AUGUST 2019 M.Sc. in Civil Engineering ABDULATEEF SAEED ABDULAZEZ


**REPUBLIC OF TURKEY**

**GAZİANTEP UNIVERSITY**

**GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES**


# PERFORMANCE EVALUATION OF DOUBLE SKIN STEEL TUBE FILLED BY CONCRETE AS COMPOSITE BEAM

**M.Sc. THESIS**

**IN**

**CIVIL ENGINEERING**


**BY**

**ABDULATEEF SAEED ABDULAZEZ**


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**M.Sc. Thesis**
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**Supervisor**
**Asst. Prof. Dr. Mehmet Tolga GÖĞÜŞ**


**by**
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REPUBLIC OF TURKEY
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GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES
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Prof. Dr. Hanifi ÇANAKCI
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This is to certify that we have read this thesis and that in our consensus opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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**Abdulateef Saeed ABDULAZEZ**

## ABSTRACT

## PERFORMANCE EVALUATION OF DOUBLE SKIN STEEL TUBE FILLED BY CONCRETE AS COMPOSITE BEAM

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**M.Sc. in Civil Engineering**
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This study is presented in order to show how Concrete-Filled Double Skin Steel Tube (CFDSST) beams behave under the pure bending. Laboratory investigations were made on thirteen test specimens that involved twelve units of the CFDSST specimens and one unit of concrete-filled steel tube beam as a control. Six of the CFDSST specimens were having a square and rectangular inner tubes in the bottom side of the outer tubes, while the other six CFDSST specimens had a centric square and centric rectangular inner tubes. Two major and important parameters were relied in this study namely, the inner tube position and inner tube shape. Based on these parameters, bending moment against mid-span deflection, deflection curves, flexural stiffness, flexural capacity, and ductility were investigated. The results of laboratory work showed clear improvement in moment capacity and strength for the CFDSST beams with inner tubes in the bottom side compared to those with centric inner tubes, in addition to show the advantages of CFDSST on concrete-filled steel tube beams. Also, this study confirmed that the effect of inner tube shape (square to rectangular and vice versa) for the same section area was slight.



**Keywords:** Concrete-Filled Double Skin Steel Tube (CFDSST) beams, Flexural strength, Double skin, Self-compacting concrete, Ductility.

# ÖZET

## KOMPOZİT KİRİŞ OLARAK BETON İLE DOLDURULMUŞ ÇİFT CİDARLI ÇELİK BORUNUN PERFORMANS DEĞERLENDİRMESİ

**ABDULAZEZ, Abdulateef Saeed**
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**Ağustos 2019**
**51 sayfa**

Bu çalışma, Beton Doldurulmuş Çift Cidarlı Çelik Boru (BDÇCÇB) kirişlerin basit eğilme altında nasıl davrandığını göstermek amacıyla sunulmuştur. Laboratuvar incelemeleri, BDÇCÇB numunelerinin on iki adedi ve kontrol olarak bir adet Beton Doldurulmuş Çelik Boru (BDÇB) kirişini içeren on üç test numunesi üzerinde laboratuvar incelemeleri yapılmıştır. BDÇCÇB örneklerinin altısında dış tüplerin alt tarafında kare ve dikdörtgen iç tüp bulunurken, diğer altı BDÇCÇB numunesinin merkezi kare ve merkezi dikdörtgen iç tüpleri vardır. Bu çalışmada iki ana ve önemli parametre olarak yani iç tüpün konumu ve iç tüpün kesiti kullanılmıştır. Bu parametrelere göre, orta açıklık yer değiştirmesine karşı eğilme momenti, yer değiştirme eğrileri, eğilme rijitliği, eğilme kapasitesi, süneklik ve öz ağırlık farklılıkları incelenmiştir. Laboratuvar çalışmasının sonuçları, BDÇCÇB kirişlerinin BDÇB kirişlerine avantajlarını göstermenin yanı sıra, merkezde iç tüplü olanlara kıyasla alt tarafta iç tüplere sahip olan BDÇCÇB kirişlerinde moment kapasitesinde ve dayanımında net bir gelişme göstermiştir. Ayrıca, bu çalışma, aynı kesit alanı için iç tüp kesitinin (kare-dikdörtgen ve tersi) etkisinin hafif olduğunu doğrulamıştır.

**Anahtar Kelimeler:** Beton Doldurulmuş Çift Cidarlı Çelik Boru (BDÇCÇB) kirişler, Kendiliğinden yerleşen beton, Çift cidar, Eğilme dayanımı, Süneklik.

To my parents….

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Special thanks to my father, my mother for all of the sacrifices that have made on my behalf, and also to my brothers and sisters. Words cannot express how grateful I am to my big brother spirit that his words and advices always led me towards the best.

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## LIST OF SYMBOLS/ABBREVIATIONS

| | |
|---|---|
| **CFST** | Concrete-Filled Steel Tube. |
| **CFDST** | Concrete-Filled Double skin Steel Tube. |
| **SCC** | Self-Compacted Concrete. |
| $f_u$ | Ultimate strength of steel |
| $f_y$ | Yield strength of steel |
| $M_u$ | Moment capacity |
| ***Du*** | Mid-span deflection at ultimate moment |
| ***DI*** | Ductility Index |
| $K_i$ | Initial flexural stiffness |
| $K_s$ | Serviceability flexural stiffness |
| $I$ | Moment of inertia |
| $f_c$ | Strength of concrete |
| $P$ | Applied force |
| $T$ | Splitting tensile strength |
| $L$ | Length of the specimen |
| $D_{0.6}$ | Deflection at 0.6 from the maximum moment |
| $f_{syi}$ | Yield strength of inner steel tube |
| $f_{syo}$ | Yield strength of outer steel tube |

# CHAPTER 1

# INTRODUCTION

## 1.1 General

In the last few decades, a good method was used to improve the stability of steel tubular members by filling them (Wright and Evans, 1991), (Ge and Usami, 1994). One common example is the concrete-filled steel tube members. This kind of members was widely used for constructing modern buildings, bridges and electrical power transmission (Tao and Han, 2006), (Guo et al. 2007) especially in the areas of high earthquake risk. CFST is progressively being used as a column, beam column and beam. The research studies conducted on the concrete-filled steel tube beams were few (Han et al., 2006), (Moon et al., 2012) when comparing with those on the concrete filled steel tube column and beam column (Du et al., 2017), (Talebi et al., 2018), (Kwon and Park, 2017). The composite construction structure gives numerous structural advantages that comprise large strength, fire resistance, high energy absorption capacity, and favorable ductility. These features are widely used and have resulted in the widespread use of concrete-filled steel tube members in civil engineering works (Elchalakani and Zhao, 2008) and (Han et al., 2014).

In recent years, some searchers such as (Elchalakani et al., 2002), (Han et al. 2004), (Uenaka and Kitoh, 2011) and etc., have been studied a new helpful technique to enhance the stability of constructions. This technique called CFDSST. CFDSST units can be defined as a type of concrete-filled steel tube constructions comprise of double steel tubes having the same center and concrete fills the gap between them. In origin, the concept of “double skin” composite construction has been inherited from using it in the tube tunnels (Han et al. 2004). It is thought that it also has a potential to contain nuclear power, blast resistant shelters, and good saving structures to store liquid and gas. Features of CFDSST over concrete-filled steel tube involve: rising of section modulus, good stability, and reducing of weight. It is also expected that resistance of fire for the CFDSST is better than that for the concrete-filled steel tube, because of the composite members being preserved by the sandwiched concrete. Furthermore, the possibility of passing lines of electric power and water networks through the inner tube of the constructional member. These features of CFDSST members have highlighted the strong potential of using CFDSST in high buildings, bridges, legs of offshore platforms in deep, high electrical towers and structures under ice loading (Khalil, H. 1991). Figure 1.1-1.3 show some constructions consisted of composite members. It is discovered that the inner tube can give adequate support to the stuffed concrete, as well as an ability of CFDSST member to work efficaciously under diverse loading cases. Also, experimental researches have implemented on the performance of CFDSST members found that the sandwiched concrete restricts the outer tube from buckling to the inside and restricts the inner tube from buckling towards the outside. In general, the composite member has many advantages, but the main advantages (Mohanraj et al., 2010), (Aghdamy, S. 2016) are: Performance as a lasting and indispensable formwork; Provides external reinforcement and Supports many levels of the structure before pumping concrete. There is a problem with this type of constructional members, which is the difficulty of flowing concrete between the steel tubes, which aids to the formation of gaps between concrete and steel, especially in the long members.

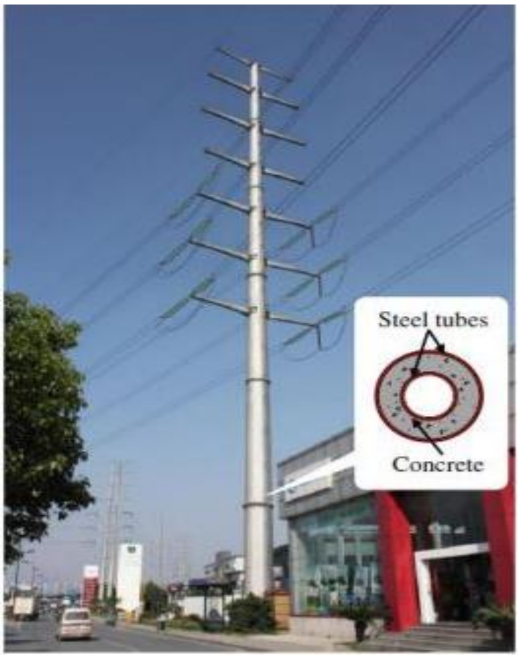



**Figure 1.1** Electric pole (Han and Bjorhovde, 2014).

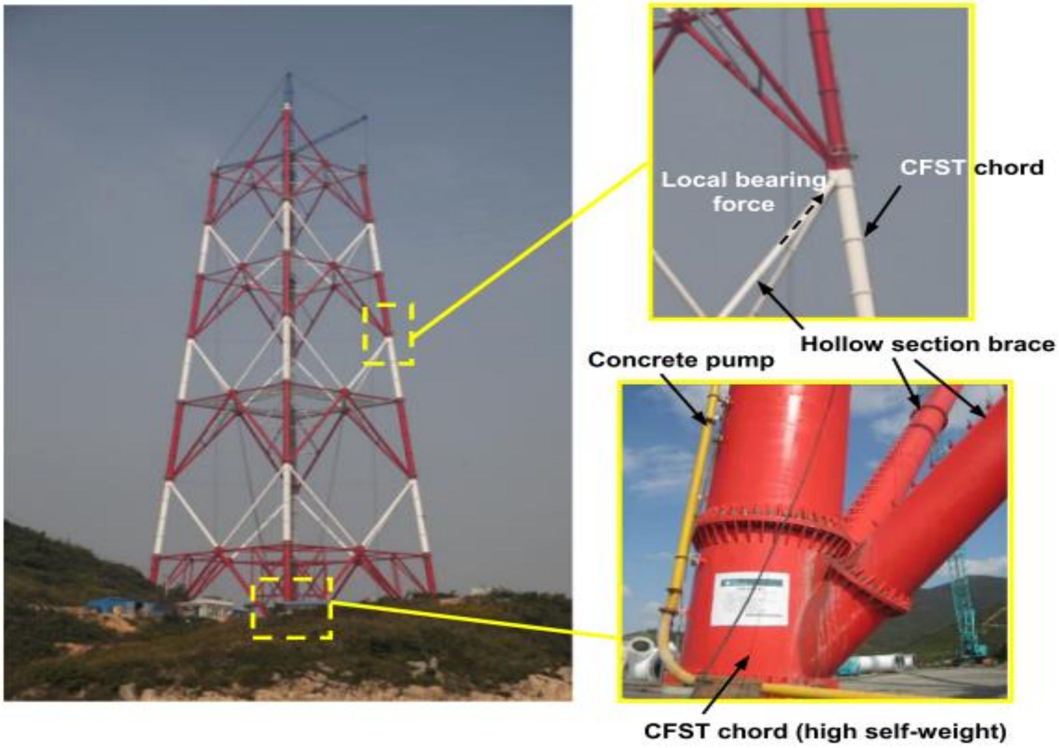



**Figure 1.2** A CFST transmission tower in China (Hou et al., 2015).

Most of the previous studies conducted on the CFDSST beam were focusing on the one that which inner tube sharing the same center with the outer tube. This laboratory work concentrates on the behavior of CFDSST units when the inner tube was located on the lower edge of the outer tube. Also, this study will consider the effect of hollow shape on the behavior of the CFDSST beam.

Self-compacting concrete has been used by many researchers such as (Han et al., 2005) as filling material for the gap between the outer and inner tube. Vibration and compacting are unimportant with this sort of materials during the casting because it contains a relatively large amount of stabilizers and superplasticizers. Also, segregation between the ingredients does not occur in this type of material because of its own weight. It's preferable to use the self-compacting concrete in CFDSST members as a stuffed material between its tubes. This sort of concrete is a good option so as to reduce the work time and reduce the work hands, as well as to reduce the noise caused by the vibration devices.

## 1.2 Research objectives and significance

Based on the above literature, the research studies conducted on the CFDSST beams were few compared to those on the CFDSST columns. These few studies on the CFDSST beams did not address the inner tube position nor its shape. Thus, the main objectives of this work are, to review the flexural normal performance of CFDSST beams through obtaining of flexural strength, failure modes, ductility, and flexural stiffness considering inner tube position and its shape and comparing results with concrete-filled steel tube.

## 1.3 Layout of the thesis

Comprises of five- chapters' summary and abridgment of each chapter are given as below:

**Chapter 1. Introduction:**

A general and simplified explanation about the performance of CFDSST members was presented as well as review the importance of research.

**Chapter 2. Literature review:**

Previous research based on the scope of the study has been reviewed and maintained. A review of the literature and general background about CFDSST beams.

**Chapter 3. Experimental investigation:**

This chapter provided an explanation and experimental investigation about the effect of inner tube position and its shape on the behavior of the CFDSST beam.

**Chapter 4. Results and discussion:**

Results obtained from the effect of inner tube position and its shape on the behavior of the CFDSST beam. Discussion of the results defined in this chapter.

