Effect of Steel and Concrete Thickness on Shear Strength of Square Concrete Filled Double Skin Tubular Beams (CFDSTB'S)

By

NAJEEB ULLAH

(NUST-2016-MS STRUCTURAL ENGINEERING- 00000172226)

Thesis submitted in partial fulfilment of the requirements for the degree of

Master of Science

In

Structural Engineering

NUST Institute of Civil Engineering (NICE)

School of Civil and Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST)

Islamabad, Pakistan

(2020)

This is to certify that the thesis titled

"Effect of Steel and Concrete Thickness on Shear Strength of Square Concrete Filled Double Skin Tubular Beams (CFDSTB'S)"

Submitted by

NAJEEB ULLAH

(NUST-2016-MS STRUCTURAL ENGINEERING- 00000172226)

Has been accepted towards the partial fulfilment

of

the requirements for the award of degree of

Master of Science in Structural Engineering

Thesis Supervisor

____

Dr. Muhammad Usman

Assistance Professor

NUST Institute of Civil Engineering (NICE)

National University of Sciences and Technology (NUST),

Islamabad, Pakistan

<u>THESIS ACCEPTANCE CERTIFICATE</u>

It is certified that final copy of MS thesis written by **Mr. Najeeb Ullah,** Registration No. **00000172226)** of **NUST INSTITUTE OF CIVIL ENGINEERING (NICE)**, has been vetted by undersigned, found complete in all respects as per NUST Statutes / Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS degree in Structural Engineering.

Signature: ______________________________

Name of Supervisor: **<u>Dr. Muhammad Usman</u>**

Date: ______________________________________

Signature: ______________________________

Head of Department: **<u>Dr. Rao Arsalan Khushnood</u>**

Date: ______________________________________

Signature: ______________________________

Dean: **<u>Dr. S. Muhammad Jamil</u>**

Date: ______________________________________

Dedication

I dedicate this effort to my family, teachers and friends without whom, this work would not have been possible. I am also thankful to Almighty Allah and His Last Prophet Muhammad (S.A.W) for the strength that I derive from Islam.

ACKNOWLEDGEMENT

I would like to thank my supervisor Dr. Muhammad Usman and my co-supervisor Dr. Syed Hassan Farooq. I also owe my deepest appreciation to myself for believing in myself, and my friends, particularly Engr. Wahab Ashraf, Engr. Rehan Alam, Engr. Asad Khan and Engr. Bilal Nasir for their help and support. Moreover, I also appreciate the cooperation of Chief Engineer, CCB, Fareed-ul-Islam Khan and CEO, Mr. Malik Ishaque for allowing me the time and space to continue with research work.

ABSTRACT

Concrete Filled Double Skin Tubular (CFDST) members are one of the most advanced forms of composite construction, consisting of two tubes, placed eccentrically or concentrically, with concrete sandwiched between the tubes. CFDST members are characterized by their increased flexural strength, improved ductility and enhanced stiffness which render them suitable for earthquake prone regions. This paper explores the shear characteristics of square CFDST beams experimentally under the application of uniformly distributed load (UDL). Two main parameters i.e. steel thickness and thickness of the sandwiched concrete, were varied and their effect on shear strength was studied along with the associated energy dissipation and ductility. It has been found that decreasing the thickness of the sandwiched concrete (by increasing the dimensions of the inner tube) for the same thickness of the steel tubes decreases the shear strength of the members. On the other hand, increasing the gauge (thickness) of the steel tubes for the same thickness of the sandwiched concrete increases the shear strength. Also, as the dimensions of the inner tube increases (thickness of the sandwiched concrete decreases) for the same thickness of the steel tubes, the associated energy dissipation decreases while the ductility increases.

Table of Contents

1. Dedication ... iii
2. ACKNOWLEDGEMENT ... iv
3. ABSTRACT ... v
4. LIST OF FIGURES ... viii
5. LIST OF TABLES ... ix
6. CHAPTER 1: INTRODUCTION ... 1
   - 6.1. Background ... 1
   - 6.2. Applications of double skin tubular members ... 3
   - 6.3. Research problem ... 4
   - 6.4. Relevance to the national needs ... 5
   - 6.5. Research Methodology: ... 5
   - 6.6. Research objectives ... 5
   - 6.7. Scope of the research ... 6
   - 6.8. Thesis Overview: ... 6
7. CHAPTER 2: LITERATURE REVIEW ... 7
   - 7.1. History of double skin tubular Members ... 7
   - 7.2. Types of double skin tubular members ... 7
   - 7.3. Previous studies conducted ... 9
     - 2.3.1 Concrete Filled Steel Tubes ... 9
     - 2.3.2 Members having inner steel tube with outer FRP Covering ... 10
     - 2.3.3 Members having inner and outer tubes made up of steel ... 13
8. CHAPTER 3: METHODOLODY ... 20
   - 2.4 Material properties ... 20
   - 2.5 CDST Samples Preparation: ... 21
   - 2.6 Testing Program Description of specimen: ... 22
   - 2.7 Test setup and procedure: ... 25
   - 2.8 Parameters studied ... 26
     - 2.8.1 Shear Load Deflection Relationship ... 27
     - 2.8.2 Energy Dissipation ... 27
     - 2.8.3 Ductility Factor ... 28
9. CHAPTER 4: ANALYSIS, RESULTS AND DISCUSSION ... 29
   - 4.1 General ... 29

9.1. Peak Shear loads and Ultimate Shear Loads 30
9.2. Comparison of Trend with Circular Beams: 33
9.3. Shear Load deflection relationship: 33
9.4. Ductility: 35
9.5. Shear Energy dissipation: 37
5 CHAPTER 5: CONCLUSIONS AND RECOMMEDATIONS 40
5.1 Conclusion 40
5.2 Recommendations 40

LIST OF FIGURES

Figure 1: Sections for Hybrid Double Skin Tubular Members [29] 2
Figure 2 Classification of CFDST beams based on material [27] 8
Figure 3 Classification of CFDST beams based on geometry [27] 9
Figure 4 Foundation supporting column [39] 11
Figure 5 orientation of fiber on beam [44] 12
Figure 6 Four Point Loading of Hybrid-CFDST beams [45] 12
Figure 7 Cross section of Hybrid-CFDST beam [22] 13
Figure 8 Different Sections of CFDST members i.e. rectangular and circular [11] 17
Figure 9 CFDST stub column [10] 18
Figure 10 Load Deflection Curve of Circular CFDST Beams [49] 19
Figure 11 Casting of CFDSTB's and prepared CFDSTB 21
Figure 12 Schematics of Cross-Sections of CFDSTB's 24
Figure 13 Cross-Sections of Casted CFDSTB's 24
Figure 14 Universal Testing Machine used for Testing 25
Figure 15 (a) Schematics of Test Setup (b) Test Setup 26
Figure 16 Data Acquisition System Consisting of (a) LVDT and (b) Data Logger................ 26
Figure 17 Determination of Yield Point and Ductility [30] 27
Figure 18 Trapezoidal Rule for Area under the Curve [54] 27
Figure 19 Actual Curve and its Bi-Linear Idealization [55] 28
Figure 20 Effect of Steel and Concrete Thickness on Peak Shear and Ultimate Shear Loads Peak Shear Loads 31
Figure 21 Peak Shear Loads and Ultimate Shear Loads for Corresponding Concrete and Steel Thickness 31
Figure 22 Load vs. Displacement Curves of Beams 34
Figure 23 Shear Cracks in CFDST Beams 35
Figure 24 Ductility Factor for 12 CFDSTB's of different Steel and Concrete Thickness based on Equal Energy Principle 36
Figure 25 Ultimate Displacements 37
Figure 26 Shear Energy Dissipation 38

LIST OF TABLES

Table 1 Steel Properties 20
Table 2 Properties of Concrete 21
Table 3 Description of Specimens 23
Table 4 Summary of Results 29
Table 5 Percentage Increment/Decrement 32
Table 6 Circular Vs. Rectangular CFDSTB’s 33

CHAPTER 1: INTRODUCTION

6.1. Background

The combination of steel and concrete is widely used in modern construction. In composite structures the combination of steel and concrete results in performance improvement, such as increased strength, ductility, stiffness and economy. One such example of composite construction is that of Concrete Filled Tubes (CFDST) members which consists of steel beams sandwiching concrete between them. They vary in sizes and shapes and can be circular or square. As compared to ordinary RC members, Concrete Filled Tubes (CFT's) as structural elements in buildings and other civil engineering structures have been found to show increased loading carrying capacity, better plasticity, improved earthquake resistance and ease of handling during construction[1, 2]. CFT's have also been found to dissipate more energy as compared to ordinary RC members**[3]**. Moreover, the confinement of the inner concrete by the tube delays the local buckling of concrete, increases the ductility and augmented the fire resistance of the members[4, 5].

Later on, Concrete Filled Double Skin Tubular (CFDST) members were introduced. The first reported use of double skin tubular members could be traced back to 1980's when they were used in the form of columns. At that time, it consisted of two concentrically placed tubes filled with concrete[6]. Afterwards, its scope increased with the inclusion of eccentrically placed tubes and concrete sandwiched between them. The use of different shapes also came under the ambit of its scope and both Rectangular Hollow Section (RHS) and Circular Hollow Section (CHS) tubes were used[5]. The CFDST members have all the advantages that ordinary Concrete Filled Tubes (CFT) carry[7, 8].

However, CFDST members possess some additional advantages which render them superior to ordinary CFT members. Due to the presence of a hollow space, the resulting structure is light weight [9, 10] and offers more compressive strengths [11, 12]. Moreover, central hollow space can also serve as opening for laying sewer pipes or wires[13]. Fire resistance is one of the main advantages of CFDST. The outer tube serve as a cover for the inner tube and allow it to maintain strength in an event of fire[14]. Also, the protected inner tube can sustain the structural loads and contribute more to the fire resistance[15, 16].

Overtime, the axial response of Concrete Filled Double Skin Tubular Columns was studied in detail[17, 18]. Concrete Filled Double Skin Tubular Columns were found to have enhanced ductility and increased strength due to the confinement of the sandwiched concrete[13]. As compared to sections with inner rectangular tubes, those with inner circular tubes showed more sensitivity towards the ratio of the hollow section[19]. For higher grades of concrete, the results are consistent only if the steel strengths are correspondingly effective[20]. Also, they have been found to depict improved seismic performance [21-23].

With the aim of further improvement, a slight modification to the CFDST with addition of Fiber Reinforced Polymer (FRP) to the outer layer, referred to as hybrid CFDST, has been studied. These members, like CFDST members, have been found to possess higher ductility as compared to ordinary rectangular reinforced concrete members with greater resistance to hoop stresses when axially loaded[24, 25]. Moreover, two methods of increasing the flexural response of hybrid CFDST beams, one by providing longitudinal bars and second by change in position of the inner tube towards the tension zone, have also been studied[26]. Also, this behavior is effected by both the thickness and diameter of the inner steel tube[27]. If mechanical connectors are used on the steel tube, the gain is two pronged. Firstly, slippage is controlled and secondly, the resistance to fluctuating cyclic loads is increased. Furthermore, depending on the thickness of fiber reinforced polymer layers and the total number of layers, Hybrid-CFDST have been found to possess an enhanced stiffness and improved flexural response[28].

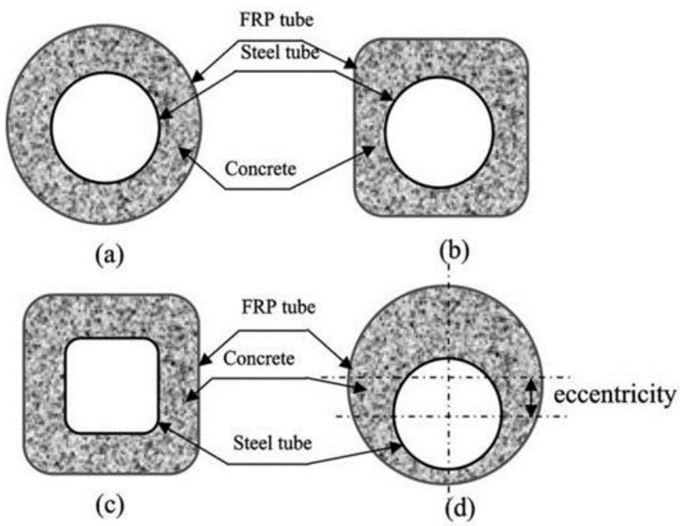


Figure 1: Sections for Hybrid Double Skin Tubular Members [29]

Recently, the effect of the flexural parameters of CFDST beams that contain Square Hollow Section (SHS) of steel on outer as well as inner side and the two tubes connected with the help of steel strips has been studied under monotonic and cyclic loading. Hollow CFDST beams with eccentric steel tube showed better flexural response in addition to being economical due to less concrete volume [30].

The shear strength of beams without stirrups depends on various factors which include, but are not limited to, fiber factor, shear span to depth ratio, longitudinal steel ratio and size of beams[31]. Also, the shear strengths at diagonal tension cracking has been found to decrease roughly linearly as the corresponding maximum stresses in the reinforcement increased[32].In Fiber Reinforced Beams without shear reinforcement, increase in quantity of fibers was found to increase the beams' stiffness and ductility, depending upon the shear-span/depth ratio and transformed the mode of failure into a more ductile one[33]. Moreover, in RC beams strengthened with fibers, the primary cause of shear failure has been found to the rapid loss of load capacity due to separation of the strengthening fibers from the base material[34]

The effect of diameter to thickness ratio and inner to outer diameter ratio on the shear capacity of circular CFDST beams under monotonic loading has also been studied and it found that shear capacity decreases with the increase in inner to outer diameter ratio and the decrease in diameter to thickness ratio, respectively[35]. However, this study is only limited to circular beams while rectangular beams are generally preferred in building construction due to their ease of handling, simpler stress distribution and more moment of inertia.

In order to abridge the research gap characterized by the non-availability of a comprehensive study on the shear characteristics of rectangular CFDSTB's, this paper presents a thorough study of the shear characteristics of square CFDST beams having both inner and outer square tubes made up of steel and the space between them filled with concrete. The effect on shear strength has been studied with the change in the thickness of the sandwiched concrete and that of steel. The experimental program selected for this purpose includes a total of 12 beams, tested under uniformly distributed load (UDL) in Universal Testing Machine (UTM). A Linear Variable Differential Transformer (LVDT) connected to Data acquisition system was used to acquire the required data.

