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ADDIS ABABA INSTITUTE OF TECHNOLOGY
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**Critical Buckling load and Effective Length of Concrete Filled Steel Tube
Column (CFST)**

A Thesis in Structural Civil Engineering

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A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of
Science

The undersigned have examined the thesis entitled “Critical Buckling load and Effective Length of Concrete Filled Steel Tube Column (CFST)” presented by Zewudu Minwyelet, a candidate for the degree of Master of Science and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that research work titled “Critical Buckling load and Effective Length of Concrete Filled Steel Tube Column (CFST)” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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ABSTRACT

The effective length and critical buckling load of concrete filled steel tube (CFST) columns are the two key parameters to determine its ultimate strength for engineering design. Design codes such as Euro codes and others have limitations regarding to critical buckling load and effective length values for the CFST columns.

Hence, in this thesis, to determine the critical buckling load and effective length factor based on linear and non-linear buckling analysis, isolated CFST columns with different end conditions were investigated. By comparing the results of linear and non-linear finite element analysis result with the current design practice, possible recommendations have been given to referring to effective length factor, and consequent critical buckling load for concrete filled steel tube (CFST) column.

The results indicate that the current theoretical and recommended effective length factors given on the EC4 is a conservative estimate which gives uneconomical design so that the currently adopted code underestimates the critical Buckling load of the CFST column.

Keywords: Concrete filled steel tube (CFST), effective length factor, finite element method (FEM), linear buckling analysis, non-linear buckling analysis, Euro code 4.

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ACRONYMS

Ac	Cross-sectional area of concrete
Ac	Cross-sectional area of concrete
As	Cross-sectional area of the steel tube
B	Overall width of square or rectangular section
D	Overall diameter of circular section or overall depth of rectangular section
Ep	Strain hardening modulus of steel
Ep	Strain hardening modulus of steel
Es	Modulus of elasticity of steel
fb0	Compressive strength of concrete under biaxial loading
fc'	Cylinder compressive strength of concrete
FEM	Finite element method
fcu	Cube compressive strength of concrete
fy	Yield strength of steel
fu	Ultimate strength of steel
Kc	Ratio of the second stress invariant on the tensile meridian to that on the compressive meridian
L	length of the CFST column
t	Wall thickness of the steel tube
ϵ	Strain
ϕ	Dilation angle of concrete
RCC	Reinforced cement concrete
CFST	concrete filled steel tube

1. INTRODUCTION

1.1 Concrete filled steel tube (CFST) column

Concrete filled steel tube (CFST) column is one kind of composite structures which could be formed by filling concrete in the hollow steel (RHS, CHS and SHS sections) tube without longitudinal reinforcement bar. Based on characteristics of steel and concrete, making full use of the interaction of the two materials under loading, CFST structure had excellent mechanical properties and construction performance. Therefore, it had been widely used in high-rise buildings, skyscraper and large span arch bridges. Many researchers had made great efforts on the research on this type structures, and many different conclusions were obtained. It lacked the stability analysis of the CFST frame. Although there were some local codes of the CFST structures, the stability calculation of the CFST frame was still relatively rare. One key issue of CFST structure design is to determine the actual effective length. Consulting the research of different literatures, the effective length factor of CFST frame columns can be calculated referring to design specification for steel structure based on analytic method. However, the real CFST structure exist initial imperfections, and its buckling mode differs from the steel structural frame. Engineers have also questioned the accuracy of this method. Hence, Due to development of the finite element software, it is increasingly used for overall stability analysis. Considering the influence of initial geometric defects, the closest actual deformation of the FEM model can be obtained from the FE analysis. This paper was made to develop a reasonable finite element method (FEM) model of isolated CFST columns to determine the critical buckling loads for different end support conditions and then substituted the result into the Euler formula to obtain the effective length factor of CFST columns. It is simple, useful and reasonable approach, and can be used as reference for the structural designer.

1.2 Objective of the Study

1.2.1. General objective

- The primary objective of this paper was to determine the effective length factors of an isolated CFST columns with different end support conditions by using FEM.

1.2.2. Specific objective

in addition to the general objective, the project aims:

- To study the effect of different parameters on buckling load and effective length of CFST column,
- To examine the advantage of CFST structures in our country, Ethiopia.

1.2.3. Scope and limitation of the study

As clearly explained on the objective part of this study, this project was done by detail review of previous literatures and test data. The scope of the project is limited only to modeling an isolated CFST columns for preliminary determination of critical buckling load and effective length factor by varying end support conditions setting the cross section be constant and compare with currently available theoretical and recommended values accordingly. Since the experimental method is highly expensive and time-consuming even though it provides dependable results about the performance of CFST structures, Finite element method was used to study the behavior of CFST structures. The behavior of composite frames also not fully understood hence the requirement for accurate and reliable analysis of a composite frame is very essential.

1.3 Statement of the Problem

Most of the time, since there are no special codes to determine the actual effective length and critical buckling load for CFST column, the designers (Engineers) are dependent on the values according with specifications for steel structure which leads to errors in some degrees during design and construction stage. Hence, the actual effective length factor for CFST column was overestimated which leads to underestimate the section capacity of the column.

1.4 Significance of the study

This study will play role as an important step for developing the industry and inputs for the Ethiopian Building Codes of Standard in considering the subject understudy in general and consulting and design firms can benefit from the output of this research work in such a way that;

- It will increase awareness and efficiency of structural engineers on the recommended effective length factors provided in our code ES EN 1998-2015.
- It will help engineers to design safe and cost-effective composite structures.

2. LITERATURE REVIEW

2.1 General

A simple definition of structural system in context with building is, “a system of connected members to support the load that results from the usage of building or only presence of building to the ground”. There are several structural systems according to purpose, size, scale and loading to which the building is subjected to. Various materials are used to make columns and beams which are vital components of any structural system. Concrete and steel are major construction materials amongst these. The choice of material depends upon numerous factors like type and purpose of building, size of building, availability of materials, topography of land, climatology and budget. RCC and steel frames have been the most common frame systems for long times whereas composite frame system has also emerged as popular system for high rise buildings for few decades. Multi-story composite frames are generally composed of structural steel members made composite with concrete. The use of concrete filled steel tubes (CFST) in building construction has been renaissance in recent years due to their numerous advantages, apart from its superior structural performance making a typical composite frame structure. Their usage as columns in high-rise and multi-story buildings, as beams in low-rise industrial buildings and as arch bridges, has become widespread in countries like China and many others in last few decades with abundant examples. But, their usage herein Ethiopia is not familiar.