**Chapter 5. Conclusions:**

Provide conclusions and summary based on the results of comparative investigations.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Concrete Filled Steel Tube Members

Concrete-filled steel tube members take advantage of both concrete and steel. These consist of a circular steel hollow section filled with concrete. They are using widely as a beam of low-rise industrial buildings that require a strong and efficient structural system and as high-rise buildings such as columns and beam-columns.

Han (2004) introduced accurate and detailed report explained through it the actual performance of the hollow steel tube beams that filling by concrete. Analysis the method of normal bonding between the concrete surfaces and steel surfaces were centered and basic point in the work. This work was standing on studying a chain of rectangular and square samples. The investigational test has been carried out when depth of tube to thickness ratio between 20 to 50, and the depth to width ratio between 1 to 2. Laboratory work and theoretical formulas were utilized to present the relationship of load against lateral deflection, also there is a good similarity has been discovered between the laboratory work results and the results of the formula. some current codes such as BS5400-1979 and AIJ-1997 have been utilized to compare the work results with them.

Yao and Liao (2006) carried out investigational study about flexural behavior for 36 specimens of composite beams that comprises of infilled self-compacting concrete. Shear span to depth ratio, diameter to thickness, yielding strength of steel and section type were the basic and important parameters of this laboratory work. Depending on this laboratory work, the performance of self-compact concrete as a filling material was the same performance of normal concrete that utilized for the same purpose. This study has been presented the curves of moment against curvature relying on the simplified models and the work results, also it was discovered a pretty tying between them.

Lachemi and Hossain (2006), presents a comparison between the behavior of axially loaded steel tube columns filled with normal concrete and a self-compacting concrete. A total of 16 columns with grade 450 for both normal cement and self-compacting concrete were tested by applying concentric axial load. Columns were without and with longitudinal and hoop reinforcement as well as the tube confinement. The slenderness of the specimens was 4.8, 9.5, 3.1 and 6.5 for Series CI and Series CII, respectively. The ductility and strength of self-compacting concrete specimens were found similar to those of their normal concrete counterparts as the maximum strength enhancement in columns between 1.1% to 7.5% only. The presence of self-compacting concrete or normal concrete and the presence of hoop and longitudinal reinforcement had no significant influence on strain development.

Chitawadagi and Narasimhan (2009), prepared a research on the strength deformation behavior of circular steel tubes in-filled with concrete of different grade under bending. The actual effect of steel tube thickness, strength filling concrete, concrete cross sectional area, concrete confinement and moment capacity were investigated. The examined flexural strength is compared with the value prophesied by EC 4-1994, Load, and the AISC-1999. A group of 99 samples with all lengths of 1m was tested with concrete filling with characteristic strengths of 20, 30 and 40 $N/mm^2$ and a diameter to thickness ratio of 22.3 and 50.8. Based on the laboratory work results, interaction has been developed to foresee the curvature and moment of the Concrete Filled Steel Tube specimens. The results indicate that in the experimental investigation are used to all the hollow section resistance moments and the corresponding increase in curvature showed ductility better than the hollow. The ductility and moment of both the hollow and the Concrete Filled Steel Tube samples are increased by increasing the thickness of the tubes. For a given thickness of the concrete-filled steel tube specimen, rising the strength of the filled concrete will not help to significantly increase its capacity. The Strength Increase Factor (SIF) proposed here aids to estimate the concrete assistance to the moment capacitance of the concrete-filled steel tube beams. Detention of infill contributes of concrete to higher performance while higher strength infill concrete has been utilized for higher wall thickness steel tube. Furthermore, EC 4-1994 foresees the moment capacity of the test samples moderately in the range of 30% to 35%. Since the influence of concrete filling is not taken into consideration and

AISC-1999 is also the same, it is very conservative to predict the moment capacity of the concrete-filled steel tube section.

Arivalagan et al. (2010) presented accurate and detailed study about the cyclic behavior and flexural performance of infilled steel tubes. Test samples stuffed with low strength concrete, quarry waste concrete, fly ash concrete and normal mixed concrete have been tested. The beam capacities have been gathered and tabulated for doing a comparison with the ultimate capacity achieved by the standards EC 4-1994, ACI-2002 and AISC-1999. The investigational study revealed that the beam specimens compared to the hollow steel section increased the moment carrying capacity of ordinary mixed concrete 28%, fly ash concrete 27% and quarry waste concrete 25%. Concrete filled increases the residual-load capacity of thin square hollow section and rectangular hollow section beams that withstand cyclic loads, especially while increasing lateral displacement and also increasing the energy absorption of hollow steel sections.

Alfawakhiri (1997) presented additional experimental data on the behavior of these structural elements and assess recent design code provisions with regard to circular concrete-filled steel tube columns. Three long beam-columns have been tested under continuous axial compression and incrementally enhanced lateral displacement reversals. In addition, one short column was tested in concentric compression. All specimens had the same cross-sectional geometry to allow for direct comparison. Both strength and deformability issues were addressed. Various aspects of concrete confinement in circular concrete-filled steel tube were analyzed. A comparative study of AISC-1999 and EC 4-1994 was carried out. The result of the test indicates that by using of high strength concrete for circular concrete-filled steel tube members does not cause any dramatic changes in the behavior. AISC-1999 was shown to be more conservative than EC 4-1994, but all codes gave conservative predictions of strength compared to the experimental results. A less conservative design approach was recommended for Canadian Standards Association.

Elchalakani and Grzebieta (2001) recorded investigational studies on the bending action of circular concrete-filled steel tube under large deformation bending have been conducted. This laboratory work compares the performance of filled and empty circular hollow cross-sections cold-formed under purely plastic bending. The concrete filling has been produced to completely restrict local buckling and elliptification of tubes that formed from cold steel with diameter to thickness ratio between 13 to 40, but in the inelastic range of concrete-filled steel tube of diameter to thickness ratio between 74 to 110. A plastic ripple has been detected. Energy absorption, strengthening, and ductility is thinner than in the case of particularly thick circular hollow section. The plasticity limit has been obtained for a concrete-filled steel tube constructed under a pure bend from a cold-formed hollow section.

Lai (2014) presented the evaluation and development of these design provisions. The CFST members have been reviewed available experimental databases and a new experimental database of tests performed on non-compact and slender concrete-filled steel tube members has been compiled. Detailed 3D Finite Element Method models have been developed for non-compact and slender concrete-filled steel tube members and benchmarked using experimental results. Design provisions of the American Institute of Steel Construction AISC-1999 for non-compact and slender Concrete Filled Steel Tube members have been evaluated by experimental test results and additional finite element method analysis dealing with experimental database gaps. The current AISC-1999 axial load bending moment interaction equation has been updated using the results of a comprehensive parametric study (directed using a benchmarked Finite Element Method model). Effective stress-strain curves of steel tubes and concrete filled have also been advanced. Validation of these effective stress-strain curves has been confirmed by implementing them in a macro model based on benchmarked nonlinear fiber analysis.

Vijay and Manoj (2014) presented a study on the flexural behavior of concrete-filled steel tube based on the previous effort carried out by Manojkumar as shown in Figure 2.1. An ANSYS model has been developed that can prophesy the performance of CFST to determine the moment carrying capacity at ultimate point. The Concrete Filled Steel Tube beam is verified against experimental data by the ANSYS software. Material nonlinearity, load, boundary conditions, and the degree of concrete containment were the important and basic parameters utilized in this work. To account for all these characteristics, the ANSYS model has been developed. The main parameter that changes in analytical research is the diameter to thickness ratio, which is the characteristic strength of filled concrete. The suggested model foresees the ultimate capacity of moment of the concrete-filled steel tube beam. For numerical analysis, circular and rectangular Concrete Filled Steel Tube cross sections are taken into account using different grades of concrete. Compare the predicted value with the experiment result. Numerical analysis shows that a good confinement effect can be obtained with a rectangular CFDSST.

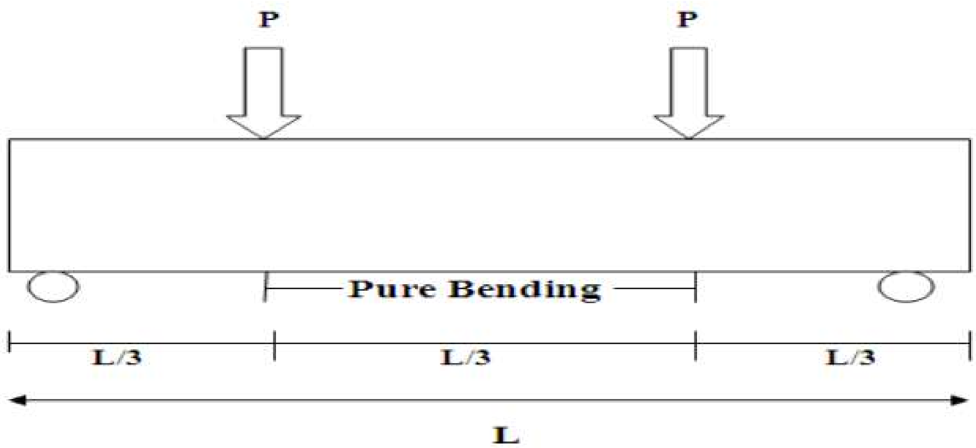



**Figure 2.1** Flexural test on CFST beam.

Li et al. (2015) presented both experimental and numerical investigations on CFST tension members subjected to eccentric loads. Experimental parameters include load eccentricity and cross section steel ratio. Failure modes showed that in-filled concrete workings efficiently on steel tube and outside of tube improves concrete. Crack pattern and Finite Element modeling was used to predict the same result. The failure mode of concrete-filled steel tube tension member subjected to eccentric load is a combination of elongation and bending. Composite members subjected to all eccentric loads showed large deformability when the rotation of the end exceeded 0.1 rad. The compressive area may happen in the composite section while the member receives an eccentric load. Due to the composite effect of steel and concrete, the strength of composite specimen was much greater than hollow steel tube. The linear tension-to-moment interaction relationship shows acceptable results for concrete-filled steel tube members. The recent design equation gives a safe and conventional estimate of the tension and flexural strength of concrete-filled steel tube tension members subjected to eccentric loads.

Varma (2002) analyzed the introduction of the category of concrete-filled steel tube structure until recently, and draw out the investigation construction of Concrete-Filled Steel Tube members. Modern concrete-filled steel tube structural members, specifically researching and developing in China, are generally described and mentioned. Different assignments in China using concrete-filled steel tube members can also be presented. Finally, several findings get for concrete-filled steel tube members. The outcomes noticed the rapid advancement analysis and implementing concrete-filled steel tube constructions in China and all over the world in the earlier years, the range of concrete-filled steel tube is expanded significantly by analysts and technicians. The feature of those concrete-filled steel tube members would be that the structural properties could be increased because of the “composite action” between filled concrete and steel tube. Basic design methods from numerous countries and several common applications of concrete-filled steel tube units in buildings, bridges, and various structures are shown and investigated. The concrete-filled steel tube structure can be treated as an alternative program to the steel or the concrete reinforcement.

Roeder et al. (2010) studied the combination of axial force and bending load and decided the best model to predict stiffness and circular resistance Concrete Filled Steel Tube. 122 specimen databases have been gathered and assessed. The result shows that the plastic stress way is a simple but effective method to predict the resistance of a circular Concrete Filled Steel Tube component under combined load. These data indicate that the current specification provides an inexact prediction of flexural stiffness and a representation of new stiffness is suggested. The suggested model allows simple but exact prediction of resistance and stiffness, allowing engineers to routinely use concrete-filled steel tube constituents in structural design.

Ammari et al. (2013) investigated the experimental behavior using the new system of the U-link of the Concrete Filled Steel Tube beam joining the concrete core on the compression side of the beam to the steel tube, resulting in a large confinement of the concrete core. Detention is attained by using the expected split-up between the two materials. As shown in Figure 2.3, two built-up concrete-filled steel tubes were experimentally tested to study the effect as reinforcement when U-link was used for a beam subjected to bending load. The state of the concrete in the tube did not show crash of the concrete when those beams have been cut at the position of the plastic hinge. Measurement of strain shown that the compressive strain of concrete is 5 to 6 times the crash strain of concrete. Investigational data exhibited that the use of a U-link as an added reinforcement in concrete filling tube improves beam bending capacity, stiffness, and ductility.

## 2.2 Concrete Filled Double Skin Steel Tube Members

CFDSST is a new sort of composite structural members that combine between the steel materials and concrete so as to obtain the best structural performance. It is comprising of dual steel tubes having the same center and concrete fills the gap between them. Many constructions all over the world such as China and Japan included this technique especially in the high buildings, bridges, and columns of offshore oil extraction facilities. This type of construction member adds safety to construction through stiffness capacity, great strength capacity, and ductility. It is also considered a modern way to resist earthquakes.

Zhao and Grzebieta (2002) conducted a good bending and compression experiments on CFDSST. It has been also utilizing theoretical formulas to prophesy the maximum strength of CFDSST beams and stub columns. Both inner and outer tubes were having a square shape. The outer tubes had four different section sizes with width to thickness ratio ranged between 16.7 and 25. The inner tube had one section size with a width to thickness ratio of 20. The ductility in the CFDSST unit under both bending and compression was better than it in the empty steel tube. The experimental conclusion clarified a good similarity between the outcomes of theoretical and experimental work.

Elchalakani et al. (2002) presented a group of accurate tests on the new kind of composite members at that time called CFDSST. The outer and inner tubes utilized in this work were formed from cold steel. The shape of the outer tube was circle while the shape of the inner tube was square. The outer and inner tubes have been combined by putting the inner tube in the center of the outer tube. The utilized sizes of the exterior tubes were eight various sizes with different width to thickness ratio ranged between

19 to 55 while the utilized sizes of the interior tubes were three sizes with different rates of width to thickness ratio having rates between 20 to 26. The high strength concrete 64 MPa was stuffed material for the gap formed between the exterior and interior skins. This work on the CFDSST clarified important features involved heightening in ductility, strength and absorbed energy on the exterior tube. Also, some equations have been helped to determine the capacity of the compressive strength of CFDSST units. Finally, a good connection has been discovered between the outcomes obtained from derivative formulas and that obtained from laboratory work.

