

4.2.6 Creation Of Interactions

Typically, the model is designed with separate outer and inner components. In order to ensure uniform application of load, it is crucial to connect all sections to each other. This can be accomplished using an interactive tool to connect all separate components to the reference point at both ends. By doing so, the load application will be uniform.

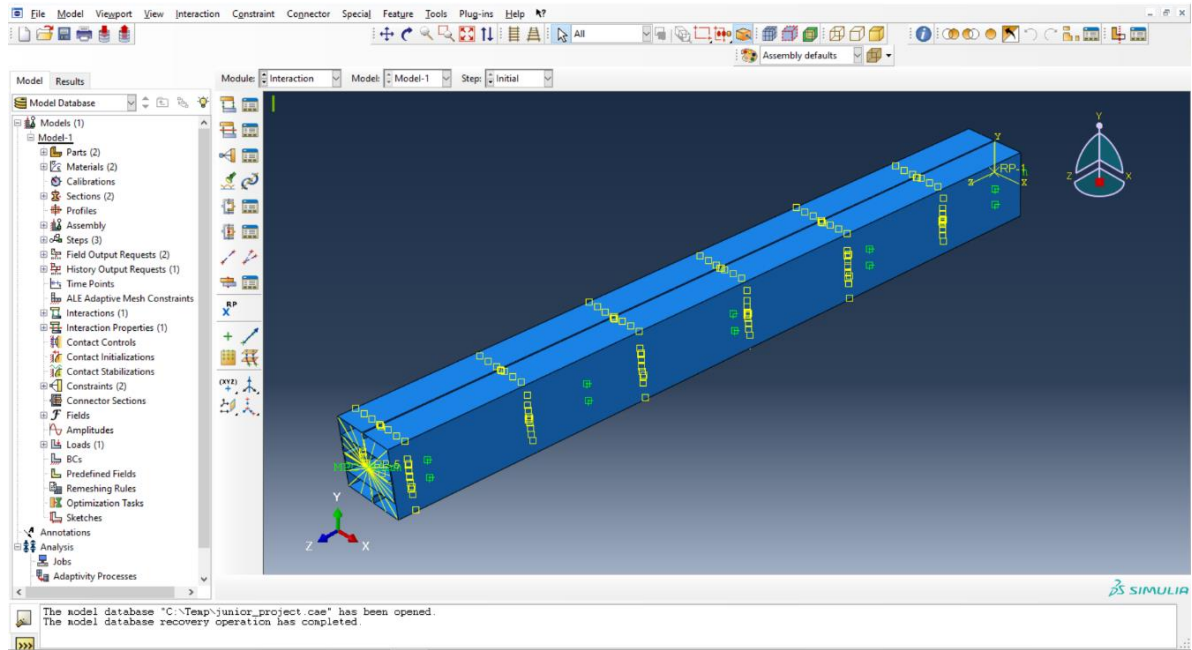


Fig. 4.6 Interaction of Built-up Column Model DCTT

4.2.7 Assigning The Bolt Hole

Once the interactions are created, bolt nut points are added using the assembly tool. The exact bolt holes positions, as specified in the design specification, is provided in this model. The diameter of the bolt-hole spacing can also be defined using this tool.