It is known that the ultimate load capacity and stress-strain relationship of a CFST column is influenced by complex interactions between the steel tube and concrete core components in composite steel and concrete structure. In short columns such actions are governed by the strength and characteristics of the materials, while for slender columns mechanical instability is a consideration. The structural action of a CFST section throughout the loading sequence may be described in terms of concrete microcracking theories and the Poisson's effects of the constituent materials.

2.2 CFST Columns

There are two typical composite columns which are concrete encased, and concrete filled composite sections. The concrete encased composite column section is also two types in which, steel section completely covered by concrete and steel section partially covered by concrete section. And the other one is concrete completely covered by steel which is called

concrete filled steel tube (CFST) column. The steel section and the uncracked concrete have the same centroid. Many researchers have been carried out to investigate the behavior of CFST columns subjected to various types of loadings. CFST sections have the following advantages:

- During construction the steel tube provides permanent formwork for the concrete.
- Prior to pumping wet concrete into the members, the steel tube can carry significant construction loads.
- The steel tube offers confinement to the concrete which increases the capacity of the concrete. The concrete also supports the steel tube, reducing or eliminating local buckling of the steel section resulting in increased load carrying capacity, ductility and energy absorption.
- The thermal properties of concrete increase the fire resistance of the steel tube.

These advantages result in quick and efficient construction as opposed to traditional RC construction. Numerous research projects were conducted on CFST columns to determine the advantages that this construction method offers. Different researcher investigation on CFST column had been discussed latter in detail

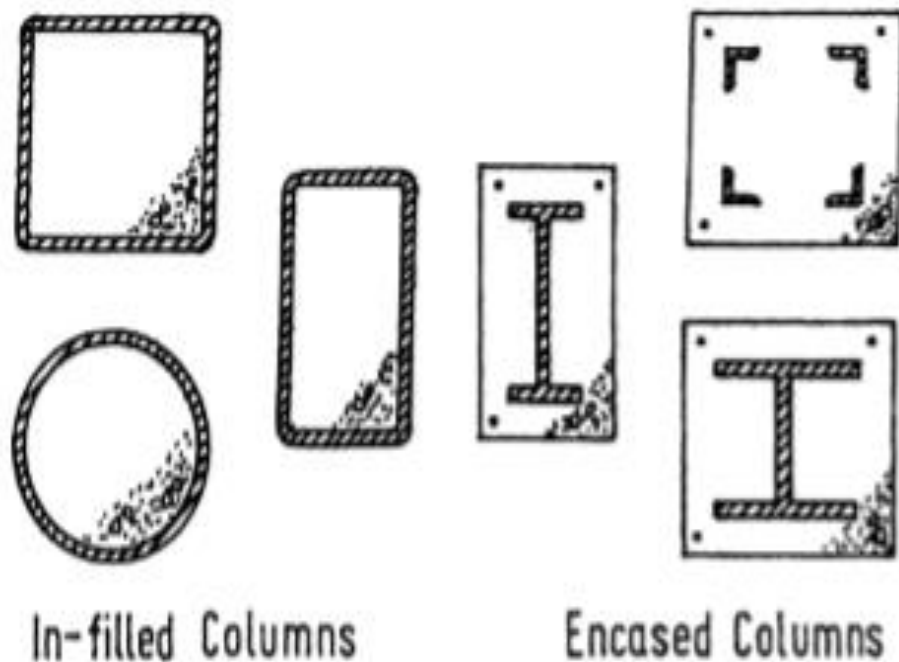


Figure 1 Types of Composite columns

2.2.1 Types of CFST column

A concrete filled steel tubular (CFST) structure consists of steel tube of square, rectangular or circular cross-section filled with plain or reinforced concrete [1]. Various forms of latter type of CFST composite columns are represented below; Composite column systems

- Reinforced composite column systems

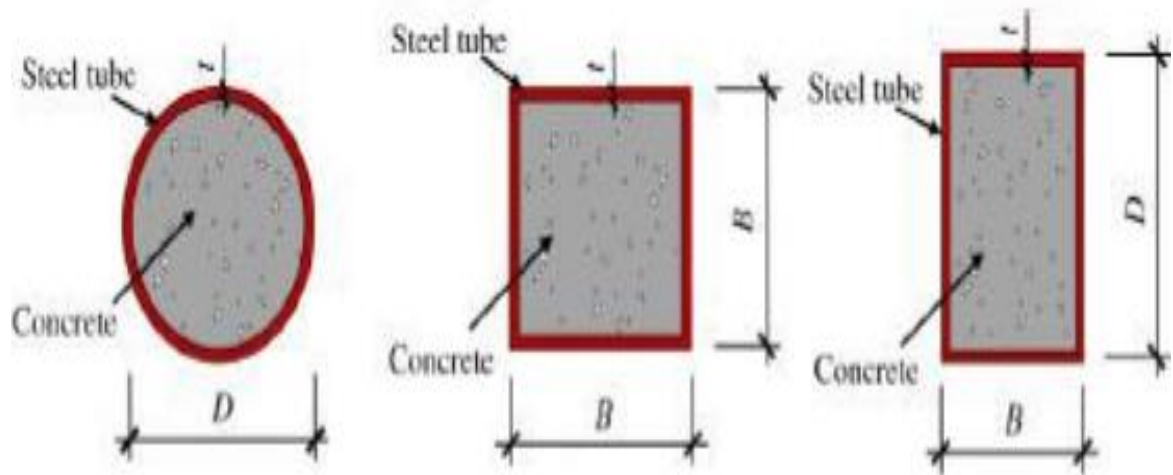


Figure 2 Normal composite column systems

- Concrete-filled double skin tubes (CFDST)