Tao et al. (2004) prepared a paper on the CFDSST member in order to discuss the structural manner of stub columns and beam-columns under certain circumstances. Fourteen samples of composite column and beam-column have been arranged and prepared. The exterior tubes for all samples were having a circular shape as is the case with the interior tubes. The major depended parameters in this work were various, they were depending on the diameter to thickness rate and hollow ratio for the stub column while they were focused on the slenderness ratio and load eccentricity for the beam-column. By depending on this study, it was reached to some accurate and necessary theoretical basis that concerned of stub columns and beam-columns. An important factor (confinement factor) have been taken a share of research by appearing the importance of concrete stuffed for the composite units. The outcomes gained by derivative formulas were nearly the same laboratory outcomes for the stub column and beam-column. Finally, the prophesying of results also was coming from simplified models.

Han et al. (2006) presented an experimental project about how to avoid damages resulted of the earthquake by studying the behavior of CFDSST beam-columns. Twenty-eight units of CFDSST member have been utilized as test samples. The samples were splitted into two groups, the first group comprised of 16 units having exterior tubes with square shapes and interior tubes with circular shapes, while the second group was comprised of 12 units having exterior tubes with circular shapes and interior tubes with circular shapes also. The testing has been started under continuous vertical load and bending loading. Three important and useful parameters have been considered, namely, the shape of section, the strength of concrete and the load applied by axial method. It was discerned that the CFDSST beam-columns have increased in dissipated energy, ductility and strength over the exterior tube. It was obvious, the capability of energy dissipation and the feature of ductility were high for circular units in comparison with units that having square shape. As concerned to the beam-columns there was a pretty and perfect connect between the prophesied cyclic responses and the test outcomes. At the finish of the study, there was a comparison for the prophesied beam-column flexural stiffness by utilizing the structural codes.

Tao and Han (2006) described a chain of tests implemented on CFDSST beams, beam-columns, and stub columns so as to check the form of load-deformation and the failure pattern of CFDSST units and doing a differentiation table between the CFDSST, Concrete-Filled Steel Tube and the tubes that have nothing inside it. The shapes of both interior and exterior skins were rectangular. The results observed beyond doubt that the CFDSST units recorded the same behaviors of the concrete-filled steel tube units in this test. The steps of experimental work clarified a good improvement in the strength as well as the ductility for CFDSST units because of a good common action between the steel and concrete. Also, this study advanced a pretty theoretical function to foresee the relation of load against deformation for the CFDSST stub column, beam, and beam-column. At the end of the experiment, the prophesied curves perfectly corresponded with the experimental curves. Simplified models were advanced to assess the final strength of CFDSST beam-columns, beams and columns. With reasonable agreement achieved, all predictions were compared with the result of tests.

Chen et al. (2015) carried out a set of experimental tests on CFDSST columns that having inner and outer tubes with a dodecagonal shape and concrete filling the gaps between them as shown in Figure 2.1. Lengths of the tested samples were from 1000 mm to 3500 mm. This study was focused on the conduct and strengths of the units having a dodecagonal shape. As well as, the investigation was conducted accurately on the local buckling of exterior and interior skins. The splitting and compression tests were carried out carefully on the elements utilized in this study according to the standard specifications to ensure the success of the experimental study. The results gained by laboratory work were compared with the values obtained by the EC 4-1994 for designation of composite members and AISC-1999. Moreover, this study was estimated appropriateness the papers introduced by another authors by compared with the results of this study, that's mean utilizing this study as a reference to another one.

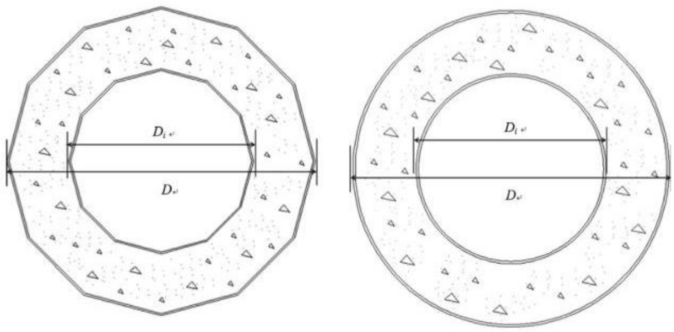


**Figure 2.2** Cross sections of dodecagonal and circular shape (Chen et al., 2015).

Han et al. (2010) made investigational tests on eight samples of CFDSST columns that comprised of fiber reinforced polymer outer skin, stuffed concrete and steel inner skin. Two sorts of loading were applied namely, the effect of continual axial load and cyclically growing bending load. The number of fiber reinforced polymer stratums and the level of axial loading were the most important parameters in this laboratory work. This work centered on studying some characteristics such as ductility, strength, stiffness, and energy dissipation. Upraised grades of energy dissipation were noticed in this sort of composite members earlier than the longitudinal rapture. Moreover, the applied load on the lateral side of the column have been witnessed a sudden decreasing. The presence of the load that applied axially on the unit may be led the ductility to a good level in the current test.

Uenaka and Kitoh (2011) carried out investigational studies to explain the mechanical behavior of CFDSST deep beam through applying three points loading test. The studies were conducted on twelve specimens with different inner tube diameter to outer tube diameter and outer tube diameter to inner tube diameter. The dimensions of all samples were as the following: 420 mm length and 160 mm outer tube diameter as shown in Figure 2.3. The results of these studies showed that the obtained modes of failure have been relying on the parameter inner tube diameter to outer tube diameter and that the strength of inner tube diameter to outer tube diameter less than 0.47 nearly were the same estimated amounts suggested in this search.

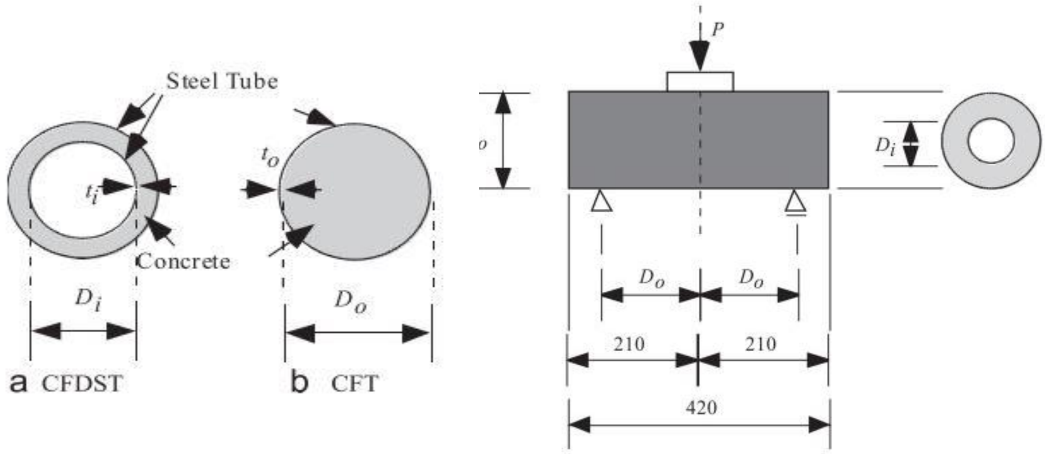



**Figure 2.3** The specimen details (Uenaka and Kitoh, 2011).

Hu and Su (2011) proposed a detailed study of CFDSST columns having tubes with circular shapes. This experiment centered on utilizing the ABAQUS software to study the normal conduct of the CFDSST columns that exposed to compressive forces that applied axially. It was confirmed that the confining forces in the CFDSST columns were good and it can give a good support to stuffed concrete. Also, the dimensions of inner tubes have an effect on the confinement, thus decreasing the dimensions of inner tubes cause increasing the supporting for the stuffed concrete. As well as experimental equations were suggested to prophesy the effect of the confinement force of concrete on the skins of columns. Lastly, a comparison has been conducted between the proposed formulation and the AISC formulas versus the laboratory data. The results obtained from the suggested equations were closer to the truth more than the results obtained according to the AISC formulas.

Han et al. (2011) implemented a group of analyses on CFDSST columns that involved its applied continuous load status for a long time. Also, the test operation involved two stages, namely applied continuous load status for a long time and maximum strength examined. Numerical patterns were presented in this study to analyze the normal performance of the CFDSST columns with consider to the long period of continuous loading. According to the obtained results from the test and that obtained from numerical models, it is clear that is a pretty similarity between them. Also, to determine the maximum value of strength, it was utilized a simplified formula under the long continuous load status.

Yang et al. (2015) presented research on the accurate behavior of CFDSST under the influence of local bearing. A chain of analyses was carried out depended on varied parameters, including hollow ratio, loading angle and chord wall thickness. This laboratory work can be considered as a complementary work of old laboratory works on the concrete-filled steel tube units. A method of numerical analysis has been employed and confirmed through applying testing data. In this study, some differentiations have been proceeded between the action of CFDSST and concrete-filled steel tube through the effect of the local bearing. The resultants clarified that the performance of members that have double tubes were better than the member section comprised of one tube because of the effect of the interaction and collaboration between the outer skin, inner skin, and sandwiched concrete. It was also found that the capacity of bearing relies on the hollow ratio. The measured and prophesied values gave excellent harmony.

Idris and Ozbakkaloglu (2015) investigated the experimental behavior using the new system of the CFDSST beam by replacing the outer steel skin by the fiber reinforced polymer. Four specimen databases have been gathered and assessed for investigating its cyclic conduct. High-strength was the feature that characterizes the concrete used in this study. Three centered parameters were depended in this work namely, both of the two skins dimensions, the presence of the stuffed concrete and the fitting of the ring that fixed about the interior skin. After looking at the results, it became clear that the most prominent characteristic of this sort of beams is the great ductility resulting from presence of fiber reinforced polymer material. The results also showed that the displacement resulted of side loading were small when the dimensions of interior tube were a large while, the displacement became large when the dimensions of interior tube became small. This condition was achieved only when the exterior tube was made of fiber reinforcement polymer material. It was observed that adding of constructional connectors on the inner skin and concrete- filling the tube both affect the overall behavior and side deflection of the fiber reinforcement polymer beam. Furthermore, the results highlighted that through the using of connectors the slip between the tubes surfaces and the concrete surface can be completely canceled. Figure 2.4 shows the beam section.

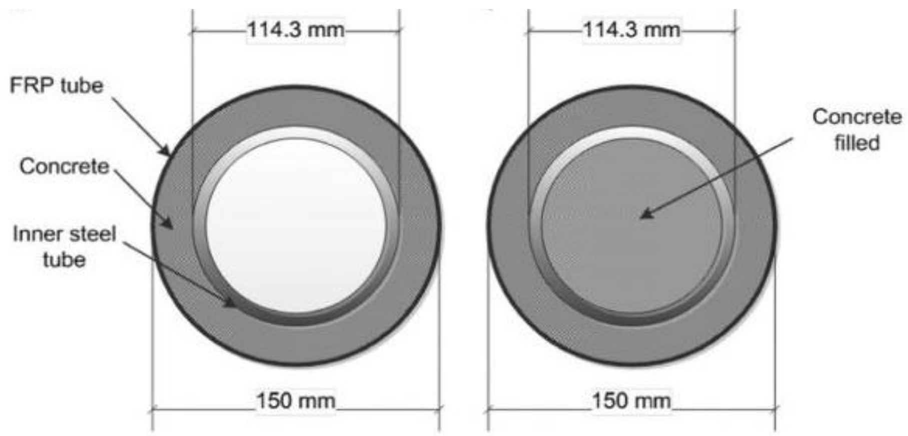



**Figure 2.4** The beam section (Idris and Ozbakkaloglu, 2015).

Chen et al. (2016) presented both experimental and numerical investigations on CFDSST tension members subjected to bending loads. The dodecagonal shape was the prominent status of this work due to there have been no previous investigations of this sort of beams. 2000 mm was the length of plates that cut and designed to dodecagonal tubes utilized as a test samples. Anything stuck in the inner surfaces of tubes was carefully removed. After preparing and installing the tubes, self-compacting concrete were casted between the interior and the outer skins without vibrating or using mixing sticks. At the end of work, excel sheet has been utilized to save data of forces, moment, deflection and failure pattern. Compare the predicted value with the experiment result. Numerical analysis shows that a good confinement effect can be obtained with a dodecagonal section.

Wang et al. (2016) investigated the normal and accurate doing of the CFDSST unit with the full help of ABAQUS software when it was drowned under the action of side impact. The software study involved also the manner of nonlinear elements and averages of strain.  It was conducted description and verification of the finite element analysis samples of CFDSST units by using current experimental results. This accurate study was touched to analyzing the strain and stress patterns after reaching the maximum loading range. Also, a deep study has been submitted to discuss the instantaneous effect of the nominal ratio of steel, impact rise, d/t ratio, the hollow ratio and elements strengths that were utilized. On the other side, some factors that have direct relationship of CFDSST units have been discussed and analyzed such as the factor of confinement and its effect on the dynamic growing factor. Finally, it was discovered that the dynamic growing factor can be accurately determined when the factor of confinement is higher than 1.03.

Zhou and Xu 2016 carried out a group of cyclically loading investigations on CFDSST beam-columns when the outer skin was having square shape and the interior skin was having a circular shape.  Accurate testing by compressive load that applied cyclically and development flexural force were managed on 24 samples to review the behavior of them. This work has been employed many parameters to discover the expected and unexpected conducts for the CFDSST units when they are exposed to loading. These parameters were, hollow ratio, compression load grade, strength of concrete and thickness of outer tube. Reports were prepared for failure patterns and hysteresis curves of the CFDSST beam-columns. The final report of this work were contained detailed information about the influence of ductility coefficient, dissipated energy, lateral load against lateral displacement curves and stiffness degradation. Also, the results highlighted that the influence of the concrete strength and hollow ratio was small when the compression load was small too while, the effect of the outer tube thickness and compression load was significant. Lastly, the prophesied values and those gathered from design codes have been assembled and compared with the results of laboratory work.