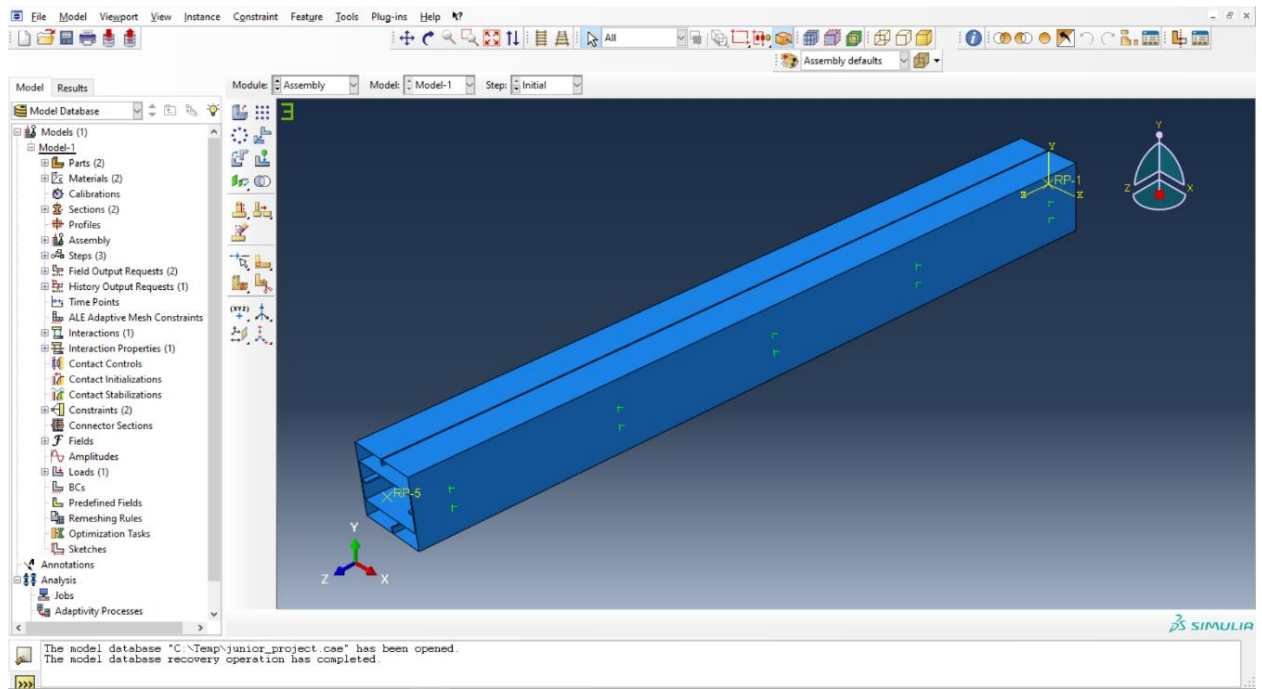


Fig. 4.7 Creation of assembly in Abaqus Model DCTT

4.2.7 Analysis Part

As the final step, after applying the load and boundary conditions to the model, we can run the analysis by creating a new job and selecting the appropriate boundary condition for the load application. Then, we can run the job and monitor the results. If any errors are encountered, they must be addressed before obtaining the final output. We can plot the results on an XY graph to check the maximum stress distribution and other values. Additionally, Fig. 4.5 below represents the buckling of the model created.