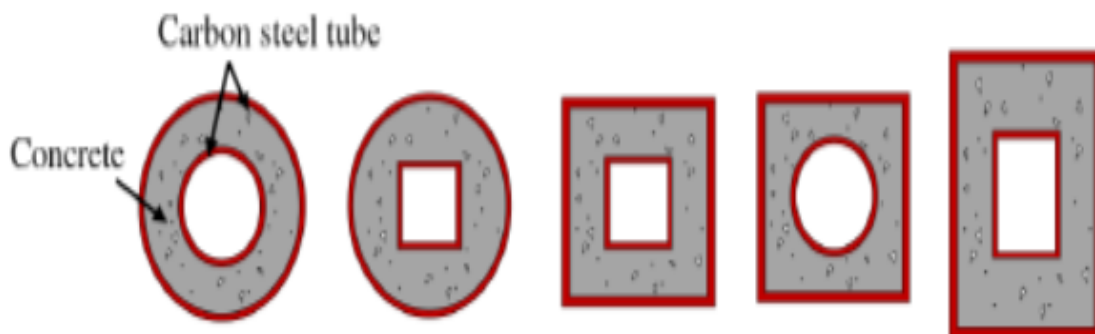


Figure 3 Concrete-filled double skin tubes (CFDST)

- Reinforced Concrete-filled double skin tubes (CFDST)

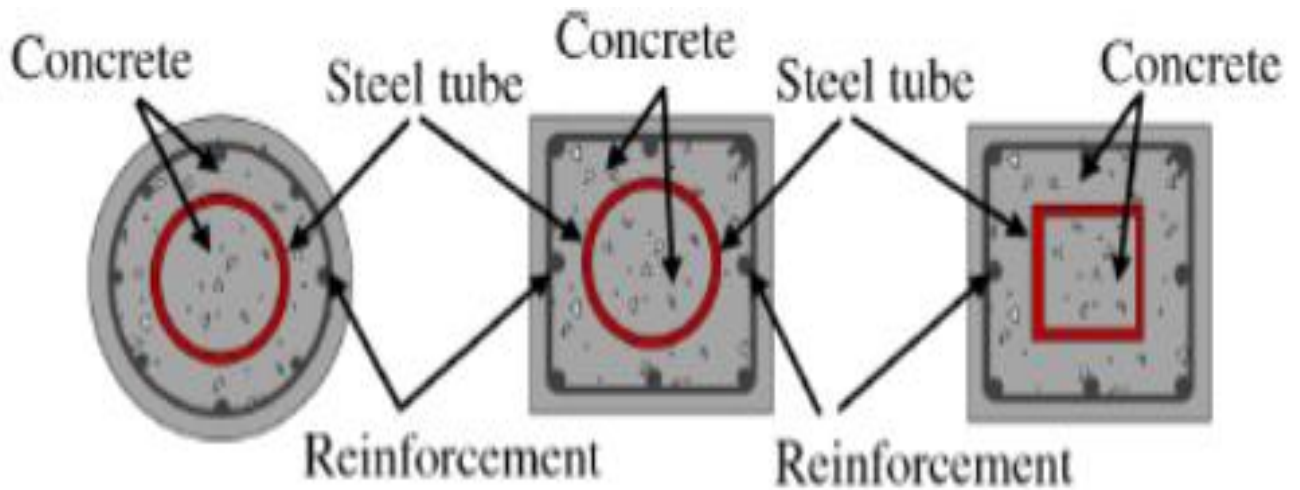


Figure 4 Reinforced Concrete-filled double skin tubes (CFDST)