Wang *et al.* (2017) presented a new and itemized test program of 22 CFDSST samples that were comprised of an exterior tube created from austenitic stainless steel and interior tube made of high strength steel as well as the stuffed concrete between them. Studying the strength and general performance were the primary topic of this program through selecting two points on the top side of the sample and applying bending force on it. 48.5 and 56.8 were the average diameter to thickness for the exterior tubes while, the average rate of diameter to thickness for the interior tubes were began with 5.0 and finished with 22.8. The concrete strengths tests were carried out on three samples with results 80,40 and 120 MPa. The final report of this study was contained the many parameters namely the moment-curvature relations, the moment capacities and failure patterns of the beams. Lastly, all gathered itemized results were tabulated and utilized to do an elaborated differentiation with the prophesied results by the modern AISC.

Zheng *et al.* (2018) performed a laboratory cyclic loading and elaborated investigational study on CFDSST columns where the outer tube was having a circular section made of stainless steel while the inner tube was having a circular section made of carbonic steel. The accurate laboratory tests of cyclic loading and compressive load were made on eight laboratory samples depending on the following parameters: (1) inner tube diameter ratio to outer tube (0.36, 0.57); (2) the presence of internal concrete; and (3) axial loading level (0.046–0.56). The lateral loads-displacement curves that were drawn by the finite element software were tabulated and utilized to do a differentiation with the accurate laboratory resultants and the influence of different parameters on the performance of CFDSST units.

Huang *et al.* (2013) presented a good chain of studies that discussed the actions of 12 samples of CFDSST units under torsion moment when four of them were having interior tubes with a circular shape and exterior tubes with square shape. Six CFDSST samples were having interior tubes with circular shapes and the same shape for the exterior tubes. The bottom and upper openings of the tubes were tightly and accurately covered with plates by welding. The connection force achieved between the concrete surfaces and steel surfaces, failure pattern and the torque-rotation plot were analyzed by the finite element program. Exterior and interior tubes strengths in case of yielding, nominal steel amount, width to thickness ratio of inner tubes, compressive strength of concrete cube and hollow ratio were the basic parameters effected on the torque vs rotation curves. Lastly, the capacity of torsion has been deliberated by the proposed analysis and design formulas. Figure 2.5 shows the experimental test.

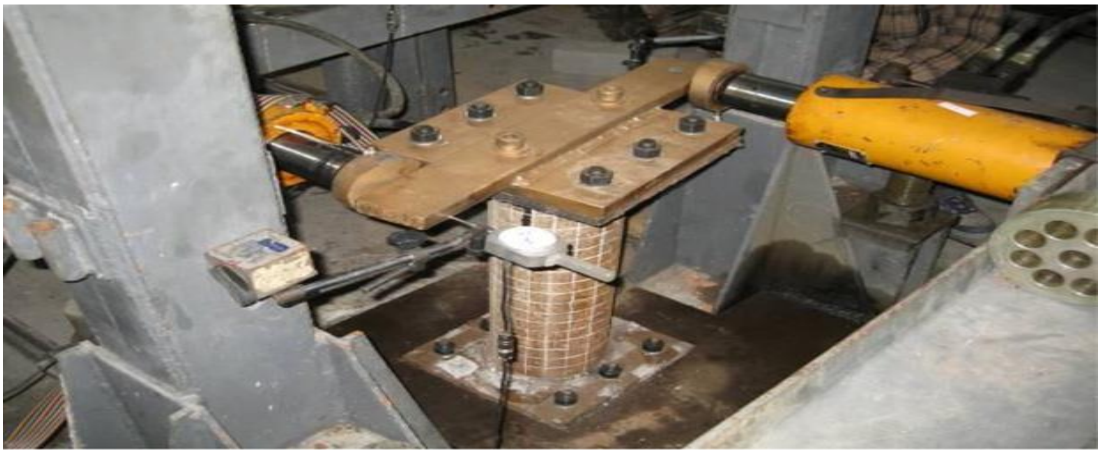


**Figure 2.5** The experimental test (Huang et al., 2013).

Hassanein *et al.* (2018) submitted an important detailed research about the effect of applying concentric compressive load on the CFDSST columns and watching its behavior during the laboratory process. The exterior skin was having circular shape while the interior skin was having square shape and there was nothing inside the interior tube. Accurate modeling and a good analyzing with concentric loads have been offered carefully by utilizing the finite elements way. The curves of stress-strain that were drawn by the finite element programs were tabulated, arranged and utilized to do a differentiation with the accurate laboratory results. Also, this study was depended on previous study to find the best combination model of concrete and steel. Many useful parameters were relied on that previous study namely, strength in yield zone and strength in case of compression mode. Finally, accurate conclusion about CFDSST columns have been offered in this detailed study.

# CHAPTER 3

# EXPERIMENTAL INVESTIGATION

## 3.1 General

This laboratory investigation is presented to study the structural performance of CFDSST beams. The study concentrated on the flexural bending behavior through a set of 12 CFDSST beams and one concrete-filled steel tube beam as a control. The parameters considered are the inner tube shape and the position of the inner tube for the same section area then comparing with the control beam. The specimens are examined to measure the behavior in term of the moment-deflection and moment carrying capacity. This chapter displays the specifications and properties of the elements are utilized to construct and testing the specimens.

## 3.2 Material properties

### 3.2.1 Self-compacted concrete

In this study, the mix proportion of the self-compacting concrete consisted of cement, fly ash, water, super plasticizer, natural fine aggregate with 4 mm maximum particle sizes, crushed Sand with range of particle sizes between 0.3 mm to 2 mm, and < 0.3mm as finer, and natural course aggregate with 10 mm maximum particle sizes are used as shown in Table 3.1 and Figure 3.1. fly ash and super plasticizer are utilized to increase workability. The mix design is done for M40 grade and the water-cement ratio is used 0.33 and the mix proportion of self-compacting concrete is given below.

**Table 3.1** Mix ratio of Self-Compacting Concrete.

| Density (kg/m$^3$) | Cement (kg/m$^3$) | Fly ash (kg/m$^3$) | Water (kg/m$^3$) | Super plasticizer (kg/m$^3$) | Coarse aggregate (kg/m$^3$) | River sand (kg/m$^3$) | Crushed sand (kg/m$^3$) |
|---|---|---|---|---|---|---|---|
| 2338.27 | 285 | 285 | 188.1 | 2.77 | 709.83 | 650.678 | 216.893 |

**Figure 3.1** Mixing of the SCC.

The characteristics and specifications of concrete were set from standard cylindrical tests. Eighteen accurate concrete cylinder tests have implemented. The mean compressive and splitting tensile strength of the mix proportion were determined in the laboratory at testing day on six cylinders 100mm by 200mm as shown in Figure 3.2. The average concrete compressive strength was 49.45 MPa while the average splitting tensile strength was 10.65 MPa. The concrete cylinder samples were tested based on the ASTM C39/C39M standard.

$$T = 2P/\pi LD \qquad (3.1)$$

where:

T = splitting tensile strength, MPa

P = maximum applied load, N

D = diameter of the specimen, mm

L = length of the specimen, mm

**Figure 3.2** Concrete cylinders.

### 3.2.2 Steel tubes

All steel tubes were manufactured from mild steel sheet to circular shapes for outer tubes and square rectangular shapes for inner tubes. The nominal thicknesses to the outer and inner tubes were 2mm and 1.5mm respectively. Tensile coupon tests were carried out to get the exact properties of steel tubes utilized in the laboratory specimens according to ASTM E8 / E8M-15a (2015) (ASTM E8 / E8M-15a, 2015) as shown in Figure 3.3. The yield and ultimate strength are listed in Table 3. 2.

**Figure 3.3** Tensile specimens.

### 3.2.3 Specimen's properties

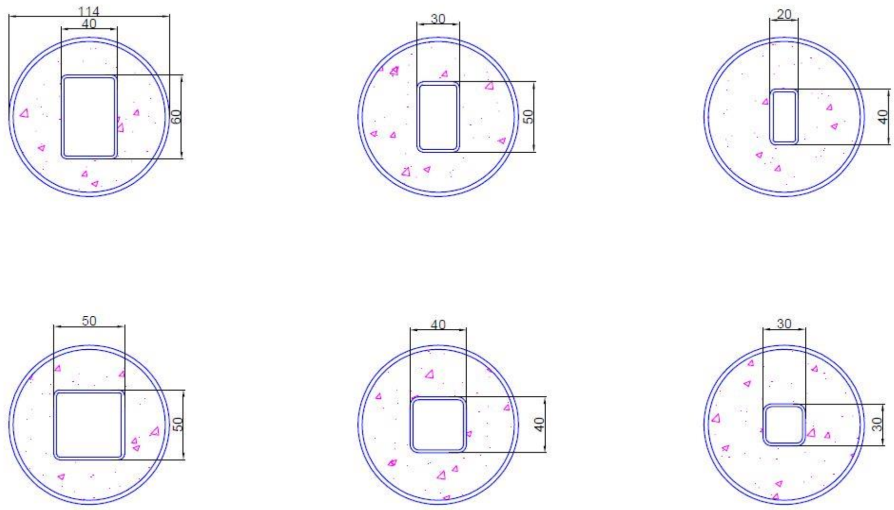
A total of 13 composite beam units were prepared and ready to carry out the laboratory investigation involving 12 CFDSST beams and one conventional concrete-filled steel tubular beam. The interior faces of the beam samples have been cleaned to remove any rusting or dust and oil deposits are cleaned. CFDSST beams were classified into three groups. Each group consisted of two pair of test specimens according to inner tube shape and inner tube position. The dimensions and specifications of each sample are noted in Table 3.3 and Figure 3.3 illustrates full details.

**Table 3.2** Specimen's details.

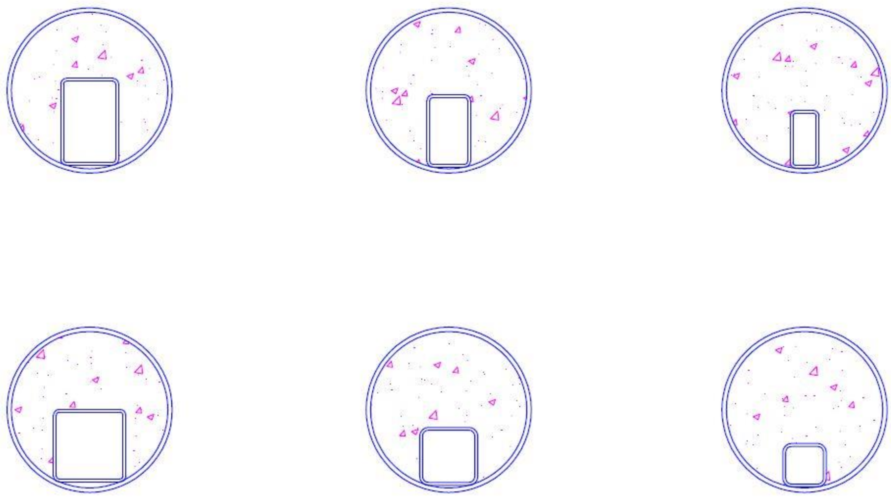
| Group name | Specimen label | $D_o \times t_o$ (mm) | $H_i \times B_i \times t_i$ (mm) | $L$ (mm) | $f_{syi}$* (MPa) | $f_{syo}$** (MPa) | $f_c$ (MPa) |
|---|---|---|---|---|---|---|---|
| | Control | 114.3×1.89 | ------- | 810 | ------ | 265.4 | 49.59 |
| G1 | 1-R-60×40-C | 114.3×1.89 | 60×40×1.41 | 810 | 256.5 | 265.4 | 49.59 |
| | 1-S-50×50-C | 114.3×1.89 | 50×50×1.43 | 810 | 365.36 | 265.4 | 49.59 |
| | 1-R-60×40-B | 114.3×1.89 | 60×40×1.41 | 810 | 256.5 | 265.4 | 49.59 |
| | 1-S-50×50-B | 114.3×1.89 | 50×50×1.43 | 810 | 365.36 | 265.4 | 49.59 |
| G2 | 2-R-50×30-C | 114.3×1.89 | 50×30×1.46 | 810 | 323.33 | 265.4 | 49.24 |
| | 2-S-40×40-C | 114.3×1.91 | 40×40×1.44 | 810 | 293.73 | 281.6 | 49.24 |
| | 2-R-50×30-B | 114.3×1.91 | 50×30×1.46 | 810 | 323.33 | 281.6 | 49.24 |
| | 2-S-40×40-B | 114.3×1.91 | 40×40×1.44 | 810 | 293.73 | 281.6 | 49.24 |
| G3 | 3-R-40×20-C | 114.3×1.91 | 40×20×1.46 | 810 | 270.36 | 281.6 | 49.52 |
| | 3-R-30×30-C | 114.3×1.91 | 30×30×1.45 | 810 | 333.34 | 281.6 | 49.52 |
| | 3-R-40×20-B | 114.3×1.91 | 40×20×1.46 | 810 | 270.36 | 281.6 | 49.52 |
| | 3-R-30×30-B | 114.3×1.91 | 30×30×1.45 | 810 | 333.34 | 281.6 | 49.52 |

* Yield stress for inner tubes.

** Yield stress for outer tubes.




(a)



(b)

**Figure 3.4** Details and dimensions of specimens.

In Table 3.2, the test units were labeled, thus the group number, inner skin shape, inner skin dimensions, and inner skin position could be recognized by the label. For example, the label ‘‘1-R-60*40-C” describes the following specimen:

- The first notation ‘‘1” indicates the group number of 1.
- The second notation ‘‘R” means that the inner skin was constructed utilizing rectangular tube.
- The third notation ‘‘60*40” refers to inner tube dimensions.
- The fourth notation ‘‘C” means that the inner skin is located in the outer tube center.

Specimens have placed upright in a bracket specially prepared for pouring concrete as shown in Figure 3.5. The bottom end of the specimen is tightly covered with steel plate 3mm thick by welding.

**Figure 3.5** The specimens before casting.

Then self-compacting concrete is casting in the steel tubes from the top without any compaction. After filling, the concrete is trimmed off using a trowel as shown in Figure 3.6.