6.2. Applications of double skin tubular members

These members have variety of applications. Nowadays, world is aiming at the development of materials that can be used for high speed construction. CFDST members can be used for precast construction which can save time and economy simultaneously. Concept of CFDST members was originally obtained from submerged tube tunnels. These structures are believed to be used for containing liquid, gasses and nuclear structures [15]. This type of construction can be used for constructing seabed vessels in deep water at the legs of platforms, for the columns having larger diameter and, in the structures that are exposed to ice loading [18]. Recently, it was used in high rise piers in japan which has reduced weight accompanied by increased energy absorption capacity [19]. The fiber reinforced polymer has found many applications in civil engineering. Main advantage for using FRP is its high strength to self-weight ratios. Researchers are trying to use them in new construction despite their applications in retrofitting [17]. CFDST has been used throughout the world as beams and as beam-columns, in both braced and unbraced elements of structural systems. They have wide range of applications such as compression member in low rise structures, construction of open floor, steel circular tubes filled The members under consideration have numerous current world applications. CFDST members can be used for precast construction can be economical and time saving. Such concepts were originally obtained from submerged tube tunnels but can also be used for structures containing liquid, gasses and nuclear containment [15]. This type of construction usually used for seabed vessels, in deep water at the legs of platforms, the columns having larger diameter and to the structures exposed to ice loading [18]. In Japan it has been recently used for deep piers, which has reduced weight with increased energy absorption capacity [19]. The fiber reinforced polymer has found numerous applications in civil engineering. Main advantage is high strength to self-weight ratios. Researchers are trying to use them in new construction despite their prevailing use in retrofitting applications [17].

CFST has been used worldwide as beams and as beam-columns in both braced and un-braced elements structural systems. They have been used in different types of constructions such as members for compression in low rise, construction of open floor, steel circular tubes filled with concrete or pre-cast concrete etc. Concrete filled square box and circular columns have been used in few of the world tallest buildings [20]

6.3. Research problem

In the contemporary times, Fiber Reinforced Polymers FRP are preferred for external strengthening of structural members. However, it is preferable for columns because of its higher hoop strength. On the other hand, for a beam, we need such a material that can resist both transverse and flexural stresses. Steel, being isotropic in nature, can provide a better flexural strength in addition to high hoop strength. It also eliminates the use of form work.

Considering the obvious flexural behavior advantages, the associated shear behavior needs to be studied in order to proceed towards large scale use of such members. However, detailed studies on double skin tubular beams, particular their shear behavior, are not available in the literature. This study aims at studying the shear behavior of the Double Skin Tubular Beams.

6.4. Relevance to the national needs

The trend of using double skin tubular sections is rising in many developed countries. Like other developing countries, Pakistan although lags in this field. However, double skin tubular members can add to our national needs by providing light weight seismic resistant structures, particularly in the high seismicity zones 3 and 4. They have improved ductility and delayed buckling, both of which can help in life safety in seismically active zones. Moreover, with the rising trend of pre-fabrication in Pakistan, these members represent a perspective highly effective source of structural members.

6.5. Research Methodology:

Research methodology consists of the following steps:

a. Mix design for high strength concrete having compressive cylinder strength of 50MPa was prepared through various trials.

b. Then the double skin tubular beams were fabricated. Fabrication processes consisted of making two L-shaped sections from steel sheets of thicknesses 2.78 mm, 1.59 mm and 1.11 mm. The 2 L-shaped sections were welded together from two ends to make square tubes.

c. The assembly formed by two tubes was filled with high strength concrete to get Concrete Filled Double Skin Tubular Beams (CFDSTB's).

d. The CFDSTB's were then kept for 28 days of curing to gain required compressive strength.

e. After that, the samples were tested using UTM and data acquisition system.

6.6. Research objectives

The main objective of the research was to study the following parameters associated with the shear behavior of Double Skin Tubular Beams:

a. The effect of hollowness on the shear strength of CFDSST Beams in order to investigate the effect of the sandwiched concrete on the shear behavior.
b. The effect of thickness of the steel tubes on the shear strength of the CFDSTB's
c. The effect of thickness of sandwiched concrete and thickness of steel on the ductility

of CFDSTB's

d. The effect of thickness of sandwiched concrete and thickness of steel on the energy dissipation of CFDSTB's.

6.7. Scope of the research

This research presents a study of square CFDST beams having both inner and outer square tubes made up of steel and the space between them filled with concrete. The effect on shear strength has been studied with the change in the thickness of the sandwiched concrete and that of steel. The study selected for the stated purpose includes a total of 12 beams, tested under uniformly distributed load (UDL) in Universal Testing Machine (UTM) using data acquisition system and LVDT's. It has been tried to abridge the gap created by non-availability of research on shear behavior of rectangular CFDSTB's through a thorough investigation.

6.8. Thesis Overview:

Chapter 1 describes the background, problem statement, research objectives, summary of methodology and thesis overview.

Chapter 2 consists of literature review. It explains the various researches and studies pertaining to the topic

Chapter 3 explains research methodology. It describes material properties, samples preparation, test setup and procedure

Chapter 4 includes a detail discussion on results of all target parameters and depicts the results in an organized and presentable form

Chapter 5 consists of derived conclusions based on the results and offers recommendations for future studies.

CHAPTER 2: LITERATURE REVIEW

7.1. History of double skin tubular Members

Double skin tubular members were first studied in late 1980s, which consists of two circular tubes placed concentrically [6]. Concrete sandwiched between steel sheets was used for construction of submerged tunnels by the team of Consultants at Cardiff UK three decades ago [36]. CFDST members have lighter weight because they are hollow. Use of formwork in construction of these members is eliminated that's why they can be used in offshore construction [9]. This member was considered good for constructing seabed vessels, in deep water at the legs of platforms, in the columns having larger diameter and to the structures exposed to ice loadings. Recently it was used in high rise piers in japan which has reduced weight with increased energy absorption capacity [37].

Concrete filled steel tubes (CFST) have been used throughout the world as beams and as beam-columns in both braced and unbraced elements structural systems. They have been used in variety of constructions such as members of compression in low rise, construction of open floor, steel circular tubes filled with concrete or pre-cast concrete etc. Concrete filled square box and circular columns have been used in few of the world tallest buildings [38]. These members are thought to be a sustainable alternative to bridge piers and heavy building columns [39]. They are also used as transmission towers. These members provide saving in material and construction cost [11]. Their use has been very common since 2000. They have been used in new construction as well as retrofitting of the existing structural elements.

7.2. Types of double skin tubular members

These members can be classified based on materials and geometry.

2.2.1 Classification based on materials

Based on the outer material used they can be classified as under

1. Members having inner steel tube with outer FRP Covering, shown in Figure 2.

2. Members having inner and outer tubes made up of steel, shown in Figure 3.

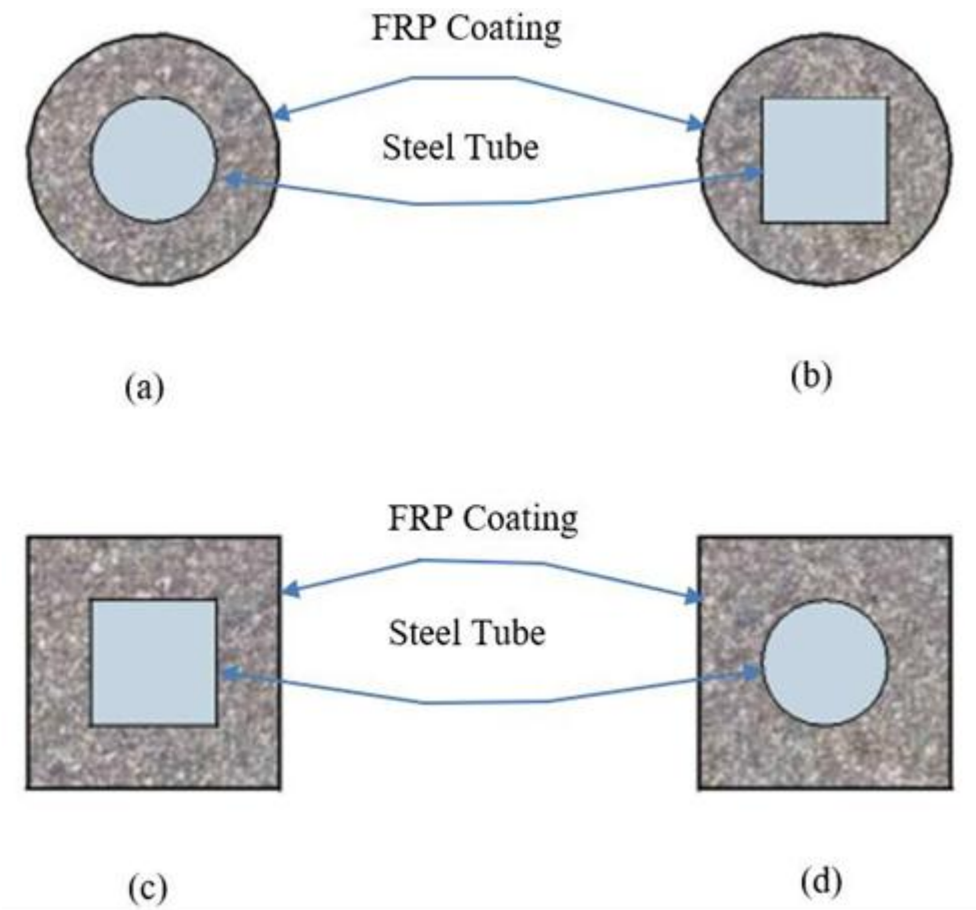


Figure 2 Classification of CFDST beams based on material [27]

2.2.2 Classification based on Geometry

Based on Geometry the members can be classified as

a) Both inner and outer tubes are of circular shape. b) Having outer circular and inner square tube.

c) Both inner and outer tubes are of square shape. d) Having outer square and inner circular tube.

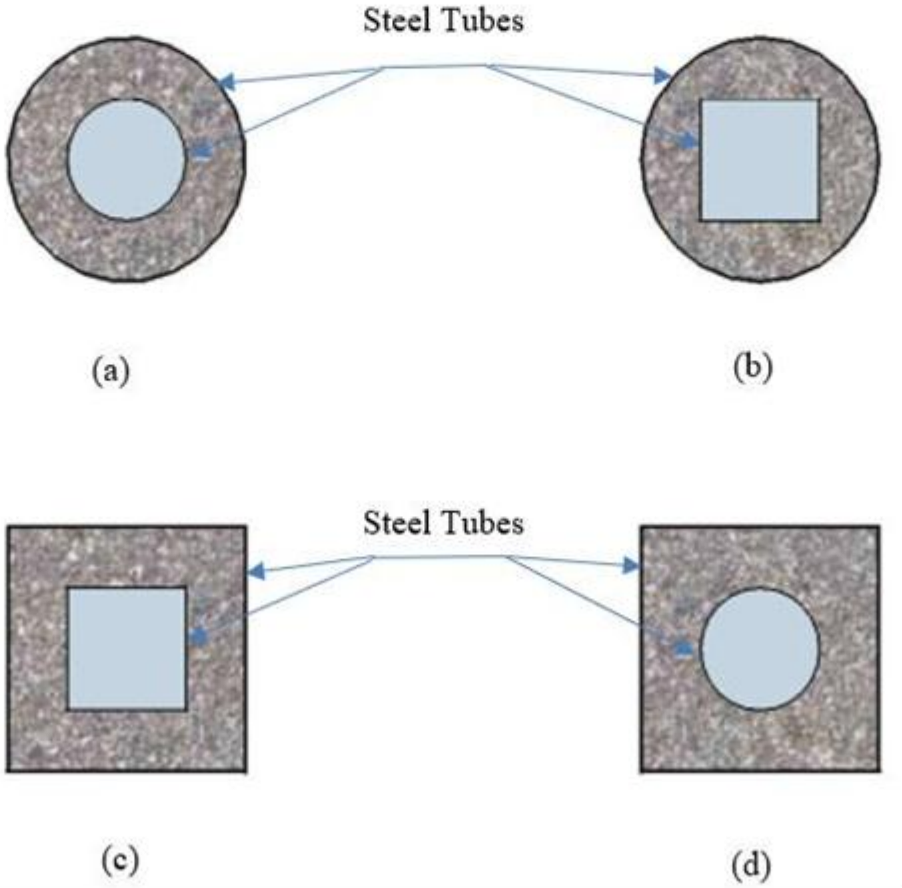


Figure 3 Classification of CFDST beams based on geometry [27]

7.3. Previous studies conducted

The literature is classified in three categories. First the concrete filled steel tubes are examined, second the Hybrid-CFDST are explained and third the CFDST members are discussed briefly.

2.3.1 Concrete Filled Steel Tubes

Large no of concrete filled square tubular beam-columns are studied under the application of the shear force in cycles. There is little experimental work on these members under uniform cyclic bending. Main objective of the research is to make some improvement in the behavior of square CFT beam-columns without consideration of the shear behavior. Experiments are carried out on eleven specimens of size 200*200*600 mm subjected to cyclic and monotonic loading. The main parameters considered are history of deformation, ratio of axial load, width to thickness ratio of the steel tubes. The tensile strength of steel and concrete cylinder strength is taken to be 50 MPa and 400 Mpa. For confined concrete and locally buckling steel, the load at failure and deformation time histories were compared with those elastic plastic responses based on proposed stress-strain behavior. There was good agreement between experimental and analytical behaviors [40].

Experimental investigations are performed on concrete filled square steel tubular (CFT) beam columns with varied strength of materials. The strength of steel used are 400 MPa, 500 MPa and 780 MPa and strength of concrete used are 40MPa and 90MPa. In addition to the variation in material, the width to thickness ratio of steel tube is also considered. Information is obtained about the hysteric behavior of CFT beam-columns with varying material strengths. 33 beams were used in the study. Higher the steel thickness and strength lead to better overall behavior of the specimen. While, the greater concrete strength has negative effect on the overall behavior of the specimen. An excellent agreement between experimental and analytical results except few exceptions is observed in this study [41].

The behavior of columns subjected to the constant axial load, accompanied by lateral cyclic load is studied. Six columns are tested in this study. Parameters studied are level of axial load, ratio of diameter to thickness and compressive strength of concrete tube. Increased ductility and enhanced strength are shown, by the specimens due to the confinement provided by the steel tube. The model foe circular CFT beam-columns is developed, that simulates interaction between concrete and steel. Good agreement between analytical and experimental result was found [42].

2.3.2 Members having inner steel tube with outer FRP Covering

Special type of Concrete Filled Tubes of Fiber Polymers (CFFT) under the application of axial loading in compression is studied. Fibers have large rupture strains, made up of recycled material and are they are considered as environment friendly. Finite element study is performed using the software LS-DYNA. The main parameters studied are column aspect ratio, size of columns, unconfined concrete strength and confinement ratio of concrete. Comparison between CFFTs and the ordinary FRP tubes members is also carried out. A hybrid material that combines the traditional material with new material in a specific manner have shown a remarkable behavior in both axial and ultimate strengths. Some equations for new hybrid system are also suggested [3].