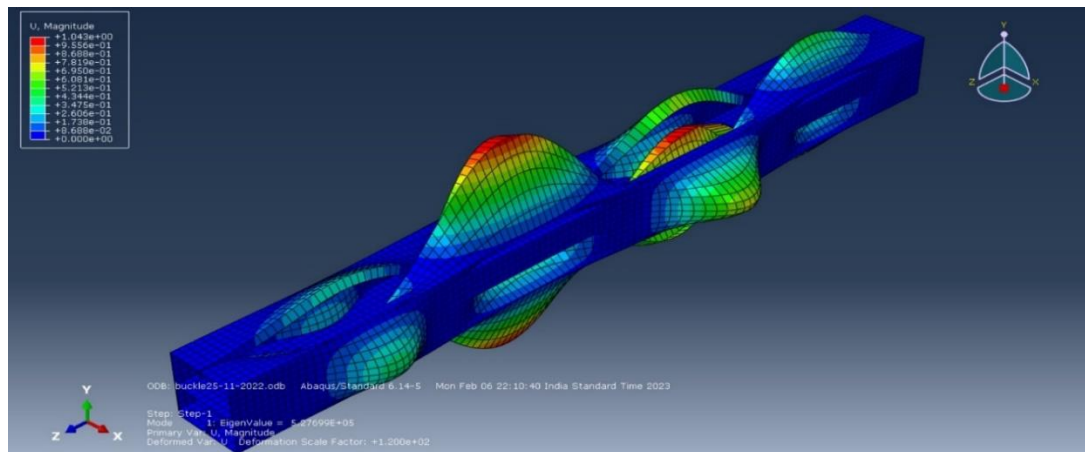


Fig. 4.8 Buckling Shape of Model DCTT

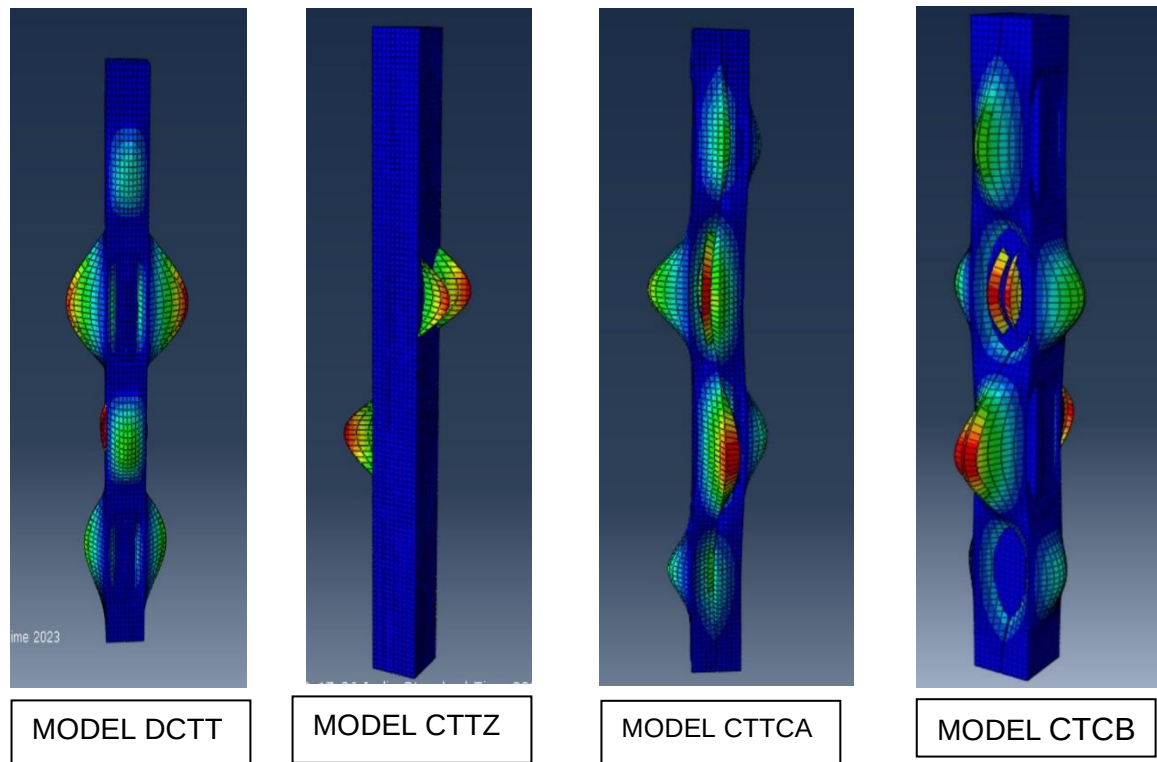


Fig. 4.9 Buckled shapes of all 4 models

Table 4.1 Analytical Results

S.NO.	MODEL	LOAD	UNIT
1	DCTT	490	kN
2	CTTZ	527	kN
3	CTTCA	306	kN
4	CTCB	490	kN

CHAPTER 5

EXPERIMENTAL INVESTIGATION

5.1 *EXPERIMENTAL SETUP*

The built-up column designed using the results from the analytical method is fabricated and set up for testing as per the procedure mentioned below

- The built-up column was fabricated according to Fig. 3.10, and another model was fabricated as shown in Fig. 3.11. The modeling was carried out in Abaqus, following the procedure shown in Fig. 3.12. Properties were applied to the modeled section, as shown in Fig. 3.13, and interactions were created using Abaqus, as shown in Fig. 3.14, to establish the reference point for load application. Then, the assembly was used to combine all parts into a single component, as shown in Fig. 3.15, and finally, the column top and bottom were attached with a base plate measuring 300mm x 300mm for uniform load application.
- The outer core and inner compound section were fastened and maintained at the same level to ensure proper load application.
- An LVDT was attached to the specimen at the collar, middle, and bottom of the column to read the buckling and stress distribution during load application.
- As the load was gradually applied, the column tended to buckle, and photos were taken to document the buckling for further reference.
- The experimental setting for the 1250-mm long specimens is shown in Fig. 3.10, The specimens were subjected to compression using an Instron testing frame with a capacity of 1000 KN. Steel loading plates were placed between the column ends and the loading platens of the Instron testing frame.
- Before testing, the specimens were aligned to make the centre of the compression platens, steel loading plates, and the net sections of the specimens coincide mutually.
- A preload of 1 KN or load as per required to hold the specimen in position before the initial load is applied and then released.
- Finally, a gradual load applied through machine operated with ease quick

testing without any lag in the reading.

5.1.1 Experimental Test Procedure

To initiate the load application in the experiment, the following steps should be followed

- A compressive test is conducted using a hydraulic testing machine with a 100 ton capacity.
- Before conducting the test, the specimens should be positioned in the testing machine with proper alignment and verticality.
- Compressive loading is applied to the specimens under displacement control with a constant rate of 0.01 mm/s, and the test is stopped when there is a reduction of at least 50% in the load.
- Various LVDT are attached to the collar of the column and mid zone of the model and then at the bottom to note down the buckling in all direction with one additional LVDT at the top to monitor the load application.
- The strain gauges are positioned at three different levels along the length of the column - top, middle, and bottom - based on the information obtained from numerical simulations.
- The strain gauges at level-1 are installed in all tested built-up cross-sections, and additional strain gauges should be positioned at level-2 and level-3.