**Figure 3.6** The specimens after casting.

After the curing period, if any shrinkage occurs, the gap filled with epoxy and then covered with another steel plates by welding, finally the specimens prepared for testing as shown in Figure 3.7 and 3.8.

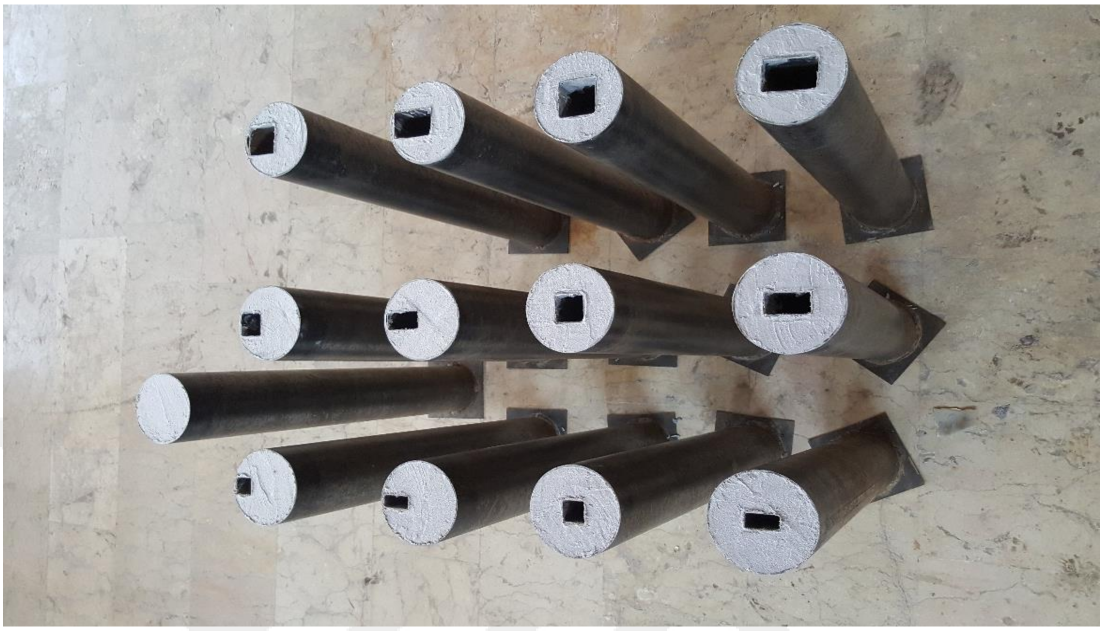


**Figure 3.7** The gap filled with epoxy after curing period.

**Figure 3.8** The specimens prepared to test.

### 3.2.4 Test procedure

The testing of beams is done by utilizing of flexure test machine with 500 kN capacity. All beams are tested under simply supported end conditions and under two-point loading with displacement control loading method with a rate of 1mm / min. Since the support is fixed at a length of 810 mm from the ends of the beam, the clear span is 750 mm. Two points loading is selected for the test and it provides a net bending area of 250 mm. The axis of the sample is accurately adjusted parallel with the axis of loading machine. Three linear variable differential transistors are fixed along the length of the beam and measure the deflection. From the three linear variable differential transistors, two are stationed at a distance of 150 mm on both sides from the mid-span, and the third mid-span is precisely fixed in the mid-span as shown in Figure 3.9. All beams are loaded up to failure.

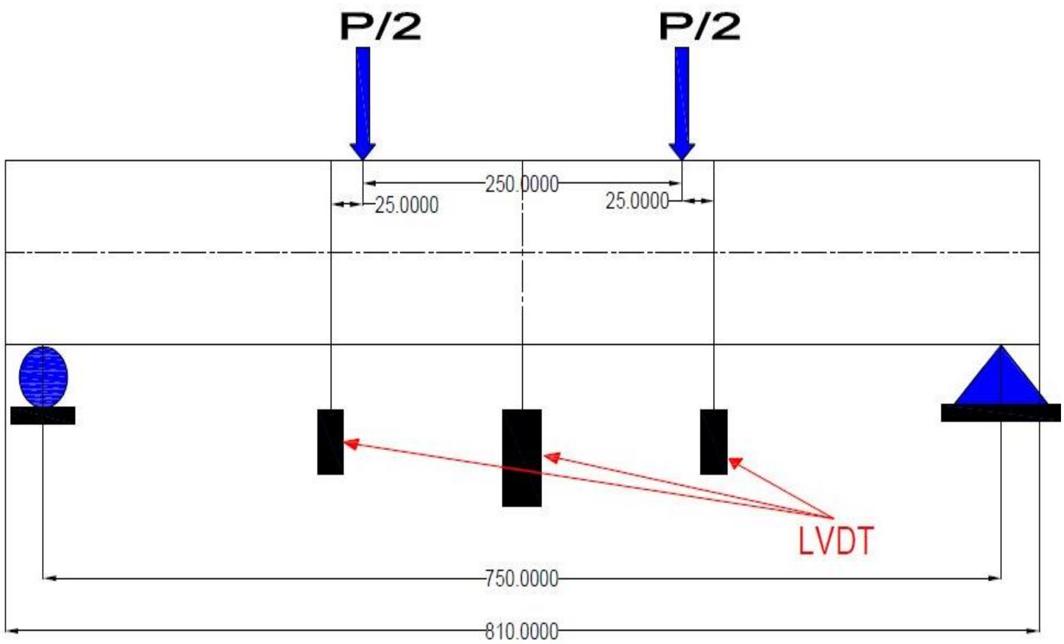



**Figure 3.9** Sketch of test details.

Pure bending is a condition of stress where a bending moment is applied to a beam without the simultaneous presence of axial, shear, or torsional forces.

# CHAPTER 4

# RESULTS AND DISCUSSIONS

## 4.1 General

When it was time to test, all investigational samples were prepared for testing. The composite beams have been loaded with equal force on the two load points until it did not take any further load. The behavior of CFDSST beams has been compared with the control tube for all groups, it found that the bending strength for the CFDSST beams is upper than that for the concrete-filled steel tube beam. Furthermore, an important comparison between the CFDSST units has been made relied on the inner tube shape and inner tube position. It turned out that the inner tube position has an obvious effect on the performance of the CFDSST beams.

## 4.2 Failure modes

For the G1, the typical failure pattern of the first two tested samples 1-R-60×40-C and 1-S-50×50-C showed local deformation at the two loading points on the outer skin. Also, an outward buckling was observed on the top side of the outer tube between the loading points. Finally, the failure has happened at the end of testing with rupture on the original welding line at a very large deformation capacity which represents a very ductile behavior. The typical failure pattern of the second two tested samples 1-R-60×40-B and 1-S-50×50-B showed local deformation at the two loading points on the outer skin as well as appearing buckling on the top side of the outer tube between the loading points at the final loading stages. Also, no tensile fractures were observed on the test samples in this stage. It was observed that the buckling has been taken a long time to appear in these specimens. The typical failure mode of the inner tubes in this group showed inward buckling as a behavior of the hollow tube. Failure pattern of the control was same to that showed by another researchers such as (Han et al. 2006), (Elchalakani and Zhao, 2001) and (Tao and Han, 2004). Figures 4.1 and 4.2 shows the failure modes of the control and the G1 respectively.


**Figure 4.1** Failure patterns of the control.

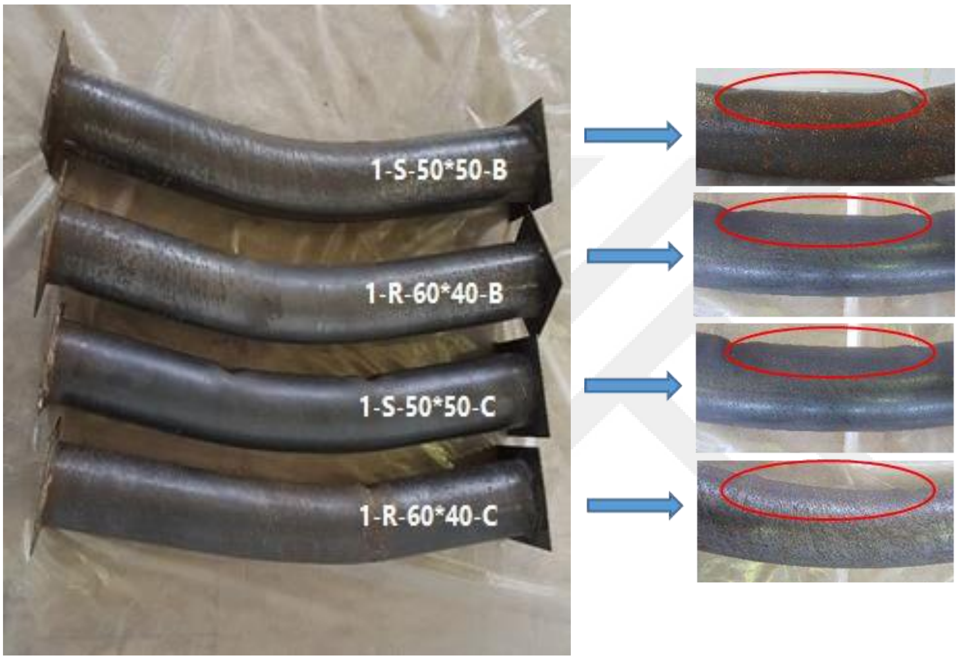



**Figure 4.2** Failure patterns of G1.

For the G2, the typical failure mode of the first two tested samples 2-R-50×30-C and 2-S-40×40-C have shown an outward local buckling on the compression zone of the outer steel tube at the final loading levels with a local deformation at the points load on the outer skin. No tension fracture or welding failure was observed in the elastic stage, however, at the end of the test, the two specimens failed by rupture at welding line at a very large deformation capacity which represent a very ductile behavior. The typical failure mode of the inner tubes in this group was inward buckling as a behavior of the hollow tube. The second two tested samples 2-R-50×30-B and 2-S-40×40-B took a longer time than the specimens 2-R-50×30-C and 2-S-40×40-C for reaching to the buckling and failing. As regards of inner tubes, there was inward buckling same as that happens in the hollow tubes. Figure 4.2 shows the failure modes of the second group.

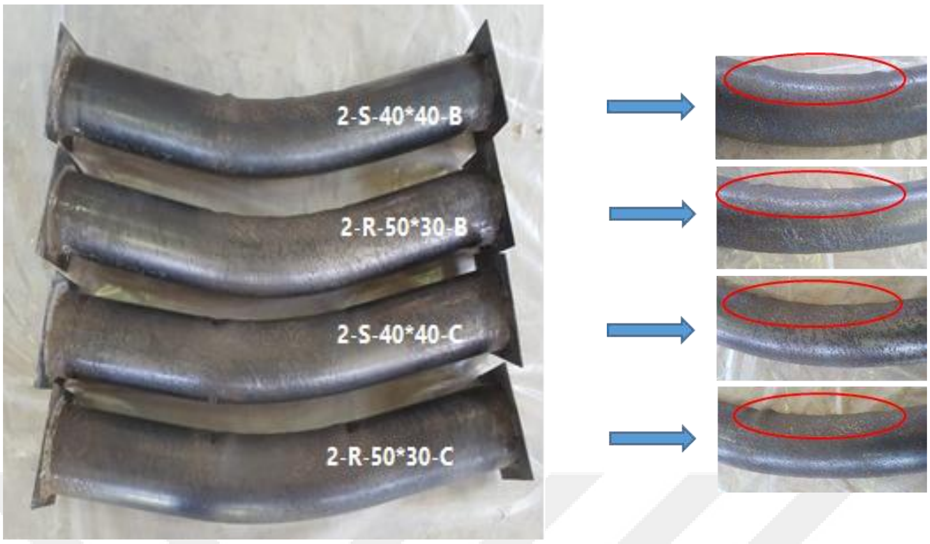



**Figure 4.3** Failure patterns of G2.

Concerning the G3, in the specimens, 3-R-40×20-C and 3-S-30×30-C outward buckling have happened on the outer tube in the compression zone near load points. The typical failure patterns of the inner tubes were similar to that in hollow tubes (inward buckling). The typical failure manner of specimens 3-R-40×20-B and 3-S-30×30-B were different from the previous two specimens, therefore, took a longer period to occur the buckling and failure. Figure 4.3 shows the failure modes of the G3.

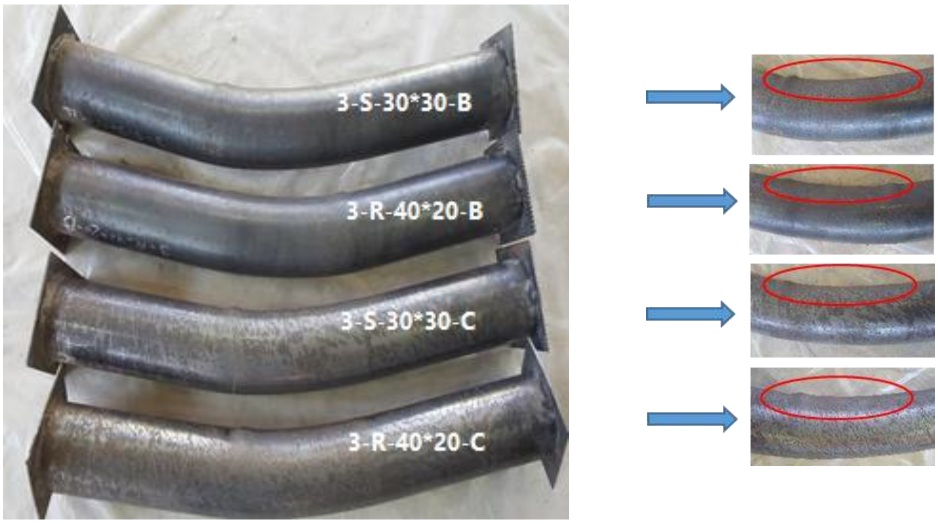



**Figure 4.4** Failure patterns of G3.

In general, the specimens that have inner tubes in the bottom side took a long time to reach the buckling and failure while specimens that have an inner tube in the center need a shorter time to reach the buckling and failure. The patterns of failure show differences in behavior between the CFDSST beam having the inner tube in the bottom and the CFDSST beam that having an inner tube in the center while the differences because of inner tubes shape are insignificant.