Finite element analysis of CFDST column having outer tube of Fiber Reinforced Polymer (FRP) and inner tube of steel is conducted. Pushover analysis is used to simulate the seismic performance of three dimensional CFDST by using FE software. The results from analytical model are compared to the experimental study conducted on seven columns. The effect of load level, number of FRP layers, diameter to thickness ratio of the steel tube and thickness of the concrete used are also studied. A complex behavior was shown by CFDST columns; effected by combination of stiffness of FRP layer, steel tube and concrete [43].

The FRP–concrete–steel Double-Skin Tubular columns (DSTCs) in which high strength (HSC) concrete is sandwiched between outer FRP tube and inner steel tube is studied. The sample of column is fixed in the foundation for testing, as shown in Figure 4. For the first time, this type of member subjected to both cyclic lateral loading and axial compressive loading is studied. 8 columns are tested with the outer diameter of 300 mm. Result shows that Hybrid DSTCs have high ductility and resistance to seismic loading even with high strength of concrete is 120 MPa. The plastic hinge development is observed at the bottom of column. It is suggested that plastic hinge can be prevented by filling the internal gap in the inner tube. An important data is provided by the experimentation, for the verification of hysteric behavior of these members with the theoretical results [39].

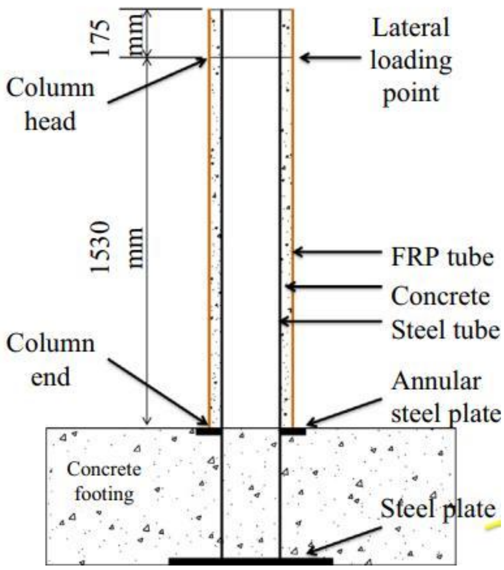


Figure 4 Foundation supporting column [39]

Work on new type of member is carried out in which inner tube is made up of steel and the outer tube is made up of high strength fiber reinforced polymer. Comprehensive tests are conducted on 18 specimens; to obtain values of rotation, bending and strain at the top and bottom fibers. Detailed information about ductility, stiffness and strength of externally reinforced members subjected to flexural loading is given. Different layouts and quantities of sheets are used in Circular Hollow Section (CHS) beams. Effect of loading capacity on orientation of fibers in transverse and longitudinal direction is studied (Figure 5). The fibers orientation and amount have a pronounced effect on strength. An analytical method which have used the concept of modular ratio and the section's slenderness limits for these members[44].

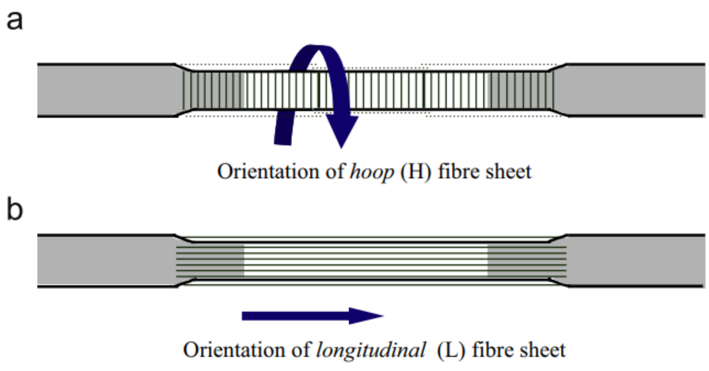


Figure 5 orientation of fiber on beam [44]

Hybrid-CFDST members filled with high strength concrete is studied and discussed in detail. Beams were tested in four-point loading setup, as shown in Figure 6. The effect of inner tube's diameter and influence of mechanical connecters on the flexural behavior of the DSTBs is studied. All the specimens have 150mm cross section and length is 1500mm. One specimen has inner steel tube's diameter of 114.4mm and yield stress of 436MPa. Other two specimens have inner tube's diameter of 76.1mm and yield strength of 398MPa. All the specimens are filled with high strength concrete. The outer layer of all the specimens is made up of two layers of aramid FRP. The third specimen is provided with steel rings of 8mm diameter that served as mechanical connecters. These members can resist high deformations in inelastic stage. The slip between the concrete and steel can be controlled by the use of mechanical connectors [45].

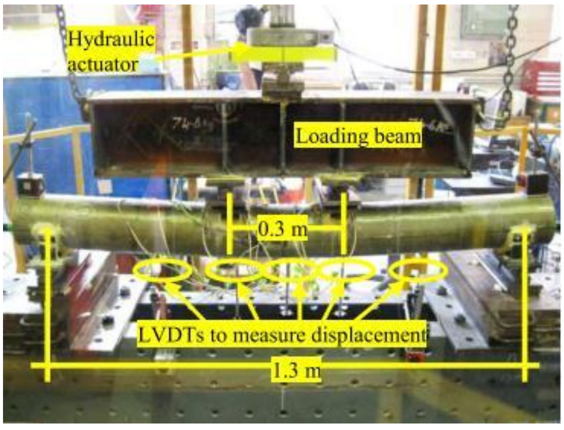


Figure 6 Four Point Loading of Hybrid-CFDST beams [45]

Four beams with Area of 200*150mm and length of 2300mm are tested. One beam is studied as a reference which is not covered with FRP sheet. Three beams are reinforced with different number of layers of FRP. Second series beams consist of testing the beams of cross section 200*150mm and length of 2000mm. These beams are wrapped with different numbers and widths of CFRP layers. These members have shown increase in stiffness and flexural response. Cracks of less width and the decreased number of cracks are observed. Moreover, a satisfactory behavior of these members is found from force-displacement diagram in cyclic loading. A good agreement between analytical and theoretical results is observed [46].

Flexural behavior of circular Hybrid FRP-concrete-steel member is studied, along with theoretical model based on fiber element approach and plan section assumption. The parameters addressed are configuration of a section, strength of concrete, and thicknesses of both steel and FRP tube. Two series of experiments were conducted on Hybrid-CFDST beams (**Figure 7**). All the specimens have inner diameter of 69mm and outer diameter of 152.5mm with overall length of 1500mm. In first series 8 tests are performed and in second series 6 tests are performed on these members. All the specimens are tested under four-point loading tests. An improvement in flexural behavior, when the inner steel tube in beam is shifted towards the tension zone is observed. There is an agreement between theoretical and experimental model, the difference is attributed to the neglect of factors that should be otherwise considered in the design [22].

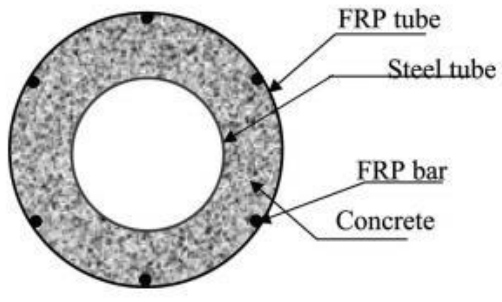


Figure 7 Cross section of Hybrid-CFDST beam [22]

2.3.3 Members having inner and outer tubes made up of steel

Double skin tubular (DST) stub-columns are studied experimentally. The inner rectangular tube is made up of Stainless steel (grade 1.4003) with the range of depth to thickness ratios from

26.1 to 42.1. Whereas, the outer tube is made up of carbon steel of grade S235 with range of width to thickness from 7.5 to 13.5. To evaluate the axial compressive behavior total of 14 beams are tested. Concrete filled between the two tubes has cylinder strengths of 40, 80 and 120 MPa. The column strengths, axial load-strain relationships and failure modes are studied in this paper. The calculated strengths are compared with different design codes. The designed models that were obtained from design codes give good anticipation for CFDST columns. The test results matches with AS5100 and EC. Results given by American specifications ANSI/AISC 360-10 and ACI are also conservative [47].

The behavior of CFDST stub columns with outer square hollow section (SHS) and Inner Square or Circular Hollow Section (SHS or CHS) is studied. The models are developed for different possibilities of CFDST stub columns using FEM software i.e. verification of FE model using different results from research papers, stress and strains in different components of the section and parameters that effect the sectional capacities are three main objectives of the study. There is good agreement between experimental and analytical results. The effect of hollow section ratio is more pronounced on sections having inner circular tubes, as compared to the sections having inner rectangular tubes. Furthermore, the increase in stiffness of a member at elastic plastic stage of axial load verses Strain is observed with the increase in hollow section ratio [17].

Series of experiments on 14 CFDST stub columns are conducted, that contains 4 beams and 12 beam-columns. Outer skin tubes comprise of square hollow section, while the inner section of all the members is circular in shape. Parameter studied are variation of hollow section ratio, outer tube width to thickness ratio varying from 40-100, eccentricity of load from 15-80mm and slenderness ratio of columns from 29-58 are considered. In addition, a mechanical model is developed to illustrate the above three members. The enhanced durability is found due to composite action of these members. Secondly, load verses axial strain relationships for stub columns and load verses deflection relationship for beams and beams-columns is also developed. The models developed for the above three members have shown good agreement with the experimental results [48].

The behavior of Hollow Core Fiber reinforced polymer Concrete Steel HC-FCS column subjected to seismic (cyclic) loading is studied. The HC-FCS section consist of inner steel tube and outer fiber-reinforced polymer that sandwiches concrete between them. The test specimen consists of fitting of column into the foundation by socket connection and the length of embedment of steel tubes is kept as 25 inches. The study consists of casting 0.4-scale HC-FCS. In this member the outer and inner diameter of column is 610 and 406mm respectively, while the height to diameter ratio is kept as 4. Research findings are compared with the column tested by ‘’Abdelkarim et al. 2015’’ under the identical loading conditions. It was found that column failed at drift of 8.4% due to wall crushing and buckling of steel, which is then followed by ductile tearing at column- footing [25].

Tests are conducted on columns in two Series. In first Series, axial force is applied at both ends both eccentrically and concentrically. The length of buckling and section depth ratio (L_k/D) is selected as 4,8,12,18,24,30. In Second Series, the cantilever beams are both subjected to axial and lateral loads. The L_k/D is kept as 6, 9, 12, 18 and 24. The parameters addressed are section depth ratio and buckling length of the column. Evaluation of the behavior and maximum load capacity by experiments is the main objective of the study. In addition, the design formulas for concrete filled slender steel tubular columns is related to those of short columns. The outer tube is a square hollow section and the inner tube is a circular hollow section, both made up of mild steel. The L_k/D=4 gives very conservative strength and the L_k/D ratios from 8 to 30 gives compatible results with the design method. Also, the design formula in cases like described above needs refinement [49].

The Concrete-filled double skin tubular (CFDST) stub columns having outer tube of stainless ferritic steel (grade1.4003) and the inner tube (S235) is made up of carbon steel are tested. 14 specimens have been tested, to investigate the axial behavior in compression and the strength acquired by CFDST specimens. Depth to thickness ratios ranges for outer and inner tubes are 26.1 to 42.1 and 7.5 to 13.5 respectively. Concrete of 40, 80 and 120MPa is used in the study. Length is changed, in order to keep the length to depth ratio constant. A uniform axial compressive force on the specimens is applied. Parameters evaluated in this research are axial strength of columns, load verses axial strain relationships and modes of failure. Test results and design codes are compared. Guidelines from European, Australian and American specifications are obtained. The existing design codes have given conservative predictions about the CFDST stub columns with outer ferritic stainless steel tubes [47].

Experiments are carried out on twelve beam-columns and twelve stub columns having, both outer and inner tube made up of circular steel hollow sections. Parameters taken into consideration are hollow section ratio, diameter to thickness ratio for stub columns. Parameters for beam-columns were slenderness ratio and eccentricity of load. A theoretical model is also developed for these members. To describe confinement action between steel and concrete tube, the concept of confinement ratio is introduced. Good agreement is observed between analytical and experimental results [8].

Fire tests are conducted on full sized self-consolidated Concrete Filled Double Skin Tubular (CFDST) columns. Failure mode of each component is studied in detail while keeping deformation, temperature and fire resistance into account. Six full size beams are casted with length of 3810mm and having different geometrical shapes of outer and inner tubes. Performance in fire is tested by outer tube's limiting temperature, concrete and steel's composite action and the effect of fire endurance on different parameters. Limiting temperature in the CFST columns is lower than that of CFDST, and the higher fire resistance of CFDST is due to the composite action of concrete and steel tube. Also, other parameters such as cavity ratio are also dependent on fire exposure [15].

Research is conducted on Concrete Filled Double Skin Tubular CFDST members used as deep beams. The objective of study is to make a deep insight into the mechanical behavior of a CFDST members used as deep beams, subjected to both shear and bending due to static three points loading. The parameters considered are outer tube to thickness ratio and inner tube to outer tube ratio. 12 specimens are casted. Length of the tube is 420mm, outer tube's diameter is 160mm. Inner diameter to thickness ratio varied from 69.6-160 and the inner diameter to outer diameter ratio Di/Do varied from 0 to 0.70. Ratio of inner tube diameter to the outer tube diameter governs the failure mode. The strength recorded for the value of Di/Do less than 0.47 matches the calculated values [12].

Experiments are carried out on twelve beam-columns and twelve stub columns having both outer and inner tube made up of circular steel hollow sections. The parameters taken into consideration are hollow section ratio, diameter to thickness ratio for stub columns. The parameters for beam- columns were slenderness ratio and eccentricity of load. They also developed a theoretical model for two types of members. To describe the action of confinement between steel and concrete tube, the author introduces concept of confinement ratio. The author found a good agreement between analytical and experimental results [8].

A mechanical model of Concrete Filled Double Skin Tubes (CFDST) beam-columns under the application of increasing flexural cyclic load and constant axial load was developed. In this paper, sections studied have outer square tube and the inner tube is circular (Figure 8). The cyclic response obtained for the CFDST columns are in good agreement to the theoretical results. Based on theoretical model; the parametric analysis is performed based on moment verses curvature response, lateral load verses corresponding deflection relationships and ductility coefficient are also discussed. It is inferred that the theoretical and analytical results are in good agreement and the formulae generated can be used in building codes to anticipate the ductility of these members [11].