- Reinforced composite column system

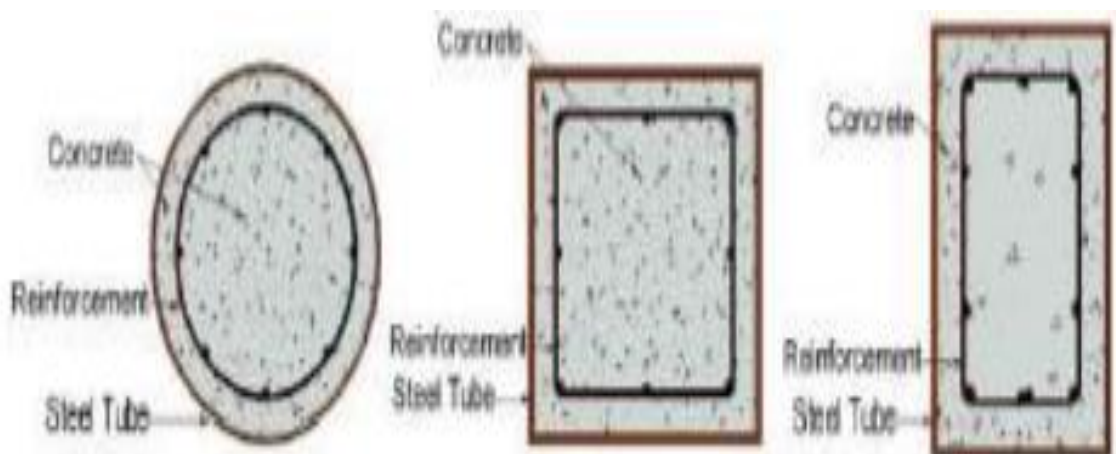


Figure 5 Reinforced composite column system

- Concrete-encased CFST columns

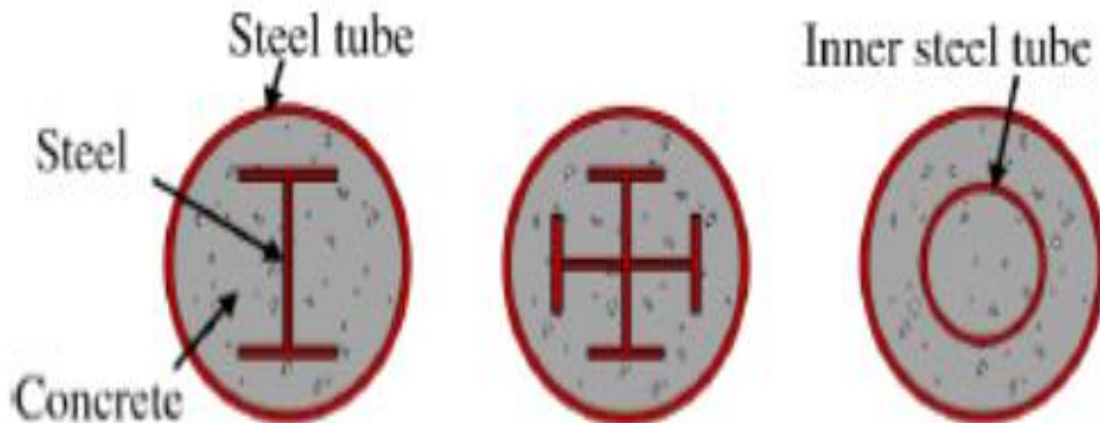


Figure 6 Concrete-encased CFST columns

- Stiffened CFST columns

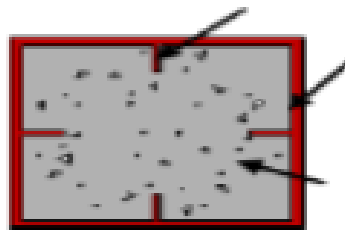


Figure 7 Stiffened CFST columns

Concrete filled steel tubular (CFST) members comprise of a steel hollow section of circular or rectangular shape filled with plain or reinforced concrete. They exploit the advantages of both steel and concrete. They are extensively used in high-rise and multistory buildings as columns and beam-columns, and as beams in low-rise industrial buildings where a strong and efficient structural system is required.

2.2.2 Advantages of CFST column

According to current construction technology and innovation in the world, there are several distinct advantages related to such structural systems in both terms of structural performance and construction system. The distribution of materials in the cross section also makes the system very efficient in term of its structural performance. The steel lies at the outer perimeter where it performs most effectively in bending. It also provides the greatest stiffness as the material lies furthest from the centroid. This, combined with the

steel's much greater modulus of elasticity, provides the greatest contribution to the moment of inertia. The essential buckling problem related to thin-walled steel tubes is either prevented or delayed due to the presence of the concrete core. Furthermore, the performance of the concrete in-fill is improved due to confinement effect exerted by the steel. The concrete core gives the greater contribution to resisting axial compression [2]. The main advantages of CFT structural system in comparison with ordinary steel or reinforced concrete system are listed below.

Improvement of structural performance due to material properties:

The steel tube acts as an external reinforcement and the steel ratio in the CFST cross section is much higher than those in the reinforced concrete sections. Steel of the CFST section is well plasticized under bending since it is located on the outside of the section which could reduce local buckling at large. The improvement of properties of the concrete in-fill is enhanced due to confinement pressure exerted by the steel tube. The characteristic buckling problem of thin-walled steel tubes is controlled due to the presence of the concrete in-fill and the strength deterioration after the local buckling is decreased due to the restraining effect of concrete. Shrinkage and creep of concrete are much smaller than ordinary reinforced concrete.

Due to Geometrical properties:

It provides the maximum stiffness as the material lies farthest from the centroid and provides the greatest contribution to the moment of inertia. The steel as the outer part of core concrete performs most effectively both in tension and bending, whereas the concrete core gives the greater contribution to resisting axial compression.

Improvement of Constructional Performance During fabrication:

Steel tube of CFST columns are simple to fabricate, and construct compared to conventional reinforced concrete, where skilled workers are needed to cut and bend complex forms of reinforcement. Steel tube of CFST columns are generally less than 40 mm thick and easily available. Hence, they are convenient to fabricated and assemble and the constructional procedure is fast due to easy handling and erection.

During Construction:

Formwork is not required as the steel tube acts as permanent formwork thus saving costly and time-consuming formwork. Casting of concrete is done by pumping method, which saves both the manpower and constructional cost and time. The infill concrete is less likely to be affected by adverse temperature and winds. The infill concrete is generally cured quickly. Erection schedule is not dependent on concrete curing time.

During finishing:

Reduced construction depth, in turn, reduces the story heights, foundation costs, paneling of exteriors, and heating, ventilating and air-conditioning spaces. The concrete filling is protected against mechanical damage. Slender columns reduce the application time and cost of applied finishes.

Improvement of Post Constructional Performance:

Concrete improves the fire resistance performance, and the amount of fireproof material can be reduced, or its use can be omitted. They exhibit better corrosion resistance capability than steel columns.

Larger spans of columns and beams:

The larger spans of columns can be opted resulting in more inside space. The size of CFST column is smaller than that of RC column, hence, usable floor area and visibility is increased and aesthetically pleasing.

Cost reduction

The dimension of CFST column is nearly with the outline dimension of a steel column. Hence, the space occupied by CFST column is not more than that of a steel column making it equivalent in terms of space. The lesser concrete is used in CFST columns and lesser steel is required than that in RC columns. This reduces the carbon footprint on the environment. CFST columns use approximately half the steel in comparison with a steel column. This decreases the cost to a larger extent making it very efficient and judicious to use. The cost of transportation and assembly of columns is reduced because they are built by erecting the hollow steel tube first, then pouring concrete into it. These structures need low maintenance. Because of the merits listed above, a better cost performance is obtained by replacing a steel or RCC structure by CFT structure. Major drawback of the traditional CFT system is the compactness of concrete around the beam-to-column connection, especially in the case of inner and through type diaphragms. But self-compacting concrete is common construction practice these days to cast a high-quality concrete with low water content and good workability using a super plasticizer.

2.3 Review of design codes

Different design regulations were produced for various cross-sections of CFST structures. Different approaches and design philosophies have been adopted in different design codes. ACI-318 adopts the traditional reinforced concrete approach which do not consider concrete confinement. AS 3600-1994 also uses the concept of reinforced concrete design. On the other hand, AISC-LRFD is based on the concept of structural steel [3]. The Euro

code 4, being a dedicated code for composite construction, combines the design approach of both structural steelwork and reinforced concrete columns. Different limitations on the compressive strength of concrete, steel yield strength, diameter-to thickness ratio, steel ratio and confining coefficient are prescribed in different codes [4].