### 4.3 Moment mid span deflection curves

The test results showed that all specimens passed through three steps of linearity, yielding and plasticity, in addition, to showing a smooth moment deflection curve with large deflection up to failure as shown in Figure 4.5.

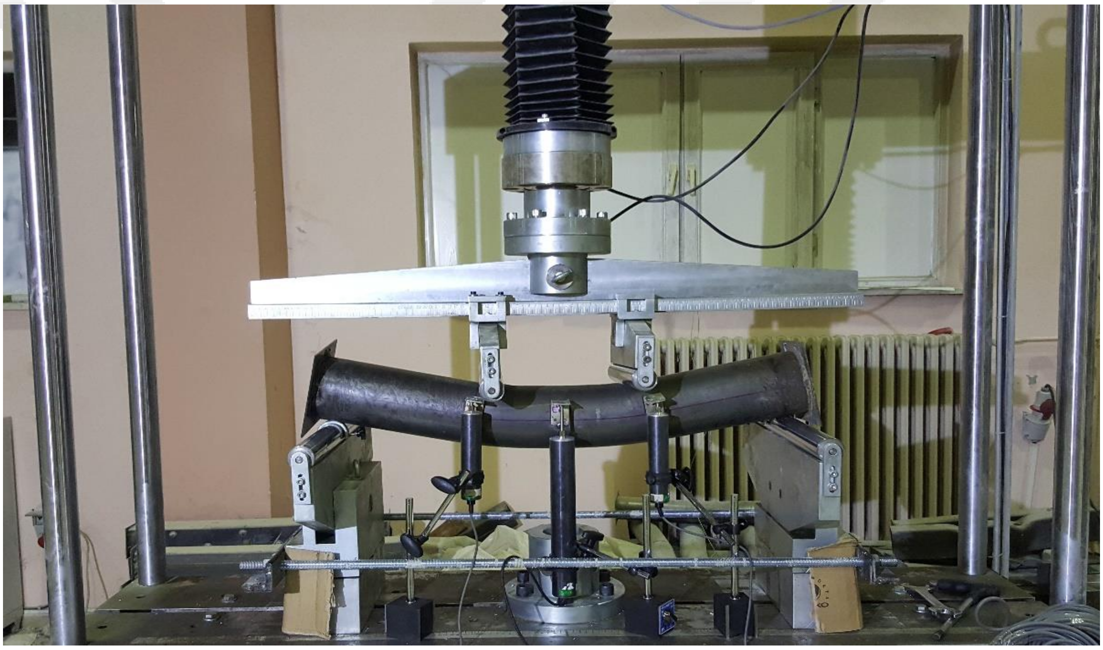


**Figure 4.5** Deflected specimen.

The concrete-filled steel tube beam has been compared with CFDSST beams for all groups, it found that the CFDSST beams have a chain of features and advantages on the Concrete Filled Steel Tube beam, such as bending stiffness, high strength and long loading time. Also, the CFDSST units were compared with each other in each group based on the shape and position of the inner tubes. According to the observations during the laboratory work and load vs. deflection curves, the laboratory samples showed elastic behavior at the first step of loading. Then, the curves follow an elastic path with decreasing stiffness until arriving at the maximum bending capacity.

However, the specimens with bottom inner tubes show a better stiffness and bending moment capacity than specimens with centric inner tubes while, the inner tube shape has a slight effect on the moment-mid-span deflection curve. Figures 4.6-4.8 show the moment-displacement curves in specimens for G1, G2, and G3, respectively.

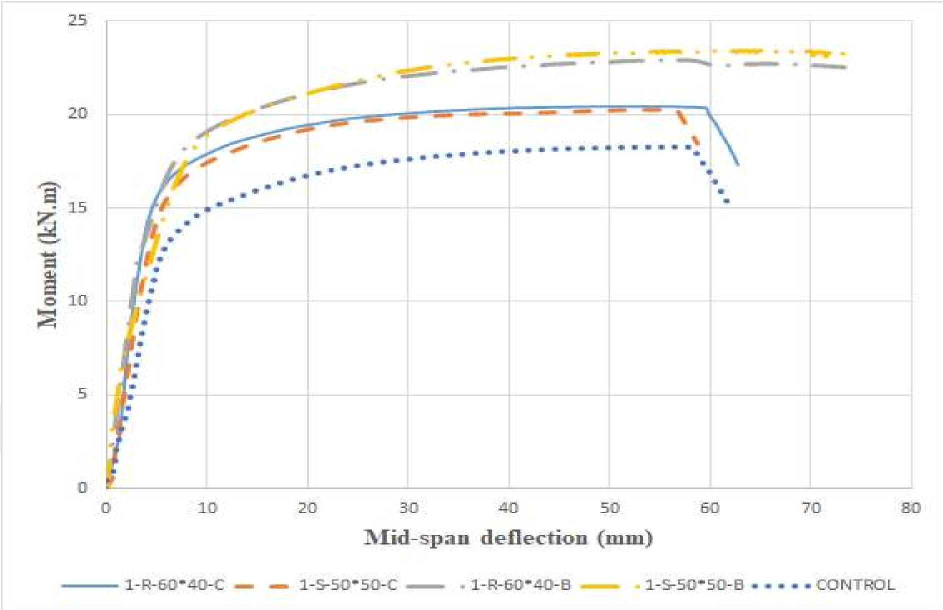



**Figure 4.6** Moment capacity vs. mid span deflection for G1.

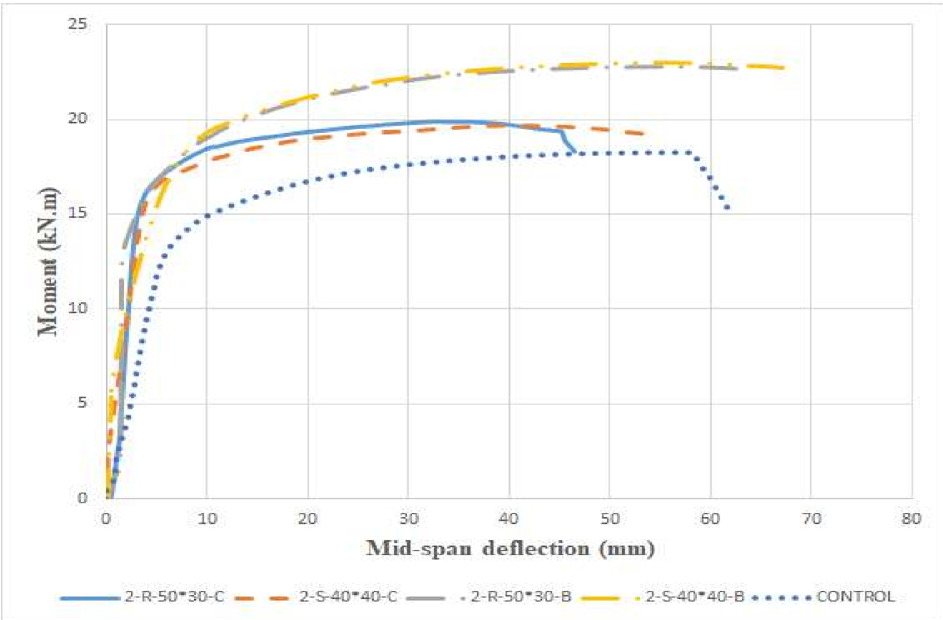



**Figure 4.7** Moment capacity vs. mid span deflection for G2.

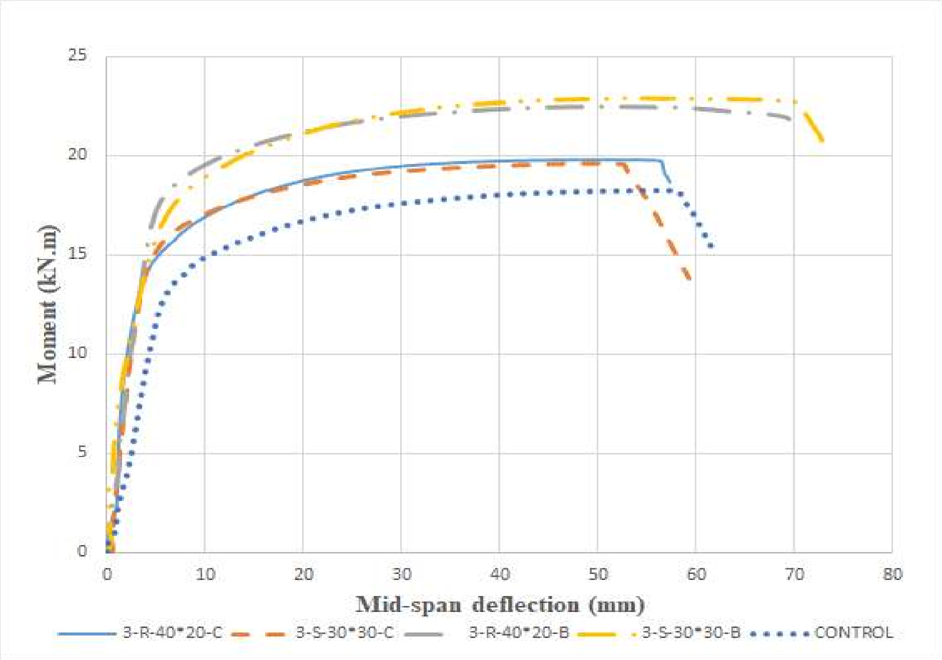



**Figure 4.8** Moment capacity vs. mid span deflection for G3.

## 4.4 Bending Moment Capacities

The maximum values of experimental bending moments for all specimens in all groups and percentage of increase in moment capacity of the CFDSST beams compared to the control beams are listed in Table 4.1-4.3.

**Table 4.1** Moment capacity for G1.

| Group name | Designation of beams | Moment Capacity *(kN.m)* | % Increase in Moment Capacity *(kN.m)* |
|---|---|---|---|
| | Control | 18.281 | ------ |
| G1 | 1-R-60×40-C | 20.463 | 11.94 |
| | 1-S-50×50-C | 20.238 | 10.71 |
| | 1-R-60×40-B | 22.897 | 25.25 |
| | 1-S-50×50-B | 23.388 | 27.94 |

For G1, the percentage increases in the ultimate moment for the CFDSST beams are ranged from 10.71% for specimen 1-S-50×50-C to 27.94% for specimen 1-S-50×50-B. It is obvious that the maximum advantage of using CFDSST beam was achieved by depending inner tube in the bottom side of the beam. While the minimum increase obtained by depending square inner tube in the center of the beam. Also, the percentage increase in the ultimate moment for the specimen1-R-60×40-C was slightly greater than the ultimate moment for specimen 1-S-50×50-C. That's mean the effect of inner tube shape on the moment capacity is not significant for the same section area of inner tube.

**Table 4.2** Moment capacity for G2.

| **Group name** | **Designation of Beams** | **Moment Capacity *(kN.m)*** | **% Increase in Moment Capacity *(kN.m)*** |
|---|---|---|---|
| | Control | 18.281 | ------ |
| **G2** | 2-R-50×30-C | 19.926 | 9.00 |
| | 2-S-40×40-C | 19.652 | 7.50 |
| | 2-R-50×30-B | 22.764 | 24.52 |
| | 2-S-40×40-B | 22.972 | 25.66 |

For G2, the percentage increases in the ultimate moment for the CFDST beams are ranged from 7.5% for specimen 2-S-40×40-C to 25.66% for specimen 2-S-40×40-B. It is clear that the maximum advantage of using CFDSST beam was achieved by depending inner tube in the bottom side of the beam. While the minimum increase obtained by depending square inner tube in the center of the beam. Also, the percentage increase in the ultimate moment for the specimen 2-R-50×30-C was slightly greater than the ultimate moment for specimen 2-S-40×40-C.

**Table 4.3** Moment capacity for G3.

| **Group name** | **Designation of beams** | **Moment Capacity *(kN.m)*** | **% Increase in Moment Capacity *(kN.m)*** |
|---|---|---|---|
| | Control | 18.281 | ------ |
| **G3** | 3-R-40×20-C | 19.826 | 8.45 |
| | 3-R-30×30-C | 19.592 | 7.17 |
| | 3-R-40×20-B | 22.497 | 23.10 |
| | 3-R-30×30-B | 22.921 | 25.38 |

For G3, the percentage increases in the ultimate moment for the CFDSST beams are ranged from 7.17% for specimen 3-R-30×30-C to 25.38% for specimen 3-S-30×30-B. It is clear that the maximum advantage of using CFDSST beam was achieved by depending inner tube in the bottom side of the beam. While the minimum increase obtained by depending square inner tube in the center of the beam. Also, the percentage increase in the ultimate moment for the specimen 3-R-40×20-C was slightly greater than the ultimate moment for specimen 3-R-30×30-C as shown in the table above. It's mean the effect of inner tube shape on the moment capacity is insignificant.

Overall, the investigational results show that the average moment capacity for the G1 is greater than that for the G2 and G3 because of the effect of the section area of the inner tubes. A comparison in moment capacity among all specimens is shown in Figure 4.9.