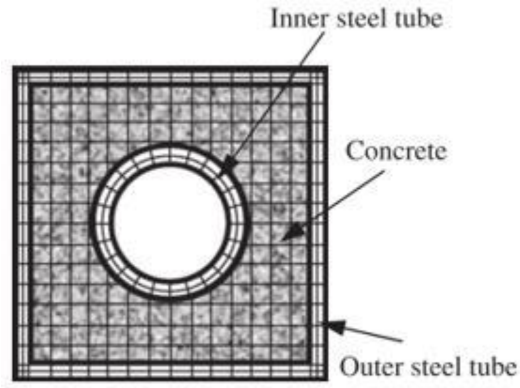


Figure 8 Different Sections of CFDST members i.e. rectangular and circular [11]

Tests are conducted on number of Concrete Filled Double Skin Tubes CFDST exposed to bending and compression. The inner and outer tubes both are made up of Square Hollow Sections SHS of cold formed steel (C450), as shown in Figure 9. The width to thickness ratio of outer tubes 16.7 to 25 are chosen for four different section sizes. Whereas, the section size for inner tube is kept as 20, for all sections. AS4600 is used to determine the geometry of the specimen to be tested. Length of the specimen is taken as 375mm. An increase in ductility of these members and three time increase in rotational capacity of CFDST member, as compared to empty outer tubes with outer tube to thickness ratio of 17 to 25, is observed. There is good agreement between theoretical and experimental models [10].

Figure 9 CFDST stub column [10]

Hybrid-CFDST sections used as beams with circular cross sections have some limitations. FRP has greater tensile strength only in one direction. FRP is relatively weak in bending and have linear stress strain behavior. The lower value of ductility make performance of these sections weak in earthquake loads [50]**.** In addition, the square section has moment of inertia greater than circular section. Stress distribution in circular section is also difficult to understand as compared to the section with square cross section.

The shear strength of beams without stirrups depends on various factors which include, but are not limited to, fiber factor, shear span to depth ratio, longitudinal steel ratio and size of beams [47]. Also, the shear strengths at diagonal tension cracking has been found to decrease roughly linearly as the corresponding maximum stresses in the reinforcement increased [17]. In Fiber Reinforced Beams without shear reinforcement, increase in quantity of fibers was found to increase the beams’ stiffness and ductility, depending upon the shear-span/depth ratio and transformed the mode of failure into a more ductile one [48]. Moreover, in RC beams strengthened with fibers, the primary cause of shear failure has been found to be caused by the rapid loss of load capacity due to separation of the strengthening fibers from the base material [25]. The effect of diameter to thickness ratio and inner to outer diameter ratio on the shear capacity of circular CFDST beams under monotonic loading has also been studied and it found that shear capacity decreases with the increase in inner to outer diameter ratio and the decrease in diameter to thickness ratio, respectively [49].

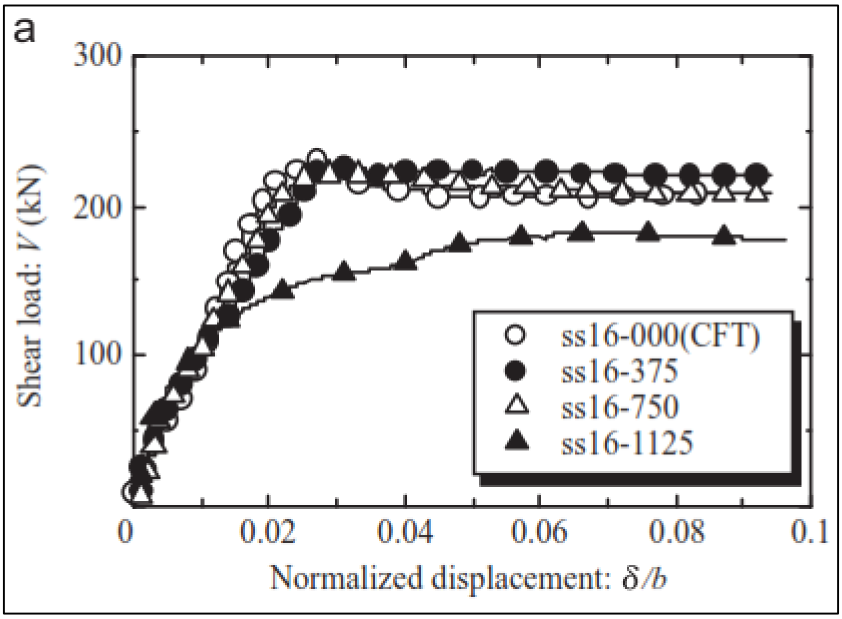


Figure 10 Load Deflection Curve of Circular CFDST Beams [49]

However, this study is only limited to circular beams while rectangular beams are generally preferred in building construction due to their ease of handling, simpler stress distribution and more moment of inertia.

This thesis presents a study of square CFDST beams having both inner and outer square tubes made up of steel and the space between them filled with concrete. The effect on shear strength has been studied with the change in the thickness of the sandwiched concrete and that of steel. The experimental program selected for this purpose includes a total of 12 beams, tested under uniformly distributed load (UDL) in Universal Testing Machine (UTM).

CHAPTER 3: METHODOLODY

2.4 Material properties

Steel and concrete were the main materials used in the research work. Concrete consisted of coarse aggregate, fine aggregate, Cement, super-plasticizer and silica fume. The coarse aggregate, having maximum particle size of 12.5 mm, was brought from Margalla Crush Plant. Fine aggregate, consisting of coarse sand, was brought from Nizampur. In fine aggregate and in coarse aggregate, the maximum sizes are 2 mm and 12 mm respectively. Cement used was manufactured by Bestway Cement Pvt Limited. Cement was ordinary Portland cement of grade 53 conforming to the Pakistan Standards PS-232-2008. To gain high strength, the super-plasticizer of first generation (Viscocrete 3110) and Silica Fume was used. These products were bought from Sika Chemicals Rawalpindi.

The steel sheet used for fabrication of steel tubes was bought from Lal Steel City, Saddar Road Rawalpindi. The two sections were welded together at Lal Kurthi, Rawalpindi. The support system used and the plate placed above the beams were already available in the laboratory.The steel tubes of thicknesses and dimensions presented below (see Table 1) were fabricated by welding two L-shaped bent sections into square cross sections. The properties of the steel i.e Elastic Modulus (E), Yeild Strength (fy) and Ultimate Strength (fu) were determined using ASTME8/E8M-13A[51]. Steel of three thickness were used i.e. 2.78 mm, 1.59mm and 1.11mm.

Table 1 Steel Properties

Do(mm)	Di(mm)	t(mm)	E(MPA)	Fy(MPA)	fu(MPA)	L(mm)
160	0	2.78,1.59,1.11	200	389	423	160
160	37.5	2.78,1.59,1.11	200	389	423	160
160	75	2.78,1.59,1.11	200	389	423	160
160	112	2.78,1.59,1.11	200	389	423	160

Mix design of concrete, to achieve the target strength, was found by making some trials. The cylinders of size 100*200 mm were tested, in compliance with ASTM C31[52], for each trial.

Finally, mix design for the compressive strength of 50 MPa was obtained. Mix Design for 50 MPa is shown in the Table 2.

Table 2 Properties of Concrete

Concrete mix design for compressive strength of 50 MPa	
Concrete Mix Design	1:1.5:1.5
Coarse Aggregate	Maximum particle size is 12mm
Fine Aggregate	Nizampur sand
W/C ratio used	0.35
Super-plasticizer Viscocrete 3110(1st generation)	1% by weight of Cement
Silica Fume (Sika Chemicals, Rawalpindi)	10% by weight of cement

2.5 CDST Samples Preparation:

The steel tubes of thicknesses and dimensions presented above (see **Table 1**) were fabricated in two step. First, L-shaped sections of the required dimensions were manufactured by the supplier. Then the two L-shaped sections were then welded together into square cross sections. The same process was repeated for both the inner and outer tubes. Binding wires were used to hold the inner tube at fixed length inside the outer tube.

It was then followed by casting. The concrete was poured in the tubes while keeping the tubes in the vertical position. A narrow tapping rod was used for compaction. The binding wires kept the inner tube in place. A beam casted has been shown in the figure

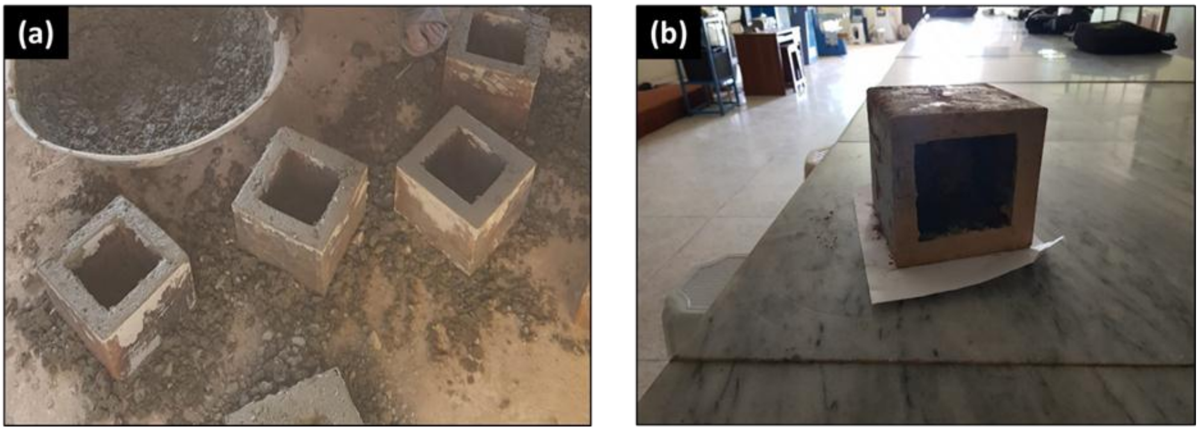


Figure 11 Casting of CFDSTB's and prepared CFDSTB

2.6 Testing Program Description of specimen:

The testing program consisted of 12 DSTB's tested as simply supported beams. The outer dimensions of all the beams were kept the same i.e. 160 mm*160 mm while the inner dimensions were different as presented in table 3. In the designation of the specimens, the first letter 'B' stands for Beam, the second number (e.g. 12) stands for the gauge of steel(thickness) and the third entry after the hyphen (e.g. 37.5) represents the dimension of the inner tube. '0' in the last entry denotes the absence of inner tube. A total of three thicknesses were used i.e. 2.78 mm, 1.59 mm and 1.11 mm were used. Both the outer dimension fo the square tube and the length were kept the same i.e. 160mm. A summary of the description of the specimens has been shown in **Table 3**

Table 3 Description of Specimens

Specimens	Do(mm)	Di(mm)	t(mm)	L(mm)
B12-0	160	0	2.78	160
B12-37.5	160	37.5	2.78	160
B12-75	160	75	2.78	160
B12-112	160	112	2.78	160
B16-0	160	0	1.59	160
B16-37.5	160	37.5	1.59	160
B16-75	160	75	1.59	160
B16-112	160	112	1.59	160
B19-0	160	0	1.11	160
B19-37.5	160	37.5	1.11	160
B19-75	160	75	1.11	160
B19-112	160	112	1.11	160

The cross-sections of the CFDSTB's were kept such that shear failure could be ensured. 4 dimensions of the inner tube were used for three different gauges of steel yielding a total of 12 cross-sections. The schematics of the cross-sections has been shown below:

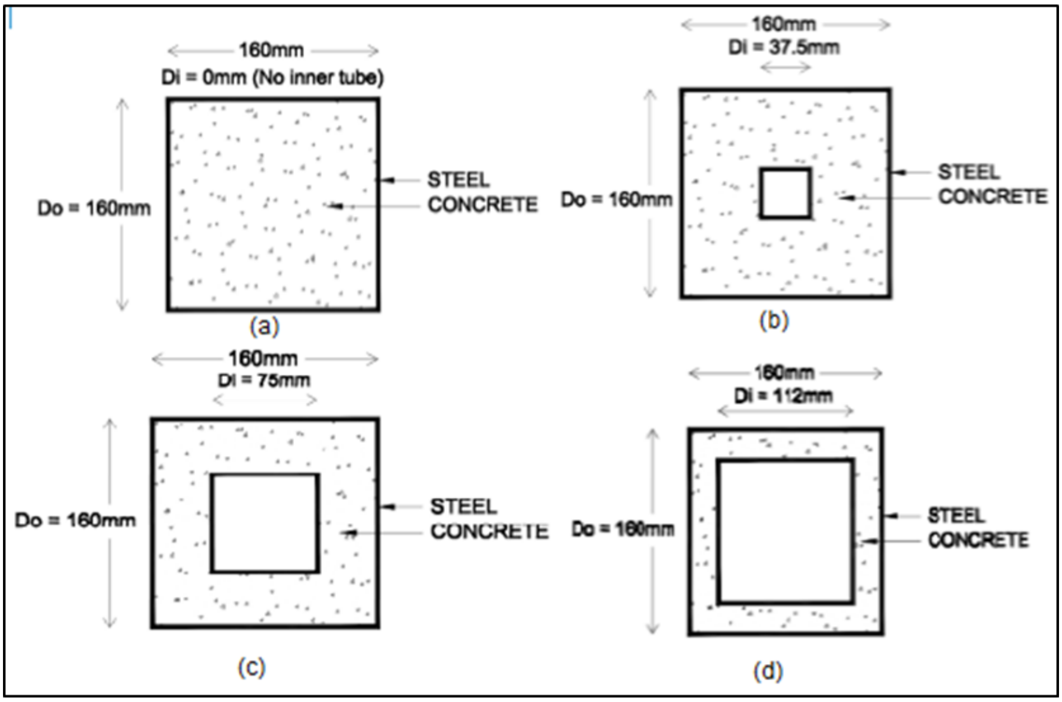


Figure 12 Schematics of Cross-Sections of CFDSTB's

The following 4 beams were prepared in 3 different gauges of steel. The same were then tested in UTM along with data acquisition system

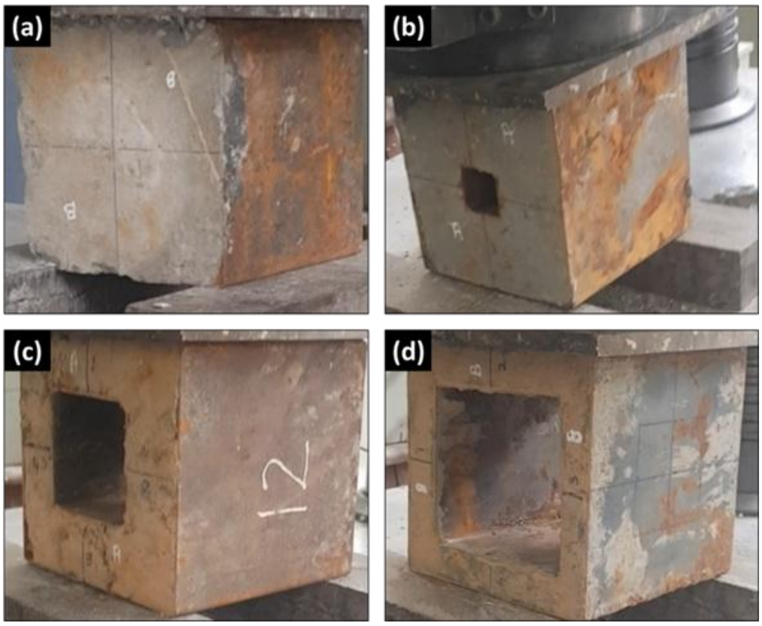


Figure 13 Cross-Sections of Casted CFDSTB's

2.7 Test setup and procedure:

The testing program consisted of 12 DSTB's tested as simply supported beams. The outer dimensions of all the beams were kept the same i.e. 160 mm*160 mm while the inner dimensions were different as presented in Table 2. All the tests were carried out using a Universal Testing Machine (UTM). The loading rate was kept at 35.6 KN/min

Figure 14 Universal Testing Machine used for Testing

In order to induce a shear failure, two steps were taken. Firstly, the size of the beams were kept small(with length equal to height) and secondly, a plate of 200 mm*200 mm was placed over each beam to transfer the load of the loading jack as uniformly distributed load. A Linear Variable Differential Transformer (LVDT), connected to a data acquisition system, was attached with the bottom platform of the UTM to measure the deflection while the same was also recorded automatically with the movement of the jack. The average deflection was then calculated to minimize errors.