5.1.2 Purchasing Of CR Sheets

In line with the design of the 4 column models, the required amount of sheet metal is calculated and procured. The sheets have a thickness of 2mm and a dimension of 1200mm x 2400mm.



Fig. 5.1 Purchase of CR sheet

5.1.3 Laser Cutting Of CR Sheet

The predetermined cutting size and dimensions are implemented by utilizing Auto-Cad software and then the material is cut using both laser and manual brake pressing machine

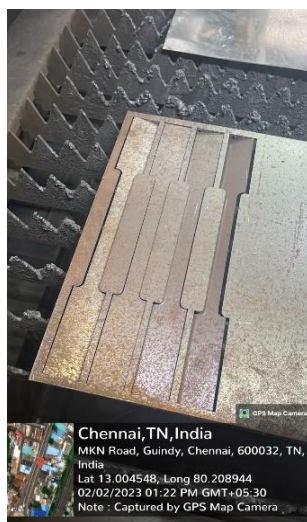


Fig. 5.2 Laser Cutting of CR Sheet

5.1.4 Folding Of CR Sheets

The brake pressing machine is used to fold the cut sheets according to the specified dimensions for all four models with precise measurements.



Fig. 5.3 brake pressing machine

5.1.5 Welding And Fasteners



Fig. 5.4 Welding and Fasteners

We used TIG welding to fabricate the models as shown in section 3.4 and then fastened them with bolts and nuts. Welding inside the section was difficult due to the fixed outer core, so we opted for the bolt and nut method instead

5.1.7 Experimental Results



Fig. 5.5 Experimental Buckling Shapes of Model DCTT & Model CTTZ

Table. 5.1 Maximum Load In Axial Direction Set 1

S.NO.	MODEL	LOAD	UNIT
1	DCTT	375	kN
2	CTTZ	398	kN



Fig. 5.6 Experimental Buckling of Model CTTCA & Model CTCB

Table. 5.2 Maximum Load In Axial Direction Set 2

S.NO.	MODEL	LOAD	UNIT
1	CTTCA	195	kN
2	CTCB	320	kN

CHAPTER 6

RESULTS AND DISCUSSION

6.1 RESULTS AND DISCUSSION

Based on the experimental and analytical results, the following discussions can be made to study the difference in load-carrying and maximum performed section with a weight-to-strength ratio

- The load vs deflection graph shows that the experimental deflection is significantly higher compared to the analytical results.
- The axial load-carrying capacity of the four models is 15-30% similar to the results noted from the Abaqus software, indicating that the software can be used to determine the real-time load-carrying application of the complicated models for construction applications or simulation of the performance before using it in real-time projects.
- The intermediate column with a slenderness ratio used in the experiment showed good performance in both experimental and analytical tests, making it suitable for use in real-time applications where an intermediate column is required.
- Buckling in Model CTTCA occurred at the column's center zone exactly opposite each other, resulting in the least performance.
- Buckling in Model CTTZ occurred on all four sides, indicating that the model withstood heavier loads with the best performing among all 4 models.

6.1.1 Axial Load Carrying Capacity Comparison

To conduct the experiment, a loading frame is used to apply gradual load along the Y-axis to the 4 samples. The load vs deflection data is collected at each increment to plot the load vs deflection graph, which is then compared with the analytical results.

The buckling of the columns is visually observed and evaluated with the analytical buckling location. In addition, LVDT is attached to the top and middle zones to measure the deformation of the shape when buckling is minimal.