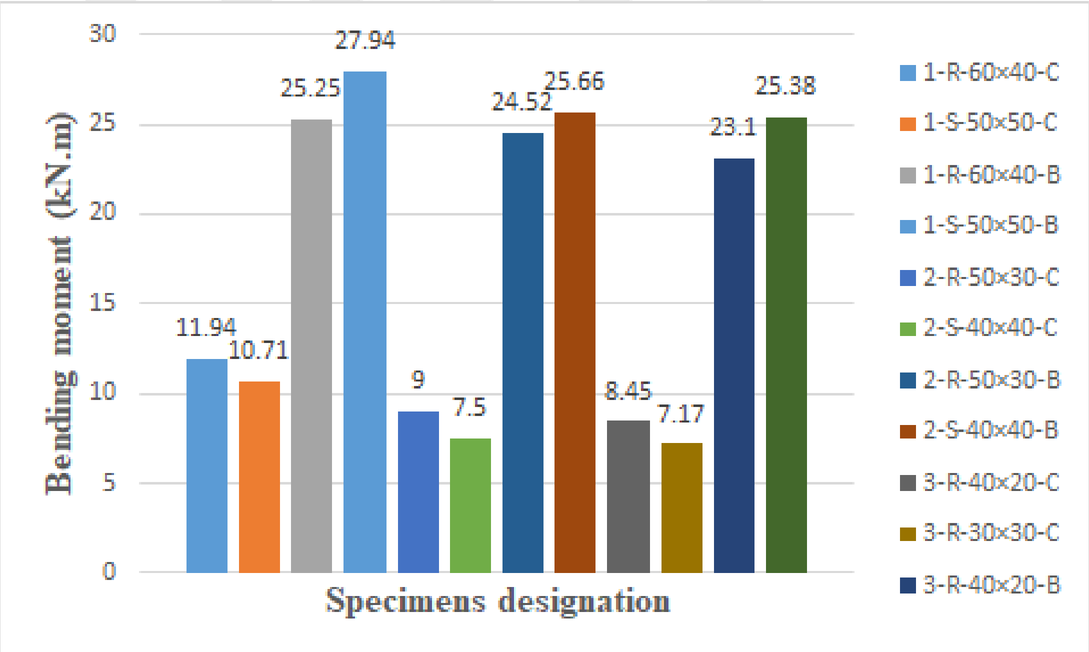



**Figure 4.9** A comparison in moment capacity among all specimens.

### 4.5 Deflection curves

Figures 4.10 - 4.14 show the deflection shapes of the specimens in G3. When loads are applied and increases gradually on the beam models, the member responses occur in the form of deformation. The initial beam conditions are attainable when the models undergo elastic deformation. Each material follows the constitutive properties and provided the strain energy form to correspond the deformation response of the members. The beam models followed approximately the half sine wave curve during the course of the test. (Han, L. 2004).

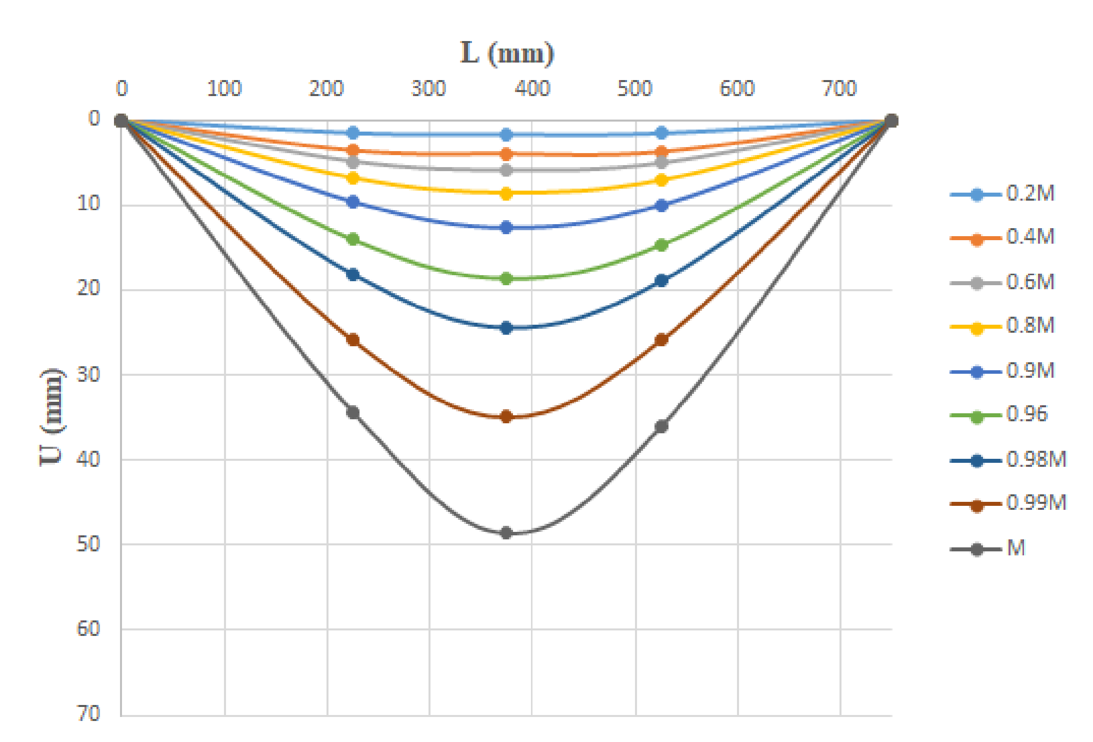



**Figure 4.10** Deflection shape of the specimen 3-R-40×20-C.

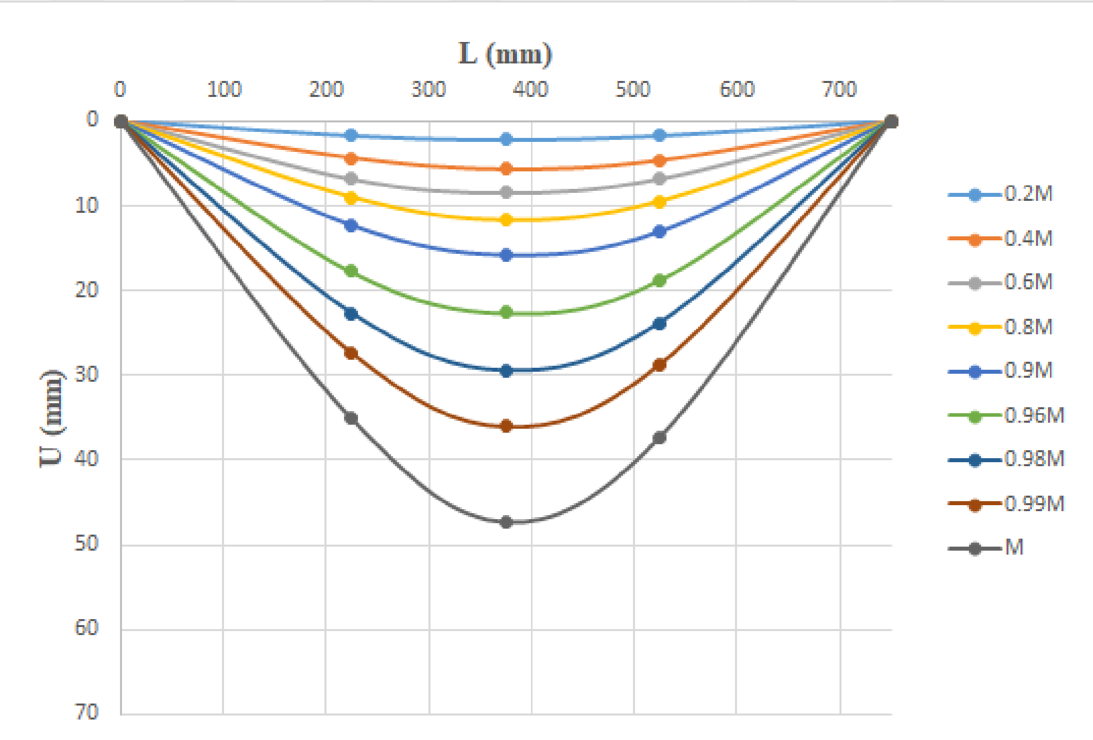



**Figure 4.11** Deflection shape of the specimen 3-S-30×30-C.

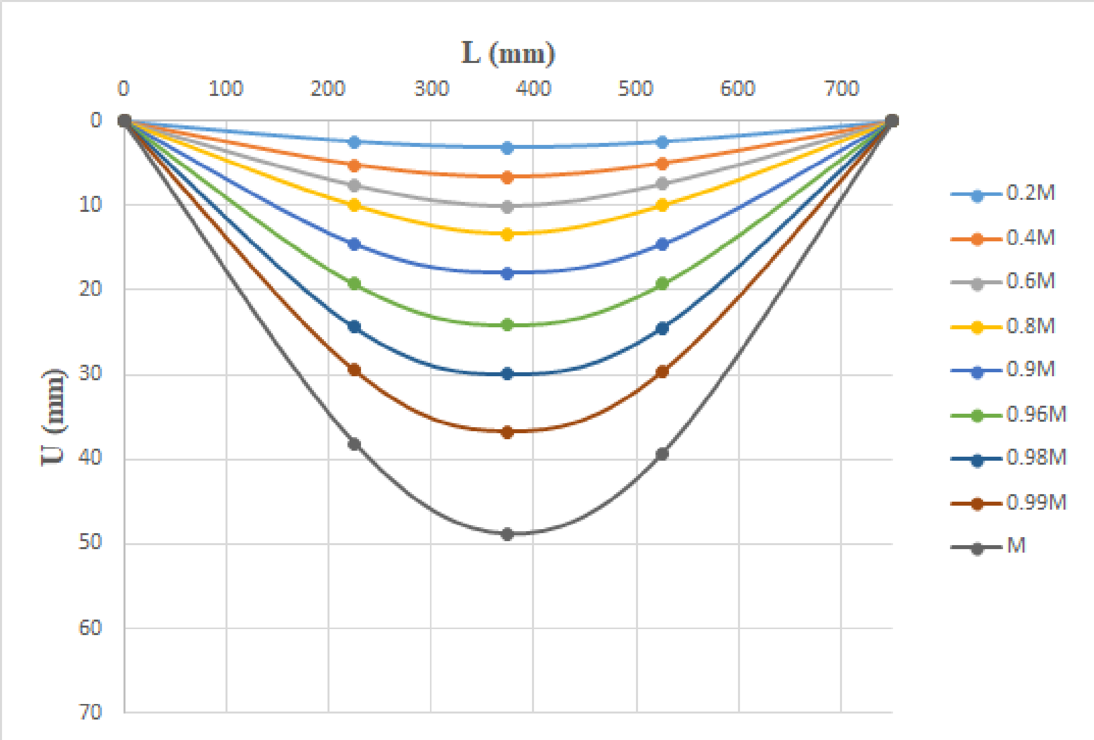



**Figure 4.12** Deflection shape of the specimen 3-R-40×20-B.

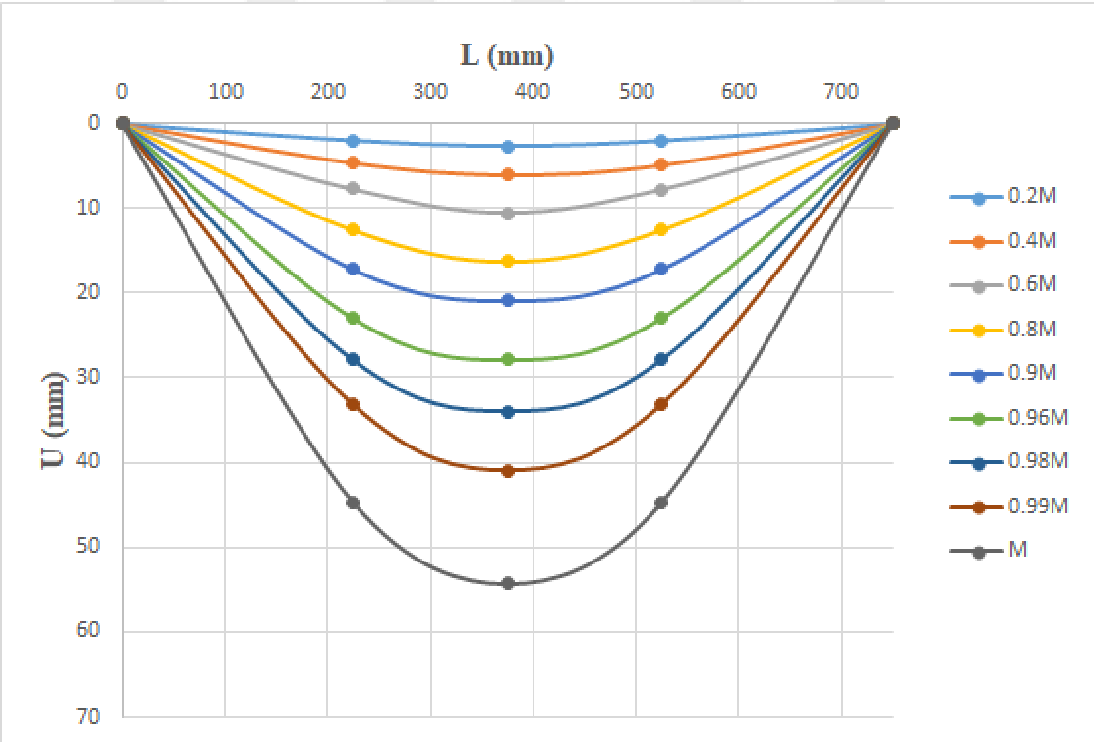



**Figure 4.13** Deflection shape of the specimen 3-S-30×30-B.

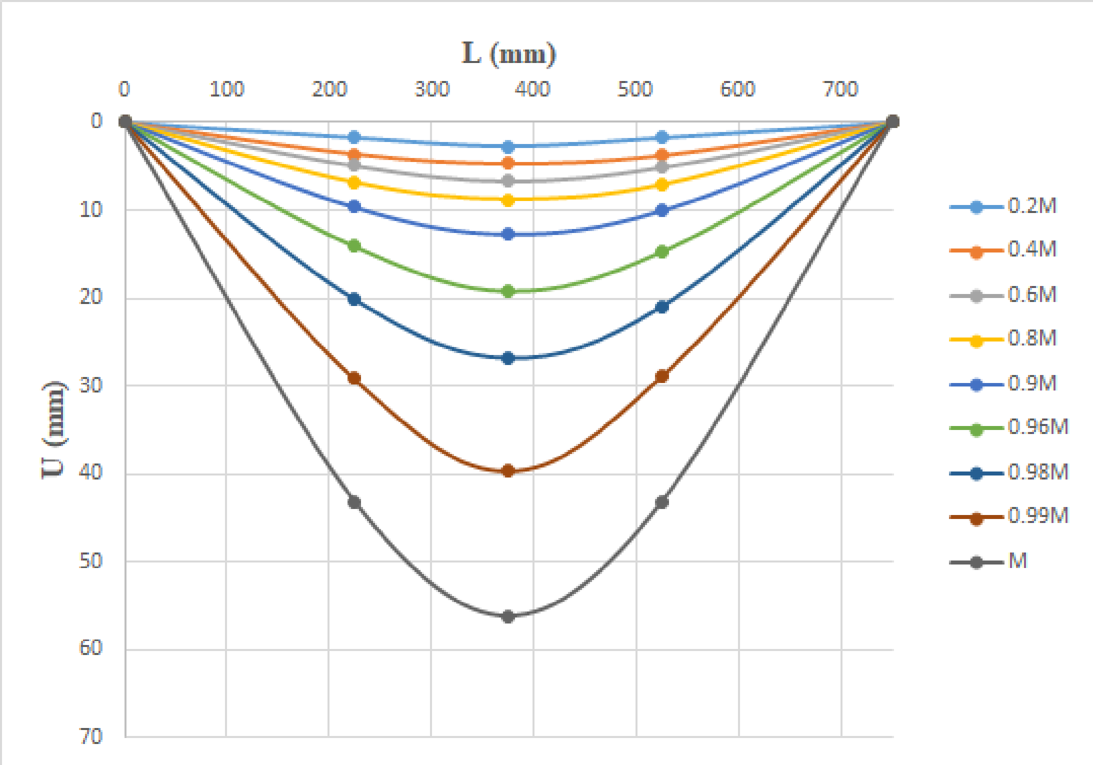



**Figure 4.14** Deflection shape of the control.

## 4.6 Ductility

Ductility can be defined as the capability of a material to be drawn or deformed without rupture. It is, therefore, a sign of how pliable the material is. The ductility index of beams has been determined for all groups as shown in Figure 4.12 and Table 4.4. The DI is defined as follow:

$$DI = D_u / D_{0.6} \tag{4.1}$$

where**:**

$D_u$ = displacement at the maximum moment.