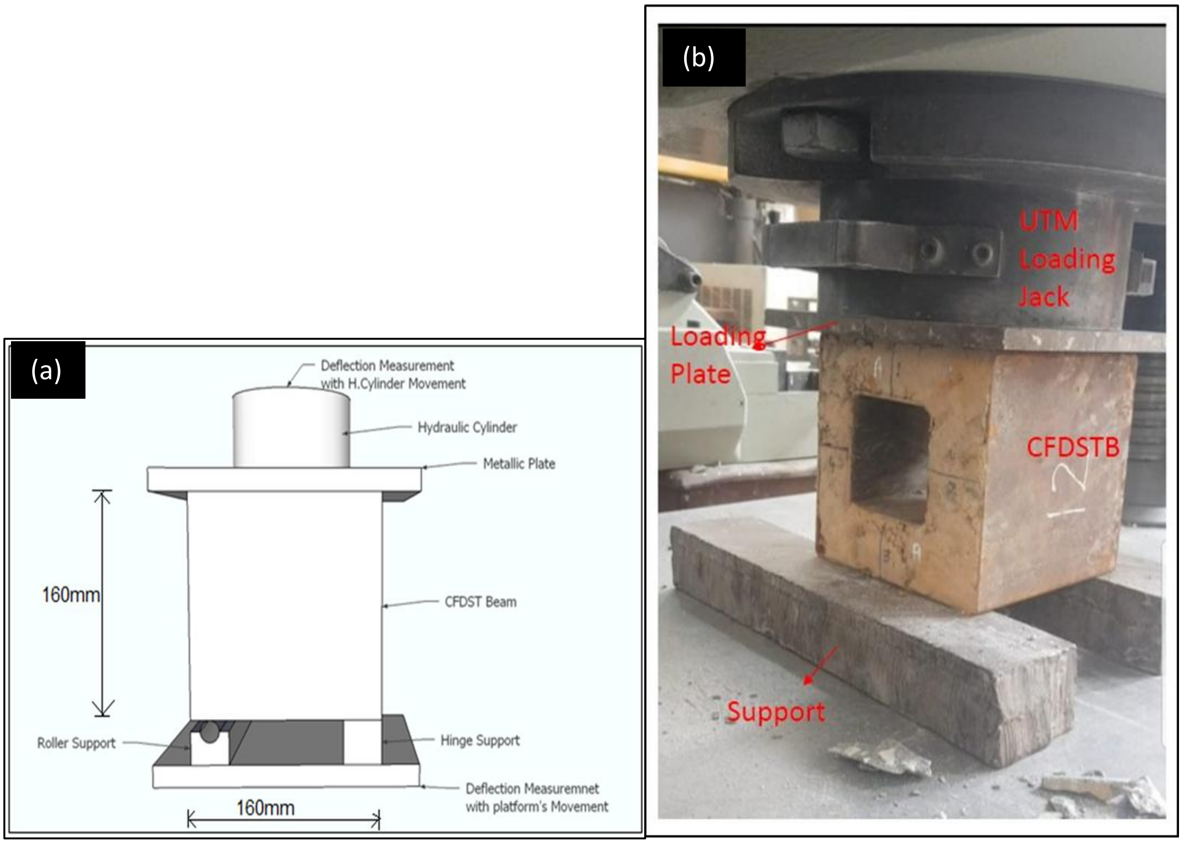


Figure 15 (a) Schematics of Test Setup (b) Test Setup

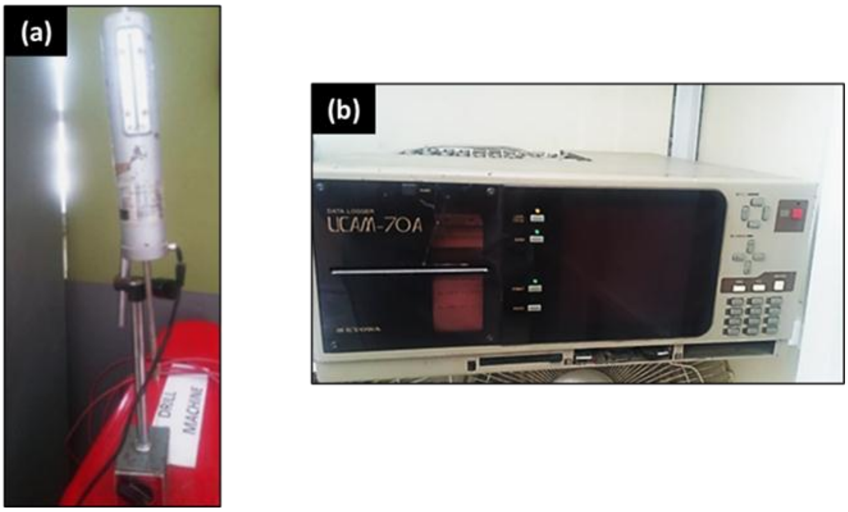


Figure 16 Data Acquisition System Consisting of (a) LVDT and (b) Data Logger

2.8 Parameters studied

The studied has focused on the effect of sandwiched concrete and steel thickness on the shear strength of square CFDSTB's. Correspondingly, the Load-Deflection relationships, the energy dissipation and the ductility factors have been studied and discussed.

2.8.1 Shear Load Deflection Relationship

When we apply load on beam, it will deflect; increasing the load will increase the deformation. To study the response, three points are taken into consideration i.e. yield point, Peak point and ultimate load. The yield displacement of an elasto-plastic system is calculated by taking reduced stiffness which can be found by taking secant stiffness, taken at 75 percent of the ultimate load. The method used to calculate yield point is shown in **Figure 17**.

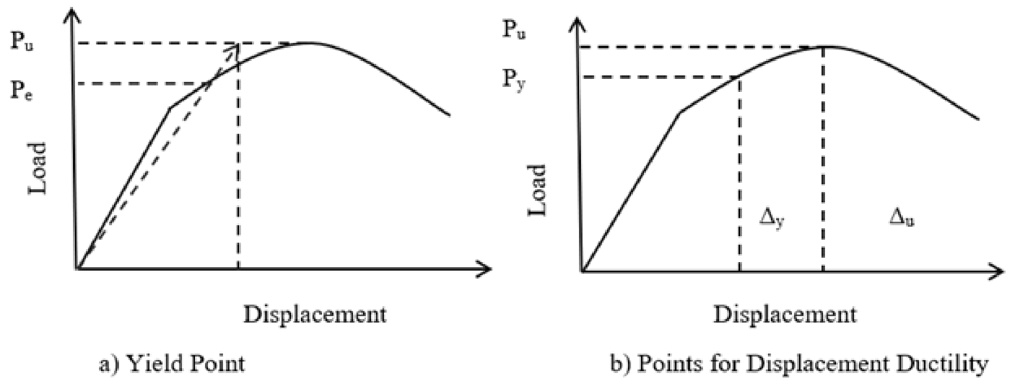


Figure 17 Determination of Yield Point and Ductility [30]

2.8.2 Energy Dissipation

The energy dissipated has been calculated as the area under the load displacement curve [53]. Trapezoidal rule has been used to find the value. The curves were divided into number of trapezoids and the final area was obtained using integration under the trapezoid

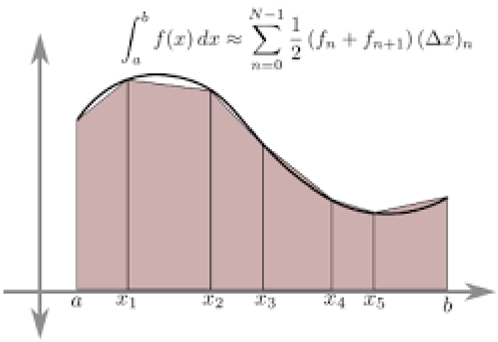


Figure 18 Trapezoidal Rule for Area under the Curve [54]

The area under the curve is found by the following formula:

$$\int_a^b f(x)dx = \sum_{n=0}^{n-1} 0.5(\mathrm{f_n} + f_{n+1})(\Delta \mathrm{x})_{\mathrm{n}}$$

Where Δx= interval length

n= number of intervals

f(x)= area under the curve

2.8.3 Ductility Factor

The ability of a structure to deflect beyond yield point, without significant loss in strength is called ductility. Ductility Factor has been calculated with the help of equal energy principle based on actual curve and its bi-linear idealization at 20% degradation of peak load [18]. The extra area included at the junction between the first and the second limb is compensated by the area excluded above the second limb.

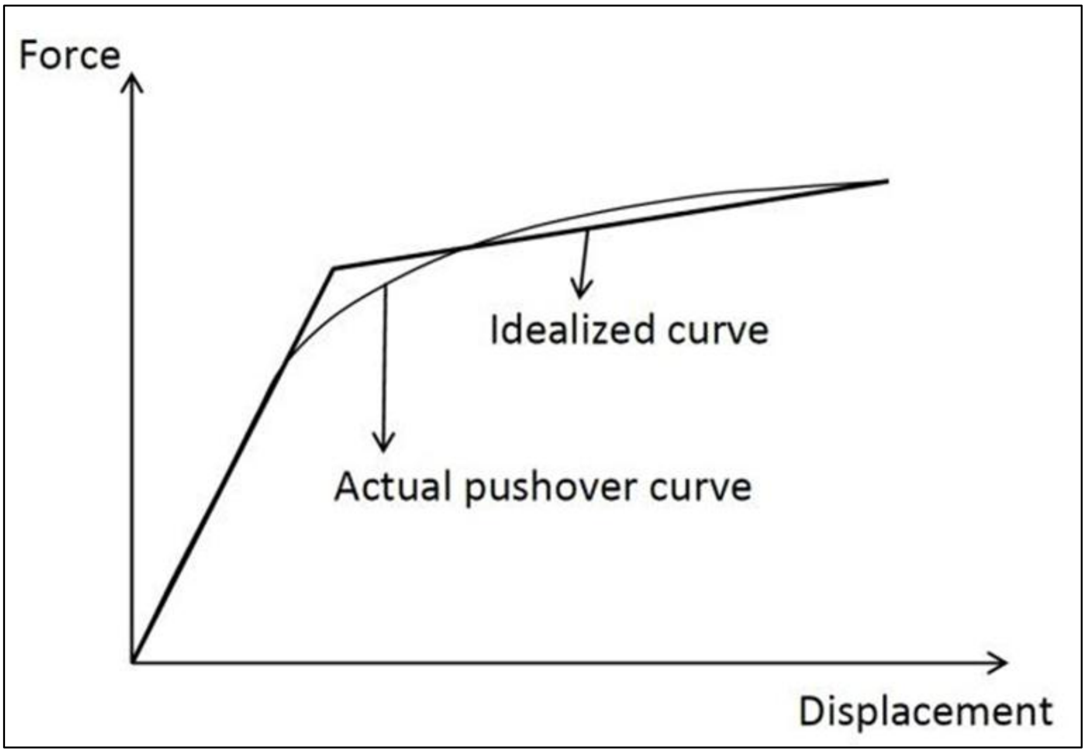


Figure 19 Actual Curve and its Bi-Linear Idealization [55]

CHAPTER 4: ANALYSIS, RESULTS AND DISCUSSION

4.1 General

12 CFDSTB's were tested in line with the procedure described in chapter 3. In addition to the values of peak shear loads, the connected data acquisition system-consisting of an LVDT and a Data Logger-provided the values of displacements corresponding to the applied loads throughout the process. Consequently, the data was processed to obtain Peak Displacements, Ultimate Displacements, Ductility Factor and Energy Dissipation, using the procedure depicted in chapter 3. A summary of all the results has been shown below:

Table 4 Summary of Results

Specimen	Peak Displacement (mm)	Ultimate Displacement (mm)	Peak Load (KN)	Ultimate Load (KN)	Ductility Factor	Energy Dissipation (KJ)
B12-0	2.240	2.912	420.000	336.000	1.554	1.146
B12-37.5	2.636	3.093	411.840	329.472	1.650	0.700
B12-75	2.880	4.056	300.000	240.000	1.803	0.520
B12-112	3.104	4.133	282.700	226.160	2.493	0.495
B16-0	1.622	2.050	400.000	320.000	1.510	0.462
B16-37.5	1.668	2.592	341.000	272.800	1.590	0.439
B16-75	1.742	3.017	195.600	156.480	1.765	0.433
B16-112	1.928	3.416	172.700	138.160	2.135	0.400
B19-0	1.432	1.819	301.440	241.152	1.446	0.355
B19-37.5	1.607	2.070	239.840	191.872	1.540	0.292
B19-75	1.720	2.334	190.330	152.264	1.608	0.283

B19-112	1.918	2.678	139.800	111.840	1.730	0.222

Deflection at peak point is deflection calculated at peak point of loading. Ductility Factor has been calculated with the help of equal energy principle based on area of the actual curve and its bi-linear idealization[56, 57]. Also, the energy dissipation has been computed by calculating the area under Load deformation curve [53]. The least count for load application was 0.02 KN while that for the LVDT was 0.001 mm.