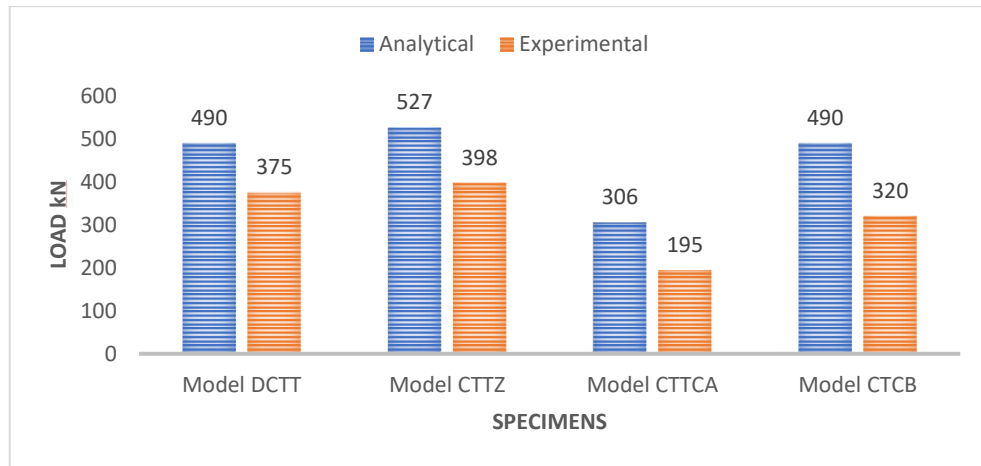


Fig. 6.1 Axial Load Carrying Capacity of Experimental And Analytical Results

6.1.2. Analytical Results

Fig. 6.2 displays the results of all four models, indicating that the loads in these models are not gradual based on the shape of the internal compound layer. The performance of each model varies with respect to this unique shape compounded and the CTTCA model is the least performing among them.

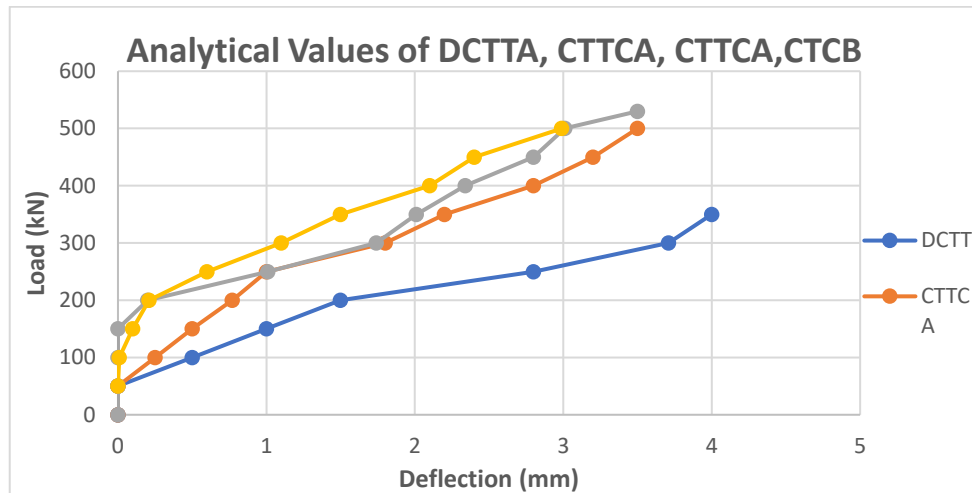


Fig. 6.2 Load vs Deflection curve for Model DCTT, CTTCA, CTTCA and CTCB – Analytical Values

6.1.3. Experimental Results

The results of all four experimental models are presented in Fig. 6.3, with the models arranged in order from least to most effective. Surprisingly, the CTTC model, which has a smaller cross-sectional area, outperformed the other models. Conversely, the CTCB model, which has a larger cross-sectional area, was the least effective of the four.