$D_{0.6}$ = displacement at 0.6 from the maximum moment.

**Table 4.4** Ductility index for all specimens.

| Group name | Specimen label | $D_u$ | $D_{0.6}$ | *DI* |
|---|---|---|---|---|
| | Control | 56.13 | 4.68 | 12.13 |
| G1 | 1-R-60×40-C | 42.5 | 3.42 | 12.42 |
| | 1-S-50×50-C | 53.58 | 4.00 | 13.40 |
| | 1-R-60×40-B | 56.24 | 4.5 | 12.49 |
| | 1-S-50×50-B | 55.84 | 4.10 | 13.66 |
| G2 | 2-R-50×30-C | 33.10 | 2.43 | 13.62 |
| | 2-S-40×40-C | 41.54 | 2.58 | 16.10 |
| | 2-R-50×30-B | 56.22 | 2.73 | 20.54 |
| | 2-S-40×40-B | 53.98 | 3.91 | 13.81 |
| G2 | 3-R-40×20-C | 52.10 | 3.88 | 13.43 |
| | 3-R-30×30-C | 48.61 | 3.10 | 15.68 |
| | 3-R-40×20-B | 50.23 | 3.50 | 14.35 |
| | 3-R-30×30-B | 54.89 | 2.87 | 19.1 |

Based on the collected results for G1, the DI ranged from 12.42 for specimen 1-R-60×40-C to 13.66 for specimen 1-S-50×50-B. Thus, the maximum DI obtained of CFDST beams is 13.66 for specimen 1-S-50×50-B. For the control beam, DI is 12.13 and therefore, the ductility of the control beam is less than the CFDSST beams.

With regard to G2, the DI ranged from 13.62 for specimen 2-R-50×30-C to 20.54 for specimen 2-R-50×30-B. The maximum value of DI is 20.54 for specimen 2-R-50×30-B. While for control beam the DI is 12.13. It is clear that the ductility of the CFDSST beams is better than the control.

For G3, the DI ranged from 13.43 for specimen 3-R-40×20-C to 19.10 for specimen 3-S-30×30-B. The maximum DI for CFDSST beams obtained is 19.10 for specimen 3-S-30×30-B. whereas for control beam the DI is 12.13, thus the ductility of control beam is less than the CFDSST beams.

Based on DI, the best benefit was obtained for a CFDSST beam with the specimens that have inner tube position in the bottom side of the outer tube. The lowest DI result were obtained in the control.

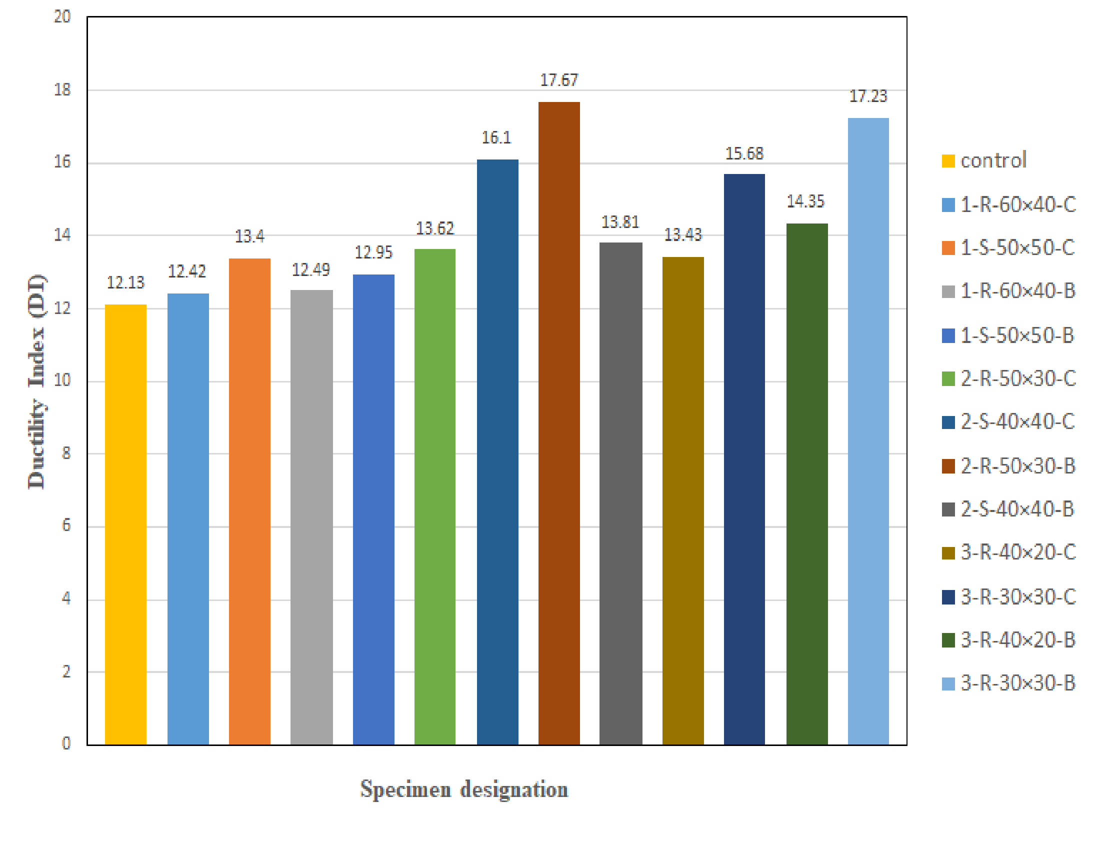



**Figure 4.15** A comparison in DI among all specimens.

## 4.7 Flexural stiffness capacity

Initial and serviceability flexural stiffness have utilized in this laboratory work. Initial flexural stiffness has calculated when the moment was equal to 0.2 from the moment ultimate while, the serviceability flexural stiffness has calculated when the moment was equal to 0.6 from the moment ultimate (Al-Shaar and Göğüş, 2018), (Han, L. 2004) and (Varma et al., 2002). Table 4.5 below displays the values of initial and serviceability flexural stiffness gained from this study. The maximum value of initial flexural stiffness was achieved in the specimen 1-S-50×50-B while, the maximum value of serviceability flexural stiffness achieved in the specimen 2-R-50×30-B. These values refer that the stiffness for the CFDSST units is higher than the Concrete Filled

Steel Tube specimen also, the flexural stiffness obtained from the CFDSST units with bottom inner tube is better than that with the centric inner tube.

**Table 4.5** Initial and serviceability flexural stiffness for all specimens.

| **Group name** | **Specimen label** | $K_i$ ($kN.m^2$) | $K_s$ ($kN.m^2$) |
|---|---|---|---|
| | Control | 116.714 | 133.511 |
| **G1** | 1-R-60*40-C | 204.475 | 149.79 |
| | 1-S-50*50-C | 160.1748 | 153.003 |
| | 1-R-60*40-B | 372.8174 | 173.994 |
| | 1-S-50*50-B | 888.525 | 185.552 |
| **G2** | 2-R-50*30-C | 265.788 | 210.392 |
| | 2-S-40*40-C | 414.7843 | 260.446 |
| | 2-R-50*30-B | 183.141 | 116.031 |
| | 2-S-40*40-B | 620.2767 | 199.899 |
| **G3** | 3-R-40*20-C | 209.2392 | 148.348 |
| | 3-R-30*30-C | 192.7541 | 118.284 |
| | 3-R-40*20-B | 194.252 | 119.798 |
| | 3-R-30*30-B | 373.2244 | 207.346 |

### 4.8 Moment capacity vs. weight

Table 4.6 below exhibits the moment capacity against the weights of the CFDSST specimens and the control specimen. Although the control sample is heavier than the CFDSST units, it is having moment capacity less than the CFDSST beams. Also, group one were lighter from group two and group three but it is having the best moment capacity. These values highlight a main advantage of the CFDSST on the Concrete Filled Steel Tube beams. The light weight feature of structural parts provides ease of transport and installation and thus reduce costs by reducing the time of achievement and reducing manpower. Based on the above, the use of CFDSST beams can be considered better than the use of concrete-filled steel tube beams to save time and money.

**Table 4.6** Moment capacity vs. weight for all specimens.

| Group name | Specimen label | Moment Capacity ($kN.m$) | % Increase in Moment Capacity ($kN.m$) | Weight ($kg/m$) |
|---|---|---|---|---|
| | Control | 18.281 | ------ | 29.63 |
| G1 | 1-R-60×40-C | 20.463 | 11.94 | 26.62 |
| | 1-S-50×50-C | 20.238 | 10.71 | 26.62 |
| | 1-R-60×40-B | 22.897 | 25.25 | 26.62 |
| | 1-S-50×50-B | 23.388 | 27.94 | 26.62 |
| G2 | 2-R-50×30-C | 19.926 | 9.00 | 28.22 |
| | 2-S-40×40-C | 19.652 | 7.50 | 28.22 |
| | 2-R-50×30-B | 22.764 | 24.52 | 28.22 |
| | 2-S-40×40-B | 22.972 | 25.66 | 28.22 |
| G3 | 3-R-40×20-C | 19.826 | 8.45 | 29.16 |
| | 3-R-30×30-C | 19.592 | 7.17 | 29.16 |
| | 3-R-40×20-B | 22.497 | 23.10 | 29.16 |
| | 3-R-30×30-B | 22.921 | 25.38 | 29.16 |

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

This study centered on the normal performance of CFDSST beams that subjected to pure bending when the outer tubes were having circular shapes while the inner tubes had rectangular and square shapes. A comparison was made between the CFDSST specimens depending on the inner tube shape and the inner tube position as well as comparing these specimens with the control specimen. Based on the experimental results, the following conclusions can be indicated;

- The failure mode of the control appeared clearly in the form of outward buckling in the compression zone in addition to occurring local deformation on the points of loading.
- The failure mode of the CFDSST beams appeared slightly in the form of outward buckling in the compression zone in addition to occurring local deformation on the points of loading and it took longer to reach failure.
- The deflection curves along the effective length with different moment levels followed approximately the half sine-wave curve during the course of the entire test.
- The CFDSST beams showed elastic and ductile behavior at the first stage of loading better than the control beam.
- For G1, the highest increase in ultimate moment capacity in the CFDSST beams is about 27.94% for the specimen that has square inner tube in the bottom side of the outer tube as compared to the ultimate moment capacity of the control beam.
- For G2, the highest increase in ultimate moment capacity in the CFDSST beams is about 25.66% for the specimen that has square inner tube in the

bottom side of the outer tube as compared to the ultimate moment capacity of the control beam.

- For G3, the highest increase in ultimate moment capacity is about 25.38% for the specimen that has square inner tube in the bottom side of the outer tube as compared to the ultimate moment capacity of the control beam.
- For all groups, the lowest increase in moment capacity as compared to control was obtained in the specimens that have a centric square inner tube, while the highest increase in ultimate moment capacity was obtained in the specimens that have inner tube in the bottom side of the outer tube.
- According to the results, the DI for the CFDSST beams greater than that for the Concrete Filled Steel Tube beam.
- Basing on the results, the max value of initial flexural stiffness was 88.525 kN. $m^2$ for specimen that has an inner tube in the bottom side of the outer tube while the max value of serviceability flexural stiffness was 396.031 kN. $m^2$ also for specimen that has an inner tube in the bottom side of the outer tube.
- The light weight of CFDSST beams assists to lessen the cost through reducing the manpower.
- According to the results, this study showed the main advantages of CFDSST beam on concrete-filled steel tube beam such as increasing flexural stiffness, moment capacity, ductility and self-weight.
- Use of CFDSST beams provides the possibility of passing lines of electric power and water networks through the inner tube of the constructional member.

## 5.2 Recommendations for future researches

According to the above literature, limited researches were conducted in the field of CFDSST beams. Furthermore, up to now, no previous study was carried out on the CFDSST beam with an inner tube in the bottom side of the outer tube. So that the research in this field is still in the primary stage and more efforts are required to fill this gap in the literature. This study depended on using circular outer tubes and inner tubes with rectangular and square shapes. The thicknesses used in this study were 2 mm for the outer tubes and 1.5 mm for the inner tubes. There is still a wide range of CFDSST beams with no different thickness to use in future research. Besides the circular tube, some situations may arise in practical applications that need to use another shape of the tubes. Also, finite element method can be used to study the flexural behavior of this kind of member. Thus, additional research is necessary to understand the behavior of the CFDSST beam with different shapes of the tubes sections.

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