2.4 Finite element modeling

In order to accurately simulate the actual behavior of concrete-filled columns it is important to model the three mains of the section correctly. These are:

- The concrete.
- The steel tubes
- The interaction between the concrete and steel tube.

Once these three parts are modelled correctly, choosing a mesh size and element type will help to achieve accurate and computationally efficient result. The assumptions made in the development CFST modeling for proper simulation can be used as a starting point, together with the literature study into previous works conducted. The finite element modelling performed by other authors on normal concrete-filled steel tube columns could be useful to gain insight into the tube-concrete interaction.

2.4.1 Material modeling of concrete

The two main failure mechanism of concrete are cracking under tension and crushing under compression. The strength of concrete in a simple stress state, uniaxial compression or tension, differs from its strength under biaxial loading, which in turn differs from the strength under triaxial loading.

Finite element software uses the concrete damaged plasticity (CDP) model, which is a modification of the Drucker-Prager strength hypothesis. The modifications includes:

- The parameter K_c which changes the shape of the failure surface in the deviatoric plane. Parameter K_c can range from 0.5 to 1.0. If $K_c = 1.0$ then the failure surface is circular, as in the Drucker-Prager model.
- In a similar manner the shape of the surface's meridians in the stress space can be changed by adjusting the plastic potential eccentricity. Which is a small positive number. When the eccentricity is zero the surface's meridians are linear, as with the Drucker-Prager model.

- A parameter that can be specified if the point in which the concrete undergoes failure under biaxial compression (f_{b0}/f_c') is the ratio of strength in the biaxial state to strength in the uniaxial state.
- The last parameter characterizing the performance of the concrete under multi-axial stress in the dilation angle. This is the angle of inclination of the failure surface towards the hydrostatic axis measured in the meridional plane.

2.4.2 Material modeling of steel

The steel tube in CFST columns is bi-axially stressed due to the concrete expanding under axial loading and the axial load itself. The expanding concrete causes a hoop stress in steel tube which reduces the yield strength in the longitudinal direction of the steel tube. A simplified model that consists only of two linear stages was used for high strength steel; and an idealized multi-linear stress-strain model was adopted for cold formed steel tubes.

2.4.3 Modeling of the steel-concrete interface

Ellobody used interface elements that allows the two surfaces to separate under tension and to penetrate each other under compression. The friction between the two faces is maintained if the surfaces remain in contact. The coefficient of friction is taken as 0.25 in the analysis. No research was found on the bond behavior of CFST columns. It is expected that the behavior of CFST stub columns is not sensitive to the bond between the concrete and steel tube, since the two components are loaded together. This is confirmed by the FE modelling of Huang also uses a surface-based interaction with a contact pressure model in the normal direction, and a Coulomb friction model in the tangential direction to model the interface between the concrete and steel tube for CFST columns. A kind of “gap element” with high stiffness in the normal direction was adopted to simulate the contact and separation between the two surfaces.

2.5 Previous research studies on CFST column

Many researchers on concrete filled steel structures have given their recommendation and further verification on the buckling behavior and effective length determination. Among this,

Artiomus Kuranovas, Douglas Goode, Audronis Kazimieras Kvedaras, Shantong Zhong; the authors have done experimental analysis of 1303 specimens of CFST. Test results are compared with EC4 provided method for determining the load bearing capacity of these composite elements. Several types of CFSTs were tested: both circular and rectangular

cross-sections with solid and hollow concrete core with axial load applied without and with moment, with sustained load and preloading. For circular cross-section columns there was a good agreement between the test failure load and the EC4 calculation for both short and long columns with and without moment. For rectangular cross-section columns the agreement is good except when the concrete cylinder strength was greater than 75 MPa, when many tests failed below the strength predicted by EC4 [5].

Lin-Hai Hana, Zhong Tab, Guo-Huang Yaob; had used ABAQUS Programming for the analysis of CFST subjected to shear and constant axial compression which were previously tested by others. A comparison of results calculated using this model shows good agreement with the test results in general. The theoretical model was used to investigate the influence of important parameters that determine the ultimate shearing strength of the composite members. The parametric studies provide information for the development of formulae to calculate the ultimate strength of CFST members subjected to shear and constant axial compression. Preloading the steel tube before filling with concrete seems to have no effect on the strength [6].

Dr. B.R Niranjan, Eramma; had made an attempt to use CFST composite structural member as a column with a modification of flutes on the steel tube which enhances the aesthetics and development area of sheet by which the moment of inertia gets increased by about 17 to 40 % for rectangular flutes and 9 to 23 % for triangular flutes. Confining concrete by providing triangular and rectangular shape fluted steel tube has been investigated by a well-planned experimental work on twenty-six concrete filled steel fluted columns (CFSFC). The parameters chosen for the study are (i) Geometry of the specimen - Triangular fluted columns (TFC) and rectangular fluted columns (RFC) (ii) Different L/D ratios (size of the columns) (iii) Longitudinal reinforcement. Three series of specimens having different L/D ratios, 2500mm long have been tested with M20 grade of self-compacting concrete (SCC). It is observed that the load resistance is better in rectangular fluted columns as compared to the triangular fluted columns by 1.31 %, 1.05 % and 9.92% respectively for L/D ratio of 15, 20 and 25. The moment of inertia gets increased by about 17% to 40% for RFC and 9% to 23% for TFC [7].

Shams and Saadeghvaziri; presented the state of the art for concrete-filled steel tubular (CFT) columns including experimental and analytical work. They discussed the general response of CFT columns and the use of steel jacketing. They also presented an overview

of analytical work for CFTs, including a comparison between the different design codes and conclude that the failure load is higher than that recommended on codes [8].

Keigo TSUDA¹, Chiaki MATSUI AndEiji MINO; conducted tests on the concrete filled steel square and circular tubular columns. The test is composed of two Series. In Series I, columns are subjected to concentric and eccentric axial force at both ends. In Series II, columns are cantilever columns, and subjected to alternating horizontal load under constant vertical load. As a main experimental parameter, buckling length - section depth ratio of a column is selected. Strength and behavior are examined, and design methods for slender composite columns are investigated [9].