9.1. Peak Shear loads and Ultimate Shear Loads

The effect of the thickness of the sandwiched concrete on the peak shear loads for all the 12 CFDSTB's is clear from Figure 20. For the same gauge (thickness) of the steel tubes, the peak shear loads decreases as the thickness of the sandwiched concrete decrease (with the increase in the dimension of the inner tube). The same trend has been reported for circular CFDSTB's [35]. The beam with no inner tube has the maximum peak load. The greater the decrease in the amount of the sandwiched concrete, the greater is the fall in peak shear load. Therefore, the CFDSTB's with inner tube of 112 mm depicts the lowest values of peak shear load. This is because the decrease in shear strength due to reduction in the quantity of sandwiched concrete is more than its increase due to addition of a steel tube

Figure 20 also clearly illustrates the effect of the gauge (thickness) of the steel tubes for the same thickness of the sandwiched concrete on the peak shear loads. As the thickness of steel tubes increase, the corresponding peak shear load also increases. Therefore, the CFDSTB's with gauge 12 steel have the highest peak shear loads while those with gauge 19 steel have the lowest for the same thickness of the sandwiched concrete. Also, the effect of steel thickness seems to be more prominent for the switch from gauge 16 to gauge 19 as compared to that from gauge 12 to gauge 16 for the beams with no inner tubes (with data label "0"). On the other hand, the beams with inner of 37.5 mm shows a uniform decrement in the peak shear loads as we move from gauge 12 to gauge 19 through gauge 16. For beams with inner tubes of 75 mm and 112 mm, the drop in peak shear load is more as we move from B12 to B16 and then reduces as we approach towards B19. This has been further explained in the form of percentages in **Table 5**. Moreover, the ultimate load also shows the same trend as that of the peak shear loads as shown in Figure 21.

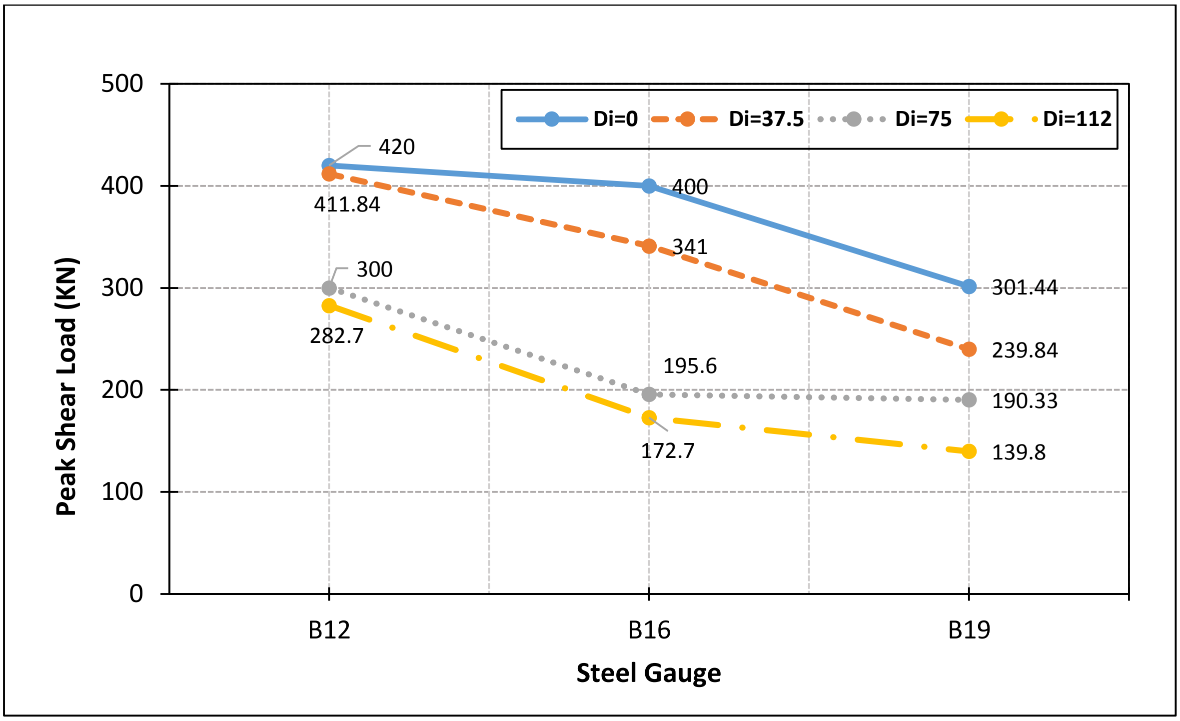


Figure 20 Effect of Steel and Concrete Thickness on Peak Shear and Ultimate Shear Loads Peak Shear Loads

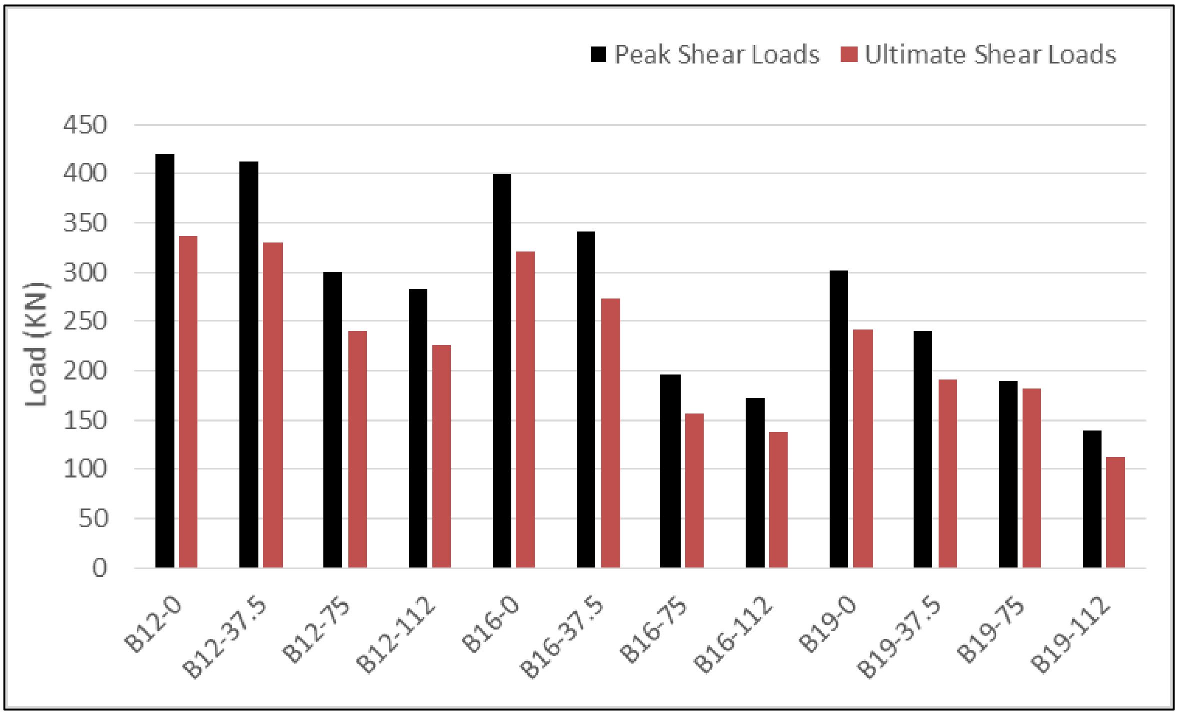


Figure 21 Peak Shear Loads and Ultimate Shear Loads for Corresponding Concrete and Steel Thickness

Table 5 shows the percentage increment/decrement in the peak shear load with the change in the thickness of the sandwiched concrete and the gauge (thickness) of the steel tubes. In column 3 of the table, B12-0 has been kept as standard for calculation of the percentages while in column 4, the beam of each gauge with no inner tube has been kept as standard for that particular gauge.

Table 5 Percentage Increment/Decrement

Designation	Peak Shear Load	Percentage(with B12-0 as standard)	Percentage(with BX-0* as standard)
B12-0	420.00	100.00	100.00
B12-37.5	411.84	98.06	98.06
B12-75	300.00	71.43	71.43
B12-112	282.70	67.31	67.31
B16-0	400.00	100.00	95.24
B16-37.5	341.00	85.25	81.19
B16-75	195.60	48.90	46.57
B16-112	172.70	43.18	41.12
B19-0	301.44	100.00	71.77
B1 9-37.5	239.84	79.56	57.10
B19-75	190.33	63.14	45.32
B19-112	139.80	46.38	33.29

As clear from Figure 20 and Table 5 Percentage Increment/Decrement, beams with gauge 12 steel depicts the highest peak shear load values. The lowest values are for the beams with gauge 19 steel. In each of the three gauges, the beam with only outer steel tube shows the maximum peak shear load. It is because the contribution of the in-filled concrete in the filled beam is more than that of the inner steel added in the CFDSTB’s. It can also be seen that in the gauge 12 steel beams, this difference of peak shear loads between B12-0 and B12-37.5 is almost negligible. This means that there is a possibility that the gauge of steel can be so adjusted to eliminate the shear strength degradation due to increase in the hollow portion.

9.2. Comparison of Trend with Circular Beams:

The shear behavior of circular deep beams was studied by Uenaka in 2013 and it remains the only detailed study till date. Owing to similar length i.e. 160mm and diameter (instead of side measurement) of 160 mm, the trends of the shear behavior represented in this study and that of Uenaka are comparable qualitatively. As the concrete strength, the steel thickness and the inner tube dimensions are different, a quantitative comparison is not feasible.

Table 6 Circular Vs. Rectangular CFDSTB's

	Uenaka 2013	Current study	Comments
Shear Strength Vs. dimensions of the inner tube	As the ratio of the inner dimension to the outer dimension increased, the shear strength decreased	As the ratio of the inner dimensions to the outer dimensions increased, the shear strength decreased	The same trend of decreasing shear strength with increasing dimensions of inner tube has been found for both circular and rectangular beams
Shear Strength Vs. Thickness of Steel	The Shear strength and thickness of the steel are directly related	Shear strength increased as the thickness of the steel tubes increased	The trend of increasing shear strength with increasing thickness of steel tube has been observed for both the studies

9.3. Shear Load deflection relationship:

Figure 22 shows the Shear Load Displacement relationship for all the CFDSTB's. It can be seen that for the beams with the same gauge (thickness) of steel, the peak displacement increases as the load carrying capacity of the beams decrease with the increase in the dimensions of the inner tube. This is because as the dimensions of the inner steel tubes increase, the beam is able to sustain more displacement as compared to the beam with more amount of sandwiched concrete. Therefore, B12-112 records the highest peak load displacement with lowest load carrying capacity, followed by B12-75, B12-37.5 and B12-0 in that order. The same is the case for B16 and B19 CFDSTB's.

The effect of the gauge (thickness) of steel on the Load-Deflection relationship is also clear from Figure 22. For the same thickness of the sandwiched concrete, the peak load deflection, along with the load carrying capacity, decreases with the decrease in the gauge (thickness) of the steel tubes. This is because lower gauge represents less steel available for the same amount of sandwiched concrete. Therefore B12-0 depicts more load carrying capacity and more peak load deflection as compared to B16-0 and B16-0 more than that of B19-0. The same is true for other CFDSTB's with other dimensions of inner tubes.

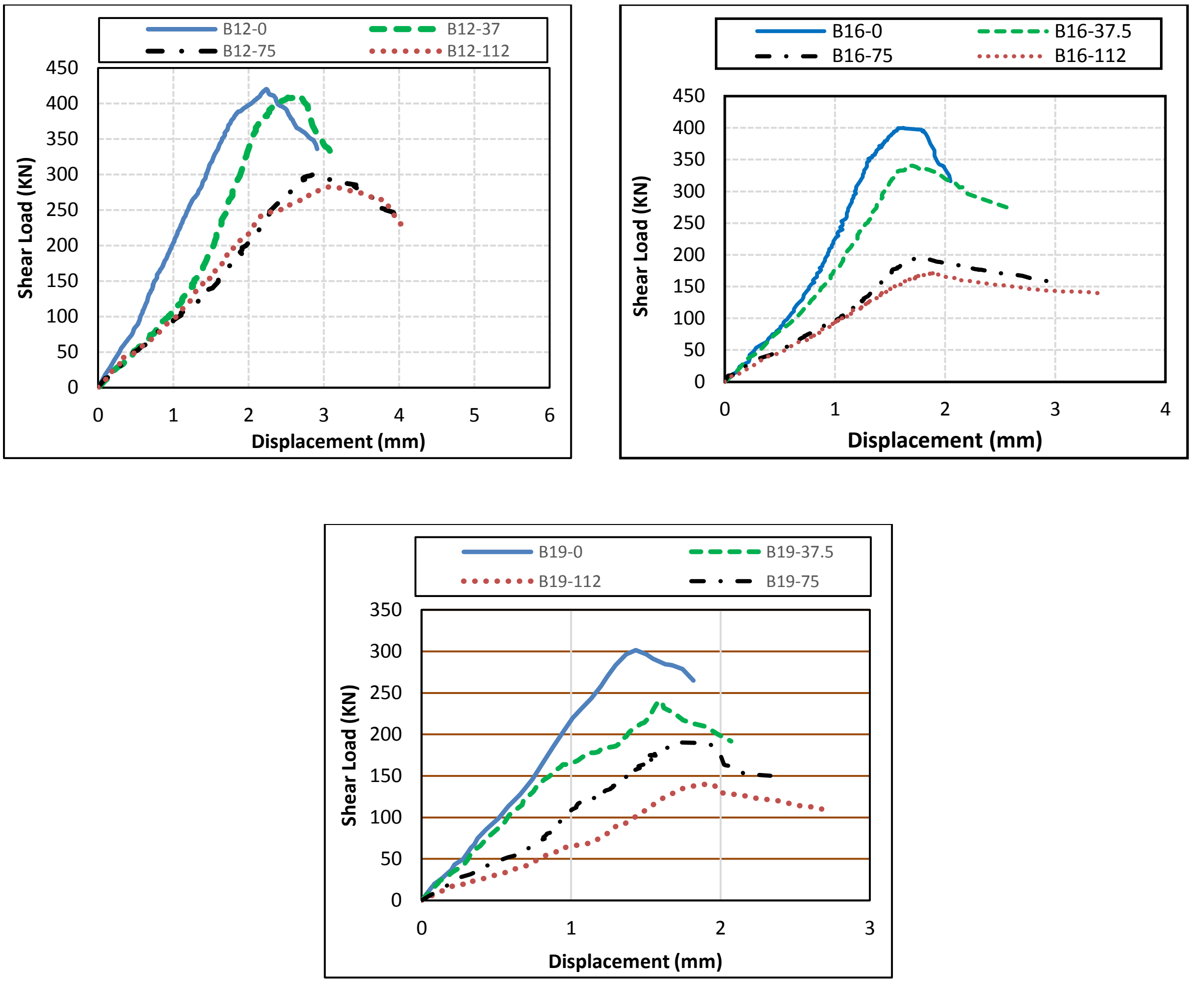
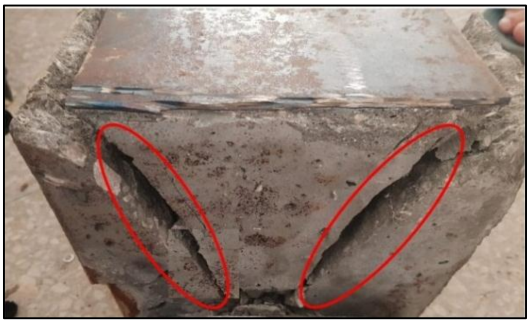