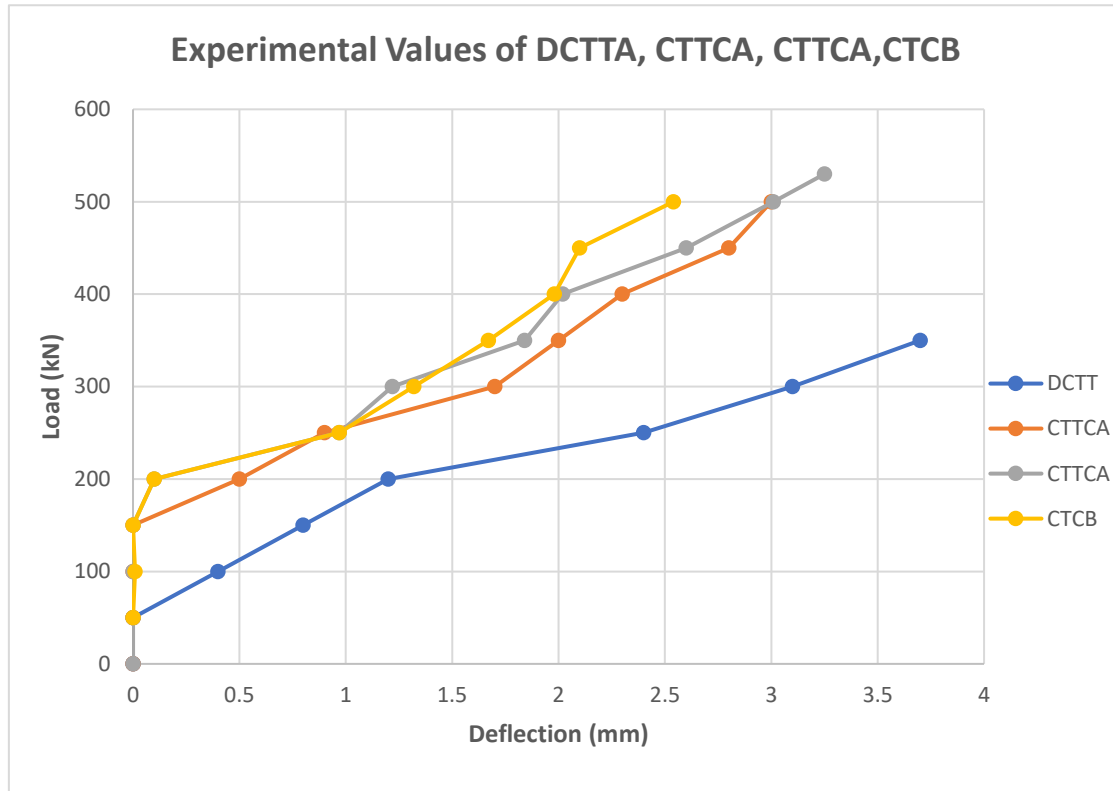


Fig. 6.3 Load vs Deflection curve for Model DCTT, CTTC, CTTC, and CTCB – Experimental Values

6.1.4. Comparison Of Analytical And Experimental Results

Comparing the results of both experiments as in Fig. 6.4, it is evident that they performed similarly, with variations ranging from 15% to 30%. These discrepancies may have arisen due to human error during welding or because of the presence of bolt holes and bend in the sheets caused during transportation. However, despite these variations, the results can be utilized in real-time projects to investigate the critical performance of the section

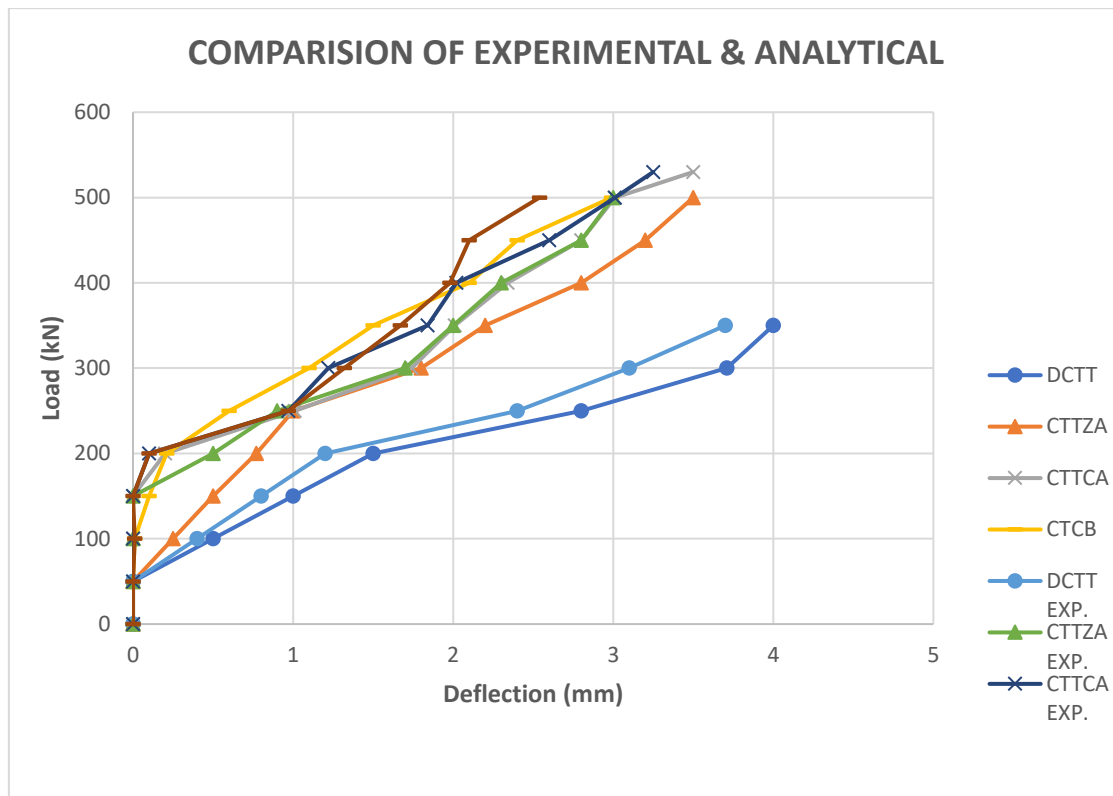


Fig. 6.4 Load vs Deflection Comparison of Both Analytical And Experimental Results.