Spacone and El-Tawil; presented a state of the art of nonlinear analysis of steel-concrete composite structures. The work was focused on frame elements, section models and fiber models, with lumped and distributed inelasticity, as well as models with perfect and partial connections [10].

J. Zeghichea, K. Chaouib; had conducted tests on 27 concrete-filled steel tubular columns and result are reported. The test parameters were the column slenderness, the load eccentricity covering axially and eccentrically loaded columns with single or double curvature bending and the compressive strength of the concrete core. The test results demonstrate the influence of these parameters on the strength and behavior of concrete-filled steel tubular columns. A comparison of experimental failure loads with the predicted failure loads in accordance with the method described in Euro code 4 Part 1.1 showed good agreement for axially and eccentrically loaded columns with single curvature bending whereas for columns with double curvature bending the Euro code loads were higher and on the unsafe side. More tests are needed for the case of double curvature bending [11].

C. Douglas Goode Dennis Lam; this paper compares test results of CFST column failure load with the prediction of Euro code 4. The comparison with Euro code 4 was discussed and shows that Euro code 4 can be used with confidence and generally gives good agreement with test results, the average Test/EC4 ratio for all tests being 1.11. The Euro code 4 limitations on concrete strength could be safely extended to concrete with a cylinder strength of 75 N/mm² for circular sections and 60 N/mm² for rectangular sections [12].

P.K. Gupta, S.M. Sarada, M.S. Kumar; have done an experimental and computational study on the behavior of circular concentrically loaded concrete filled steel tube columns till failure. Eighty-one specimens were tested to investigate the effect of diameter and D/t ratio of a steel tube on the load carrying capacity of the concrete filled tubular columns. The effect of the grade of concrete and volume of flyash in concrete was also investigated. The effect of these parameters on the confinement of the concrete core was also studied. Diameter to wall thickness ratio between $25 < D/t < 39$, and the length to tube diameter ratio of $3 < L/D < 8$ was investigated. Strength results of Concrete Filled Tubular columns were compared with the corresponding findings of the available literature. Also, a nonlinear finite element model was developed to study the load carrying mechanism of CFTs using the Finite Element code ANSYS. This model was validated by comparison of the experimental and computational results of load–deformation curves and their corresponding modes of collapse. From the experimental and computational study, it was found that for both modes of collapse of concrete filled tubular columns at a given deflection the load carrying capacity decreases with the increase in % volume of flyash up to 20% but it again increases at 25% flyash volume in concrete [13].

Hajjar J.F; had conducted the behavior and design of axially loaded concrete-filled steel tube circular stub columns were presented. The study was carried over a wide range of concrete cube strengths ranging from 30 to 110 MPa. The external diameter of the steel tube-to-thickness (D/t) ratio ranged from 15 to 80. An accurate finite element model was developed to carry out the study. Accurate nonlinear material models for concrete and steel tubes were used. The column strengths and load– axial shortening curves were evaluated. The results obtained from the FE analysis were verified against experimental results. An extensive parametric study was carried out to investigate the effects of different concrete strengths and cross cross-section geometries on the strength and behavior of concrete-filled compact steel tube circular stub columns. The column strengths predicted from the FE analysis were compared with the design strengths calculated using the American, Australian and European codes. Based on the results of the parametric study, it is found that the design strengths given by the American Specifications and Australian Standards are conservative, while those of the European Code are generally not much conservative [14].

Yu-Feng A, Lin-Hai Han and Xiao-Ling Zhao; carried out test on the behavior of very slender, thin-walled concrete filled steel tubular (CFST) columns under axial compression

was studied by the authors. A finite element analysis (FEA) was used to carry out the behavior of compressive columns. Generally, a good agreement was obtained between the predicted and calculated results. The FEA model was then used to perform analysis on very slender circular CFST columns. Parametric studies were conducted and the ultimate strengths from tested results and design codes were compared and discussed. The reliability analysis method was used to calibrate the existing design formulas given in DBJ/T13512010, ANSI/AISC 360-05 and Euro code 4 [15].

Qing Quan Liang and Sam Fragomeni [2009]; Quin and Sam had presented accurate constitutive models for normal and high strength concrete confined by either normal or high strength circular steel tubes. A generic fiber element model that includes the proposed constitutive models of confined concrete was created for simulating the nonlinear inelastic behavior of circular CFST short columns under axial loading. The confinement effect provided by the steel tube with a concrete filled steel tubular (CFST) short column increases the strength of the concrete core. The generic fiber element model developed was verified by comparisons of computational results with existing experimental data. On the fundamental behavior of circular CFST columns. A new design formula accounting for concrete confinement effects was also proposed for circular CFST columns. It is demonstrated that the generic fiber element model and design formula adequately forecast the ultimate strength and behavior of axially loaded CFST columns and can be used in the design of normal and high strength CFST columns [16].

Paul J. Barr, Baochun Chen and ZhijingOu [2011]; an experimental and analytical investigation of concrete-filled steel tubular (CFST) laced columns was carried out. The columns consist of four concrete-filled steel tubes which are laced together. A total of 27 experimental tests was carried out to quantify the column failure mechanism at ultimate loads. The experiments were performed to obtain the load-deflection curves. Experimental results showed that the compression force in the longitudinal members dominated the failure mechanism in the CFST columns. The forces in the lacing members (diagonal and horizontal bracing) were found to be small. The experimental study was used to validate an analytical parametric study. The analytical study showed that increasing slenderness ratios and eccentricities reduced the ultimate load carrying capacity. On the basis of the analytical results, a new methodology for calculating the ultimate load-carrying capacity was proposed. The proposed methodology was compared with five different building

codes like AISC, Eurocode4 and china codes (DL/T 50851999, JCJ 01-89, CECS 28:90) to quantify the accuracy [17].