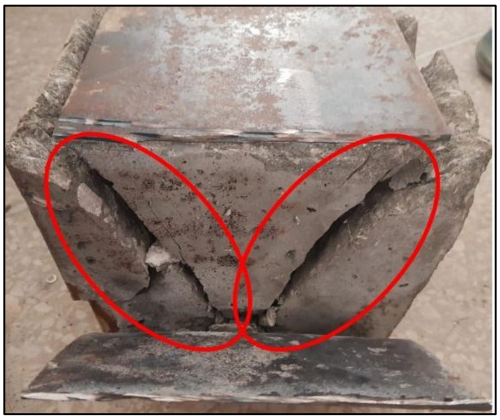
Figure 22 Load vs. Displacement Curves of Beams

The shear cracks produced in the beams have been show in Figure 23. The shear cracks have been produced approximately at angle of 45° to the surface at the peak loads as elaborated in the Load-Deflection Curves. Irrespective of their shear capacity, the specimens developed shear cracks due to diagonal tension.



Di=0

Di= 37.5mm



Di= 75 mm

Di= 112 mm

Figure 23 Shear Cracks in CFDST Beams

9.4. Ductility:

Ductility Index has been calculated as the ratio of displacement at peak to the displacement at yield. Figure 24 depicts ductility for all samples. Gauge 12 beams depict the highest values of ductility than the corresponding gauge 16 and gauge 19 beams. As the gauge decreases, the values of ductility also decrease. Moreover, for each gauge of steel, the ductility increases as the dimensions of the inner steel tube increase (and thickness of concrete decrease). The members with gauge 12 steel depicts the highest values of ductility.

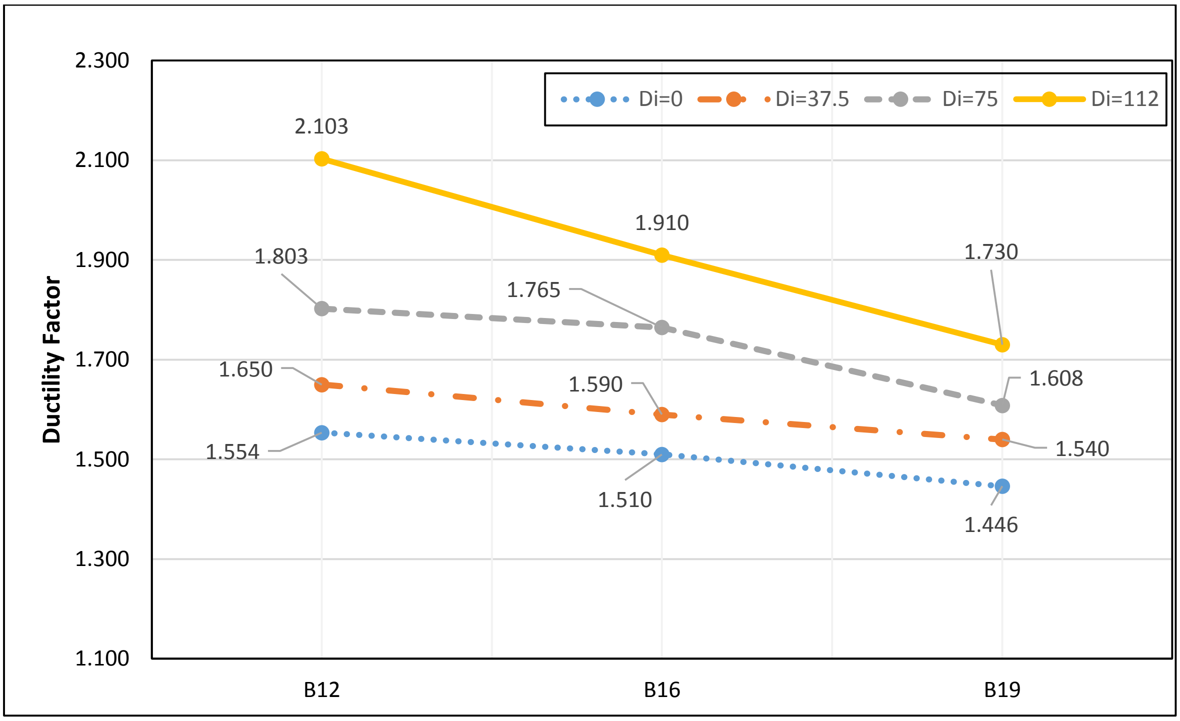


Figure 24 Ductility Factor for 12 CFDSTB's of different Steel and Concrete Thickness based on Equal Energy Principle

The ultimate displacements associated with the ductility have been shown in Figure 25. It is clear that as the dimensions of the inner steel tube increases, for the same thickness of the concrete, the ultimate displacement increases and thus the associated ductility factor also increases. Moreover, as the thickness of concrete increases for the same dimensions of the inner steel tube, ultimate displacement and hence, the associated ductility decreases. Therefore, B12-112 depicts the maximum ductility factor while B19-0 the minimum.

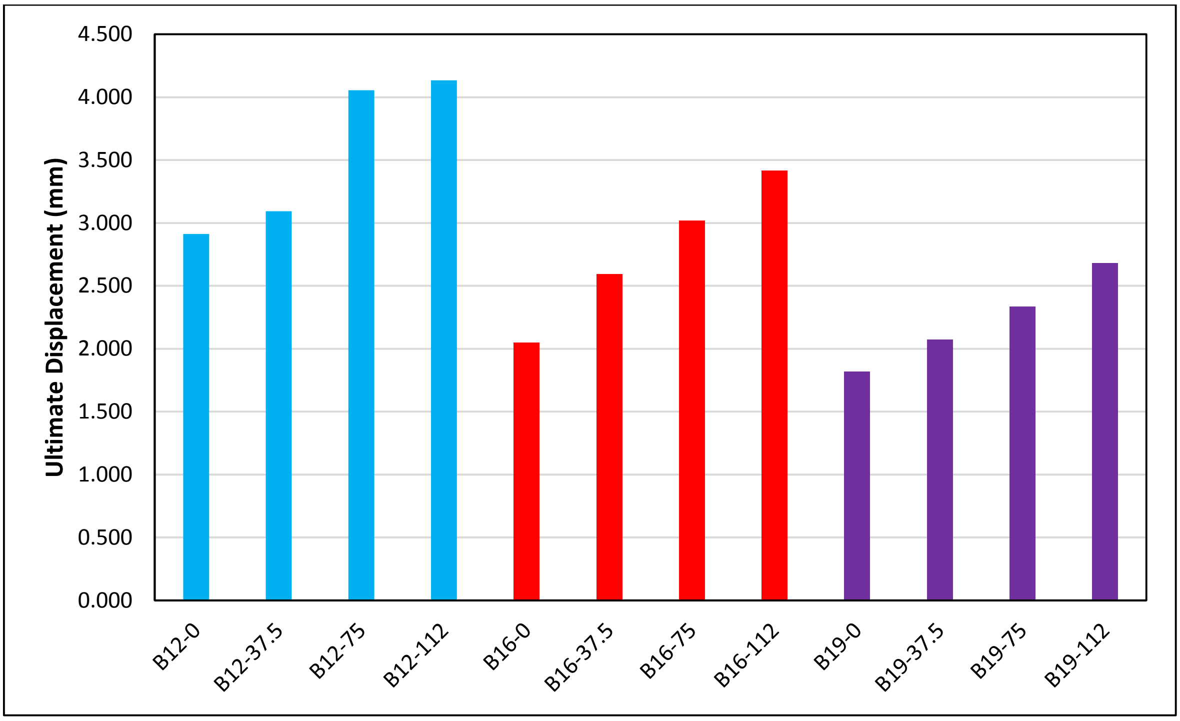
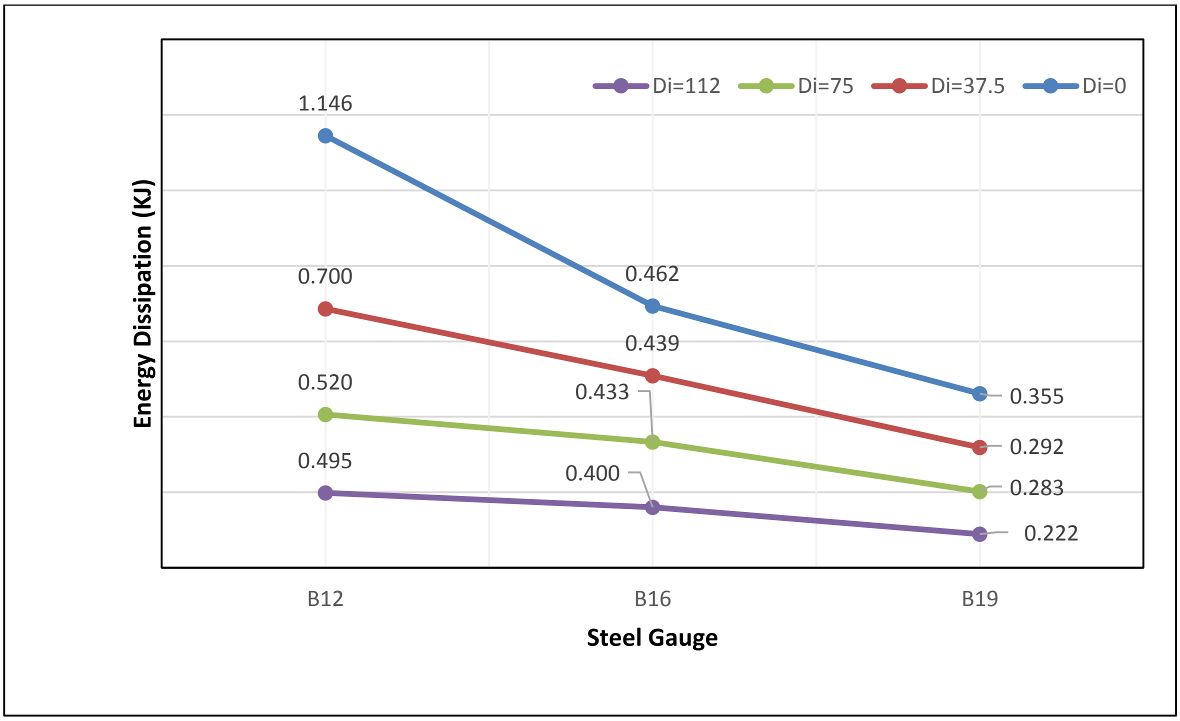


Figure 25 Ultimate Displacements

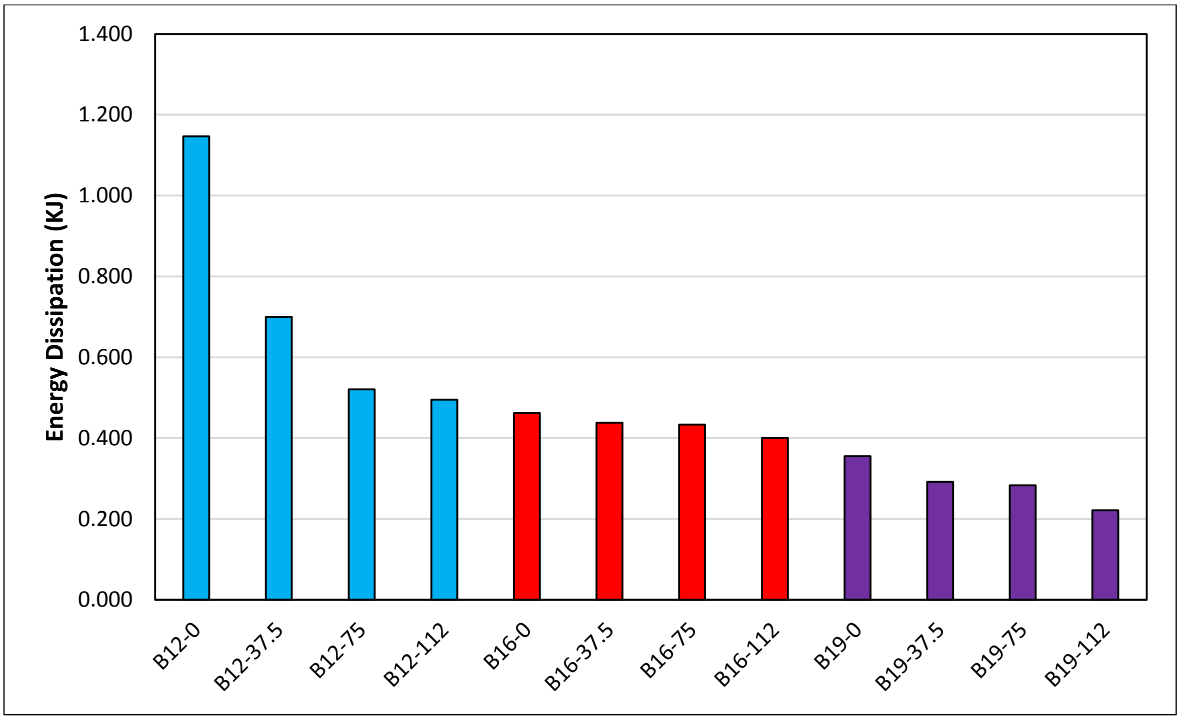
9.5. Shear Energy dissipation:

The shear energy dissipation is given by the area under the Shear Load-Deflection curve[38]. From Figure 26, it is clear that the greatest amount of energy was dissipated by the beams with gauge 12 steel. This is because as the thickness of the steel increases, its capacity to dissipate energy also increases. Therefore, the shear energy dissipation capacity decreases as we move from gauge B12's to B16's and then to B19's.