6.1.5. Weight To Strength Ratio

By comparing the strength and weight of the models we can achieve the percentages with that we can conclude whether the model with a higher cross-section performed well or it depends upon the shape which exactly takes more load.

Table 6.1 Strength To Weight Comparison

S. No.	MODEL	WIGHT (Kg)	ANALYTICAL RESULT (kN)	EXPERIMENTAL RESULT (kN)	STRENGTH-TO-WEIGHT RATIO
1.	DCTT	21.20	492	375	17.68%
2.	CTTZ	18.75	527	398	21.22%
3.	CTTCA	20.85	306	195	14.67%
4.	CTCB	21.15	490	320	15.13%

CHAPTER 7

CONCLUSION AND RECOMMENDATION

Through an extensive review of the literature, the load-carrying capacity and buckling behavior of steel built-up columns were studied, leading to the following observations.

- Analysis of literature helped in defining the project objective and formulating a methodology flow chart.
- Selection of the column shape was based on its ease of folding and use in the field, beside its maximum load-carrying capacity.
- The literature also provided insights into the behavior of cold-formed steel built-up columns under buckling and compression.
- The different shapes of built-up columns were studied through literature to understand their buckling behavior.
- The importance of incorporating lips in steel shapes was also realized through the literature review.

If this research is to be studied in detail, the following recommendations can be adopted.

- Increase the thickness of the sheet to enable a more detailed analysis of its performance in relation to thickness.
- Increase the specimen size H of a well-performing specimen to study its performance when the same shape is required but at different heights.
- To improve the reliability and durability of the samples, it is suggested to reduce the number of screw or bolt holes.
- Furthermore, testing the performance with continuous welding may yield valuable insights.

REFERENCES

- [1] Chen. M.T. and Young. B, “Tests of cold-formed normal and high strength steel tubes under tension,” *Thin-Walled Structures*, vol. 153, Aug. 2020, doi: 10.1016/j.tws.2020.106844.
- [2] Chen. M. T. and Young. B, “Beam-column tests of cold-formed steel elliptical hollow sections,” *Eng Struct*, vol. 210, May 2020, doi: 10.1016/j.engstruct.2019.109911.
- [3] Craveiro. H. D, Rahnavard. R, Laím. L, Simões. R. A, and Santiago. A, “Buckling behavior of closed built-up cold-formed steel columns under compression,” *Thin-Walled Structures*, vol. 179, Oct. 2022, doi: 10.1016/j.tws.2022.109493.
- [4] Craveiro. H.D, Rahnavard. R, Laím .L, Simões. R. A., and A. Santiago, “Buckling behavior of closed built-up cold-formed steel columns under compression,” *Thin-Walled Structures*, vol. 179, Oct. 2022, doi: 10.1016/j.tws.2022.109493.
- [5] El Hady. A.M, El Aghoury M.A, Ibrahim S.M., and Amoush E. A., “Experimental investigation of steel built-up beam-columns composed of tracks and channels cold-formed sections,” *Journal of Building Engineering*, vol. 51, Jul. 2022, doi: 10.1016/j.jobbe.2022.104295.
- [6] Evirgen. B, Tuncan. A, and Taskin. K, “Structural behavior of concrete filled steel tubular sections (CFT/CFSt) under axial compression,” *Thin-Walled Structures*, vol. 80, pp. 46–56, 2014, doi: 10.1016/j.tws.2014.02.022.
- [7] Glauz. R.S, “Strength-based requirements for end connections of built-up cold-formed steel columns,” *Thin-Walled Structures*, vol. 182, Jan. 2023, doi: 10.1016/j.tws.2022.110265.
- [8] Huang . Y and Young . B, “The art of coupon tests,” *J Constr Steel Res*, vol. 96, pp. 159–175, May 2014, doi: 10.1016/j.jcsr.2014.01.010.
- [9] Huang. Y and Young. B, “Design of cold-formed stainless steel circular hollow section columns using direct strength method,” *Eng Struct*, vol. 163, pp. 177–183, May 2018, doi: 10.1016/j.engstruct.2018.02.012.
- [10] Kesawan. S and Mahendran. M, “Post-fire mechanical properties of cold-formed steel hollow sections,” *Constr Build Mater*, vol. 161, pp. 26–36, Feb. 2018, doi: 10.1016/j.conbuildmat.2017.11.077.