Vipulkumar Ishvarbhai Patel (2012); carried out experimental and numerical research on full scale high strength thin-walled rectangular steel slender tubes filled with high strength concrete. Experimental ultimate strengths and load deflection responses of CFST slender beam columns were tested by independent researchers and used to verify the accuracy of the numerical model. The verified numerical model was then utilized to investigate the effects of local buckling, column slenderness ratio, and depth-to-thickness ratio, loading eccentricity ratio, concrete compressive strengths and steel yield strengths on the behavior of high strength thin walled CFST slender beam-columns behavior of CFST according to its different cross section like rectangular and circular which are more popular in design field. From the review of literature its shows CFST columns provide excellent seismic event resistant structural properties such as high strength, high ductility and large energy absorption capacity [18].

Accordingly, in this paper, the Critical Buckling load and effective length factor of the CFST column due to different end conditions was formulated and compare the results with Euro codes recommended values.

3. METHODOLOGY

To conduct this paper, the following steps and methodologies were adopted.

1. The materials for the modeling and their cross sectional, geometrical and elastic properties of all the CFST columns were selected for base model.
2. Different literatures and guidance references were assessed and collected different data.
3. The critical buckling load of each column with different conditions had been determined according to Euro codes and Euler's elastic critical buckling load formula.
4. Proper modeling of CFST columns with FE is formulated.
5. Based on the small displacement linear theory, the linear buckling analysis, also known as eigenvalue buckling analysis was formulated,
6. The model of the linear buckling analysis was copied for the non-linear buckling analysis, which is also called post-buckling analysis,
7. During the post-buckling buckling analysis, the '*IMPERFECTION' statement was used to introduce the first mode of eigenvalue analysis to the non-linear buckling analysis as the initial disfigurement,
8. Then the columns with different cases (support conditions) was modeled by using finite element model (FEM) ABAQUS software and the load-displacement curve was be obtained,
9. The ultimate critical buckling load then was determined.
10. After getting the critical buckling load of the columns, the effective length was determined and then the effective length factor was determined.
11. After getting the effective length values accordingly, expensive parametric study was conducted to investigate the effect of such parameters on buckling load and effective length of CFST column,
12. Finally, after deducing the results, the effective length factor and the corresponding critical buckling load were formulated.

4. GEOMETRY AND MATERIAL PROPERTY SELECTION OF CFST COLUMN

4.1 Geometric property

In order to achieve the objectives of this study, the geometric property of the CFST column shall be selected accordingly. The geometry of the selected CFST columns are within the limits and recommended geometric properties of stipulated on EC4. The thickness of steel tube on both RHS and CHS sections can be obtained as per the specification guide of CFST column on EC4.

For the case of steel column and CFST column, local buckling is a sensitive structural failed and to avoid this local buckling, there is a provision on EC4 for selection of parameters of steel. Hence, according to the provisions, the following shall be fulfilled to resist local buckling of the steel tube

$$\frac{D}{t} \leq 90 * \frac{235}{f_y} \text{ For circular CFST and}$$

$$\frac{D}{t} \leq 52 * \sqrt{\frac{235}{f_y}} \text{ For rectangular CFST column}$$

Since, the first aim was to determine critical buckling load and the effective length factor of the isolated CFST column, 18 slender CFST columns (6 CCFST, 6 RCFST and 6 SCFST) had been selected as a base model and tabulated as follows.

Table 1 Geometric property of selected base model CFST columns

Steel tube	End conditions	Dimension in mm					
		B	b	D	d	t	L
Square section	Case 1	400	380	400	380	10	6000
	Case 2	400	380	400	380	10	6000
	Case 3	400	380	400	380	10	6000
	Case 4	400	380	400	380	10	6000
	Case 5	400	380	400	380	10	6000
	Case 6	400	380	400	380	10	6000
	Case 1	400	380	300	280	10	6000
	Case 2	400	380	300	280	10	6000
	Case 3	400	380	300	280	10	6000

Rectangular section	Case 4	400	380	300	280	10	6000
	Case 5	400	380	300	280	10	6000
	Case 6	400	380	300	280	10	6000
Circular	Cases	Dimension in mm					
		Dia Outer		Dia inner		t	L
	Case 1	400		386		7	6000
	Case 2	400		386		7	6000
	Case 3	400		386		7	6000
	Case 4	400		386		7	6000
	Case 5	400		386		7	6000
	Case 6	400		386		7	6000

Where,

Table 2 Support condition and effective length factor of CFST column

Cases	End supports	Theoretical K value
Case 1	Both ends are pinned	1.0
Case 2	Both ends are fixed	0.5
Case 3	One end is pinned, and one end is fixed	0.7
Case 4	One end is free, and one end is fixed	2.0
Case 5	Both ends are fixed with some lateral translation	1.0
Case 6	The base is pinned & the top is fixed with some lateral translation	2.0

4.2 Material property

4.2.1 Concrete

Concrete has a behavior of high resisting compressive action and low in tension resistance. The tensile resistance of concrete is 10% of the compressive resistance. The following concrete property was used for this project shown below.

Table 3 Strength classes of normal strength concrete

Strength class	C12/15	C16/20	C20/25	C25/30	C30/37	C35/45	C40/50	C45/55	C50/60
Cylinder strength (f_{ck} , N/mm ²)	12	16	20	25	30	35	40	45	50
Cube strength ($f_{ck,cube}$, N/mm ²)	15	20	25	30	37	45	50	55	60
Modulus of elasticity (E_{cm} , GPa)	27	29	30	31	33	34	35	36	37

From the above table, C30/37 with E_{cm} value of 33Gpa was taken as a base model.

4.2.2 Steel

The strength classes as shown in Table 4 for mild steel and high tensile steel can be used for the design of CFST columns with hot-rolled, cold-formed or welded steel sections. The modulus of elasticity of steel is taken as 210GPa.

Table 4 Strength classes of mild steel

Grade	Nominal values of yield strength f_y (N/mm ²) with thickness (mm) less than or equal to					
	16	40	63	80	100	150
S235	235	225	215	215	215	195
S275	275	265	255	245	235	225
S355	355	345	335	325	315	295
S420	420	400	390	370	360	340
S460	460	440	430	410	400	380
S500	500	500	480	480	480	440
S550	550	550	530	530	530	490
S620	620	620	580	580	580	560
S690	690	690	650	650	650	630

From table 4 given above, the strength class of the mild steel was described and the strength class of the base model could be obtained. However, before selection of the strength class of steel tube, the material compatibility shall be investigated.