In the beams with the same steel thickness, the shear energy dissipation can be seen to reduce as the thickness of concrete decreases. This is because as the thickness of the sandwiched concrete decreases, the shear energy dissipation decreases, notwithstanding the increase in the dimensions of the steel tubes. As a result, the trend of decreasing shear energy dissipation can be seen from B12-0 to B12-112. The same is the case for B16'sand B19's.



(a)



(b)

Figure 26 Shear Energy Dissipation

Like shear strength, the shear energy dissipation depends more on the thickness of concrete as the peak load depends on the same. The greater the thickness of the sandwiched concrete, provided that the steel thickness remains the same, the greater is the energy dissipation.

Therefore, B12-0 shows the maximum energy dissipation of 1.146 KJ while B19-112 the minimum i.e. 0.222 KJ

CHAPTER 5: CONCLUSIONS AND RECOMMEDATIONS

5.1 Conclusion

The main focus of the study was to analyze the effect of thickness of the sandwiched concrete (by varying the inner steel tube dimensions) and thickness of the steel tube on the shear strength of the beams.

i. For the same thickness of the steel tubes, decreasing the thickness of concrete and increasing the dimensions of the inner steel tube decreases the shear strength of the beam. The same trend has been observed for all the thickness of the steel used. For higher thicknesses of steel, this degradation of shear strength with decrease in the thickness of the sandwiched concrete tends to decrease.
ii. Moreover, keeping the dimensions of the inner steel tube the same, increasing the thickness of the steel tubes result in increasing the shear strength of the beams.
iii. As the dimensions of the inner steel tube increase, the ductility increases. The same trend has been observed for all the thicknesses of steel. Moreover, for same dimensions, the tube with the highest steel thickness i.e. gauge 12, possess the highest ductility.
iv. As the dimensions of the inner tube increases (and the thickness of the concrete decreases), the energy dissipation capacity of the beams decreases. Moreover, for the same configuration of inner tubes, beams with greater steel thickness have been found to dissipate more energy than that of beams with lesser steel thickness.

5.2 Recommendations

It is recommended that the same testing procedure is repeated for full scale rectangular double skin tubular beams. If different gauges are used, an effort could be made to adjust the gauge and thickness of concrete to such appropriate values that can provide the additional advantages of CFDST without degrading the shear strength. The same process may also be carried out using a finite element software e.g. Abacus.

REFERENCES

[1] K. Tan and J. M. Nichols, "Properties of high-strength concrete filled steel tube columns," *Modern Civil Struct. Eng,* vol. 1, pp. 58-77, 2017.

[2] X. Zhou, T. Mou, H. Tang, and B. Fan, "Experimental study on ultrahigh strength concrete filled steel tube short columns under axial load," *Advances in Materials Science and Engineering,* vol. 2017, 2017.

[3] O. I. Abdelkarim and M. A. ElGawady, "Analytical and finite-element modeling of FRP-concrete-steel double-skin tubular columns," *Journal of Bridge Engineering,* vol. 20, p. B4014005, 2015.

[4] X. L. Zhao and L. H. Han, "Double skin composite construction," *Progress in structural engineering and materials,* vol. 8, pp. 93-102, 2006.

[5] X.-L. Zhao, B. Han, and R. H. Grzebieta, "Plastic mechanism analysis of concrete-filled double-skin (SHS inner and SHS outer) stub columns," *Thin-Walled Structures,* vol. 40, pp. 815-833, 2002.

[6] H. Shakir-Khalil and S. Illouli, "Composite columns of concentric steel tubes," 1989.

[7] M. Elchalakani, X.-L. Zhao, and R. Grzebieta, "Tests on concrete filled double-skin (CHS outer and SHS inner) composite short columns under axial compression," *Thin-walled structures,* vol. 40, pp. 415-441, 2002.

[8] Z. Tao, L.-H. Han, and X.-L. Zhao, "Behaviour of concrete-filled double skin (CHS inner and CHS outer) steel tubular stub columns and beam-columns," *Journal of Constructional Steel Research,* vol. 60, pp. 1129-1158, 2004.

[9] S. Wei, S. Mau, C. Vipulanandan, and S. Mantrala, "Performance of new sandwich tube under axial loading: experiment," *Journal of Structural Engineering,* vol. 121, pp. 1806-1814, 1995.

[10] X.-L. Zhao and R. Grzebieta, "Strength and ductility of concrete filled double skin (SHS inner and SHS outer) tubes," *Thin-walled structures,* vol. 40, pp. 199-213, 2002.

[11] L.-H. Han, H. Huang, and X.-L. Zhao, "Analytical behaviour of concrete-filled double skin steel tubular (CFDST) beam-columns under cyclic loading," *Thin-walled structures,* vol. 47, pp. 668-680, 2009.

[12] K. Uenaka and H. Kitoh, "Mechanical behavior of concrete filled double skin tubular circular deep beams," *Thin-Walled Structures,* vol. 49, pp. 256-263, 2011.

[13] Y. Essopjee and M. Dundu, "Performance of concrete-filled double-skin circular tubes in compression," *Composite Structures,* vol. 133, pp. 1276-1283, 2015.

[14] M. Hassanein and O. Kharoob, "Compressive strength of circular concrete-filled double skin tubular short columns," *Thin-Walled Structures,* vol. 77, pp. 165-173, 2014.

[15] H. Lu, L.-H. Han, and X.-L. Zhao, "Fire performance of self-consolidating concrete filled double skin steel tubular columns: Experiments," *Fire safety journal*, vol. 45, pp. 106-115, 2010.
[16] J. Wang, J. He, and Y. Xiao, "Fire behavior and performance of concrete-filled steel tubular columns: Review and discussion," *Journal of Constructional Steel Research*, vol. 157, pp. 19-31, 2019.
[17] H. Huang, L.-H. Han, Z. Tao, and X.-L. Zhao, "Analytical behaviour of concrete-filled double skin steel tubular (CFDST) stub columns," *Journal of Constructional Steel Research*, vol. 66, pp. 542-555, 2010.
[18] L.-H. Han, W. Li, and R. Bjorhovde, "Developments and advanced applications of concrete-filled steel tubular (CFST) structures: Members," *Journal of Constructional Steel Research*, vol. 100, pp. 211-228, 2014.
[19] H. Lu, X.-L. Zhao, and L.-H. Han, "Testing of self-consolidating concrete-filled double skin tubular stub columns exposed to fire," *Journal of Constructional Steel Research*, vol. 66, pp. 1069-1080, 2010.
[20] K. Uenaka, H. Kitoh, and K. Sonoda, "Concrete filled double skin circular stub columns under compression," *Thin-walled structures*, vol. 48, pp. 19-24, 2010.
[21] T. Yu, Y. Wong, and J. Teng, "Behavior of hybrid FRP-concrete-steel double-skin tubular columns subjected to eccentric compression," *Advances in Structural Engineering*, vol. 13, pp. 961-974, 2010.
[22] Y. Wong, T. Yu, J. Teng, and S. Dong, "Behavior of FRP-confined concrete in annular section columns," *Composites Part B: Engineering*, vol. 39, pp. 451-466, 2008.
[23] F. Wang, B. Young, and L. Gardner, "Compressive testing and numerical modelling of concrete-filled double skin CHS with austenitic stainless steel outer tubes," *Thin-Walled Structures*, vol. 141, pp. 345-359, 2019.
[24] J. G. Teng, T. Yu, Y. Wong, and S. Dong, "Hybrid FRP–concrete–steel tubular columns: concept and behavior," *Construction and building materials*, vol. 21, pp. 846-854, 2007.
[25] M. M. Abdulazeez and M. A. ElGawady, "Seismic behavior of precast hollow-core FRP-concrete-steel column having socket connection," *Proceedings, SMAR*, 2017.
[26] T. Yu, Y. Wong, J. Teng, S. Dong, and E. Lam, "Flexural behavior of hybrid FRP-concrete-steel double-skin tubular members," *Journal of Composites for Construction*, vol. 10, pp. 443-452, 2006.
[27] Y. Idris and T. Ozbakkaloglu, "Flexural Behavior of Hybrid Double-Skin-Tubular Beams," in *Advanced Materials Research*, 2014, pp. 525-529.
[28] Y. Idris and T. Ozbakkaloglu, "Flexural behavior of FRP-HSC-steel double skin tubular beams under reversed-cyclic loading," *Thin-Walled Structures*, vol. 87, pp. 89-101, 2015.
[29] J. Teng and L. Lam, "Behavior and Modeling of FRP-Confined Concrete: A State-of-the-Art Review," *Special Publication*, vol. 238, pp. 327-346, 2006.

[30] W. Ashraf, M. Usman, S. H. Farooq, N. Ullah, and S. Saleem, "Flexural properties of concrete filled double skin (SHS outer and SHS inner) tubular Beams," *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, pp. 1-13, 2020.
[31] M. Khuntia, B. Stojadinovic, and S. C. Goel, "Shear strength of normal and high-strength fiber reinforced concrete beams without stirrups," *Structural Journal,* vol. 96, pp. 282-289, 1999.
[32] R. G. Mathey and D. Watstein, "Shear strength of beams without web reinforcement containing deformed bars of different yield strengths," in *Journal Proceedings*, 1963, pp. 183-208.
[33] S. A. Ashour, G. S. Hasanain, and F. F. Wafa, "Shear behavior of high-strength fiber reinforced concrete beams," *Structural Journal*, vol. 89, pp. 176-184, 1992.
[34] G. Kim, J. Sim, and H. Oh, "Shear strength of strengthened RC beams with FRPs in shear," *Construction and Building Materials,* vol. 22, pp. 1261-1270, 2008.
[35] K. Uenaka, "Concrete filled double skin circular tubular beams with large diameter-to-thickness ratio under shear," *Thin-Walled Structures,* vol. 70, pp. 33-38, 2013.
[36] e. a. Wright, "The experimental behaviour of double skin composite elements," *Journal of Constructional Steel Research,* vol. 19, pp. 97-110, 1991.
[37] M. Sugimoto, S. Yokota, K. Sonoda, and F. Yagishita, "A basic consideration on double skin tube-concrete composite columns," in *Osaka City University and Monash University Joint Seminar on Composite Tubular Structures, Osaka*, 1997.
[38] C. W. Roeder, "Overview of hybrid and composite systems for seismic design in the United States," *Engineering structures*, vol. 20, pp. 355-363, 1998.
[39] B. Zhang, J. G. Teng, and T. Yu, "Experimental behavior of hybrid FRP–concrete–steel double-skin tubular columns under combined axial compression and cyclic lateral loading," *Engineering Structures,* vol. 99, pp. 214-231, 2015.
[40] H. Nakahara and K. Sakino, "Flexural behavior of concrete filled square steel tubular beam-columns," in *12th World Conference on Earthquake Engineering*, 2000.
[41] E. Inai, A. Mukai, M. Kai, H. Tokinoya, T. Fukumoto, and K. Mori, "Behavior of concrete-filled steel tube beam columns," *Journal of Structural Engineering*, vol. 130, pp. 189-202, 2004.
[42] A. Elremaily and A. Azizinamini, "Behavior and strength of circular concrete-filled tube columns," *Journal of Constructional Steel Research,* vol. 58, pp. 1567-1591, 2002.

[43] O. I. Abdelkarim and M. A. ElGawady, "Analytical and finite-element modeling of FRP-concrete-steel double-skin tubular columns," *Journal of Bridge Engineering,* vol. 20, p. B4014005, 2014.
[44] J. Haedir, M. R. Bambach, X. L. Zhao, and R. H. Grzebieta, "Strength of circular hollow sections (CHS) tubular beams externally reinforced by carbon FRP sheets in pure bending," *Thin-Walled Structures,* vol. 47, pp. 1136-1147, 2009.
[45] Y. Idris and T. Ozbakkaloglu, "Flexural Behavior of Hybrid Double-Skin-Tubular Beams," *Advanced Materials Research,* vol. 838-841, pp. 525-529, 2013.
[46] Zarringol, "Investigation of Concrete Beam Behavior in FRP Composite Layering Under Incremental Loading

" *International Journal of Appliied Engineering Research,* vol. 11, pp. pp 2429-2435, 2016.
[47] F. Wang, B. Young, and L. Gardner, "08.29: Experimental investigation of concrete-filled double skin tubular stub columns with ferritic stainless steel outer tubes," *ce/papers,* vol. 1, pp. 2070-2079, 2017.
[48] L.-H. Han, Z. Tao, H. Huang, and X.-L. Zhao, "Concrete-filled double skin (SHS outer and CHS inner) steel tubular beam-columns," *Thin-Walled Structures,* vol. 42, pp. 1329-1355, 2004.
[49] K. Tsuda, C. Matsui, and E. Mino, "Strength and behavior of slender concrete filled steel tubular columns," in *Proceeding 5th International Colloquium on Structural Stability*, 1996.
[50] M. K. Sharbatdar, "Monotonic and cyclic loading of new FRP reinforced concrete cantilever beams," 2008.
[51] ASTM, "Standard Test Methods For Tension Testing Of Metallic Materials," in *ASTM E8 E8M-13a*, ed.
[52] ASTM, "Standard Practice for Making and Curing Concrete Test Specimens in the Field," in *ASTM C31*, ed.
[53] J. Ahmad, M. Usman, M. Hassan, S. Farooq, and A. Hanif, "Enhancing lateral load performance of traditional timber wall (dhajji-dewari) by strengthening of joints," in *IOP Conference Series: Materials Science and Engineering*, 2018, p. 072002.
[54] L. N. Trefethen and J. Weideman, "The exponentially convergent trapezoidal rule," *siam REVIEW,* vol. 56, pp. 385-458, 2014.
[55] L. S. Da Silva, A. Santiago, and P. V. Real, "Post-limit stiffness and ductility of end-plate beam-to-column steel joints," *Computers & Structures,* vol. 80, pp. 515-531, 2002.
[56] P. Kumar and R. Roy, "Study and experimental investigation of flow and flexural properties of natural fiber reinforced self compacting concrete," *Procedia Computer Science,* vol. 125, pp. 598-608, 2018.

[57] S. Sivakamasundari, A. J. Daniel, and A. Kumar, "Study on flexural behavior of steel fiber RC beams confined with biaxial geo-grid," *Procedia engineering*, vol. 173, pp. 1431-1438, 2017.