- [11] Manikandan. P and Pradeep. T, "Effective Cross Section of Cold Formed Steel Column Under Axial Compression," *Journal of The Institution of Engineers (India): Series A*, vol. 99, no. 2, pp. 245–255, Jun. 2018, doi: 10.1007/s40030-018-0276-9.
- [12] Misiunaite.I, Gribniak.V , Rimkus. A, and Jakubovskis.R, "The efficiency of utilisation of high-strength steel in tubular profiles," *Materials*, vol. 13, no. 5, Mar. 2020, doi: 10.3390/ma13051193.
- [13] Nie . B, S. Xu, J. Yu, and H. Zhang, "Experimental investigation of mechanical properties of corroded cold-formed steels," *J Constr Steel Res*, vol. 162, Nov. 2019, doi: 10.1016/j.jcsr.2019.105706.
- [14] Nie. B, S. Xu, Z. Zhang, and A. Li, "Surface morphology characteristics and mechanical properties of corroded cold-formed steel channel sections," *Journal of Building Engineering*, vol. 42, Oct. 2021, doi: 10.1016/j.jobbe.2021.102786.
- [15] Poursadrollah. A, D'Aniello. M, and Landolfo. R, "Experimental and numerical tests of cold-formed square and rectangular hollow columns," *Eng Struct*, vol. 273, Dec. 2022, doi: 10.1016/j.engstruct.2022.115095.
- [16] Senthilkumar. R, Divya. M, Divya. Roy S, A. Bahurudeen, S. Avudaiappan, and K. D. Tsavdaridis, "Behaviour of cold-formed steel-concrete composite columns under axial compression: Experimental and numerical study," *Structures*, vol. 44, pp. 487–502, Oct. 2022, doi: 10.1016/j.istruc.2022.07.086.
- [17] Singh. T.G. and K. D. Singh, "Design of perforated cold-formed steel hollow stub columns using direct strength method," *Thin-Walled Structures*, vol. 168, Nov. 2021, doi: 10.1016/j.tws.2021.108265.
- [18] Tunca.O, F. Erdal, A. E. Sağsöz, and S. Çarbaş, "Structural features of cold-formed steel profiles," *Challenge Journal of Structural Mechanics*, vol. 4, no. 2, p. 77, Jun. 2018, doi: 10.20528/cjsmec.2018.02.005.
- [19] Wu. J. R., Di Sarno. L, Hesketh. S, and Phan. N, "Buckling Resistance of Axially Loaded Cold-Formed Steel Compound Sections: Numerical Simulation and Assessment of Codified Design Approach," *International Journal of Steel Structures*, 2022, doi: 10.1007/s13296-022-00641-y.

- [20] Yao. Y, Quach W. M., and Young. B, "Stress–strain model and design strength of cold-formed steel non-slender elliptical tubular stub columns," *Thin-Walled Structures*, vol. 181, Dec. 2022, doi: 10.1016/j.tws.2022.110037.
- [21] Yan. X and Gernay. T, "Local buckling of cold-formed high-strength steel hollow section columns at elevated temperatures," *J Constr Steel Res*, vol. 196, Sep. 2022, doi: 10.1016/j.jcsr.2022.107403.
- [22] Zhang. P and Alam. M.S, "Compression tests of thin-walled cold-formed steel columns with Σ -shaped sections and patterned perforations distributed along the length," *Thin-Walled Structures*, vol. 174, May 2022, doi: 10.1016/j.tws.2022.109082.
- [23] zhi Liu. J, Fang. H, and chan T. M., "Experimental investigation on material properties and residual stresses in cold-formed high strength steel irregular octagonal hollow sections," *J Constr Steel Res*, vol. 191, Apr. 2022, doi: 10.1016/j.jcsr.2022.107170.
- [24] zhi. J Liu, Fang. H, and Chan. T.M, "Experimental and numerical investigations on stub column behaviour of cold-formed high strength steel irregular octagonal hollow sections," *Thin-Walled Structures*, vol. 180, Nov. 2022, doi: 10.1016/j.tws.2022.109770.
- [25] Zhu. J.H. and Young. X, "Design of cold-formed steel oval hollow section columns," *J Constr Steel Res*, vol. 71, pp. 26–37, Apr. 2012, doi: 10.1016/j.jcsr.2011.11.013.