4.2.3 Material compatibility between steel grade and concrete class

For concrete filled steel tubular columns subjected to compression, it is necessary to ensure that yielding of the steel section occurs before the concrete core reaches its maximum stress. Otherwise, the full plastic resistance of the composite section cannot be achieved due to brittle failure of high strength concrete after reaching the maximum stress. Hence, the selections of steel grade and concrete class must ensure that the yield strain of steel is smaller than the compressive strain of concrete at the peak stress. The yield strain

of steel and the strain of concrete at peak stress may be calculated in accordance with EN 1992-1-1 (2004) and EN 1993-1-1 (2005) as:

Steel yield strain (‰):

$$\varepsilon_y = \frac{f_y}{E_a} \dots \text{Eq 1, Steel yield strain}$$

Concrete strain at peak stress (‰):

$$\varepsilon_{c1} = 0.7f_{cm}^{0.31} < 2.8 \dots \text{Eq 2, Concrete strain at peak stress}$$

Where, $f_{cm} = f_{ck} + 8$ is the mean compressive strength of concrete at 28 days, in N/mm^2 . $E_a = 210GPa$ is the elastic modulus of steel tube.

Hence, the maximum steel strength can be determined according to the concrete characteristic strength with strength class up to C90/105 using the following expression:

$$f_y \leq 0.7E_a (f_{ck} + 8)^{0.31}$$

Where,

f_y is the characteristic yield strength of steel

f_{ck} is the characteristic cylinder compressive strength of concrete

E_a is the modulus of Elasticity of steel

Table 5 Yield strain of steel

Steel grade	S235	S275	S355	S420	S460	S500	S550	S620	S690
f_y	235	275	355	420	460	500	550	620	690
ε_y (‰)	1.12	1.31	1.69	2.00	2.19	2.38	2.62	2.95	3.29

Table 6 Strain of concrete at peak stress

Concert grade	C12/15	C16/20	C20/25	C25/30	C30/37	C35/45	C40/50	C45/55	C50/60
f_{ck}	12	16	20	25	30	35	40	45	50
f_{cm}	20	24	28	33	38	43	48	53	58
ε_{c1} (‰)	1.77	1.87	1.97	2.07	2.16	2.25	2.32	2.40	2.53

The compatibility of the material (steel and concrete) had been made as follows,

Table 7 Compatibility of the material (steel and concrete)

	S235	S275	S355	S420	S460	S500	S550	S620	S690
C12/15	✓	✓	✓	x	x	x	x	x	x
C16/20	✓	✓	✓	x	x	x	x	x	x
C20/25	✓	✓	✓	x	x	x	x	x	x
C25/30	✓	✓	✓	✓	x	x	x	x	x
C30/37	✓	✓	✓	✓	x	x	x	x	x
C35/45	✓	✓	✓	✓	✓	x	x	x	x
C40/50	✓	✓	✓	✓	✓	x	x	x	x
C45/55	✓	✓	✓	✓	✓	✓	x	x	x
C50/60	✓	✓	✓	✓	✓	✓	x	x	x

Where,

✓ : Compatible

x: not compatible

Therefore, according to the materials compatibility, the milled steel S235, S275, S355 and S420 are compatible with the concrete grade C30/37. However, steel grade S460 is not compatible with C30/37 so that concrete grade of C35/45 was used during study of effect of steel grade. Hence, the steel S275 was selected as an initial base model to investigate the critical buckling load and effective length of the CFST columns.

4.3 Critical buckling load and effective length of CFST column

4.3.1 Critical buckling load of CFST column

The critical buckling load is the maximum load which a column can bear while staying straight. When a structure is subjected to compressive stress, buckling may occur. Buckling is characterized by a sudden sideways deflection of a structural member. This may occur even though the stresses that develop in the structure are well below those needed to cause failure of the material of which the structure is composed. As an applied load is increased on a column, it will ultimately become large enough to cause the member to become unstable and it is said to have buckled and the load to cause the buckling is called critical buckling load. Further loading will cause significant and somewhat unpredictable deformations, possibly leading to complete loss of the member's load-carrying capacity. If the deformations that occur after buckling do not cause the complete

collapse of that member, the member will continue to support the load that caused it to buckle. If the buckled member is part of a larger assemblage of components such as a building, any load applied to the buckled part of the structure beyond that which caused the member to buckle will be redistributed within the structure. The buckling shape of the column shown below is one and major of the possible buckling mode among other possible buckling mode shapes [19].

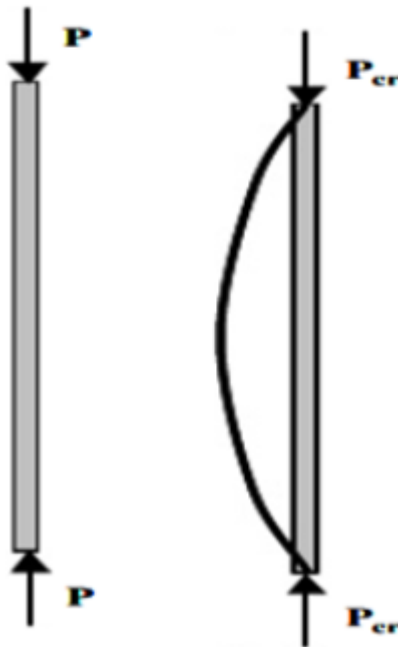


Figure 8 Column before buckling and after buckling

The critical load is the maximum load which a column can bear while staying straight. It is given by the formula

$$P_{cr} = \frac{\pi^2 E I_{eff}}{(KL)^2} \quad \dots \text{Eq 3, Critical buckling load}$$

Where,

P_{cr} = Elastic critical buckling load

L = unsupported length of column,

K = column effective length factor

$E I_{eff}$ = effective bending stiffness taken by the formula,

$$E I_{eff} = I_s E_s + 0.6 I_c E_{cm}$$

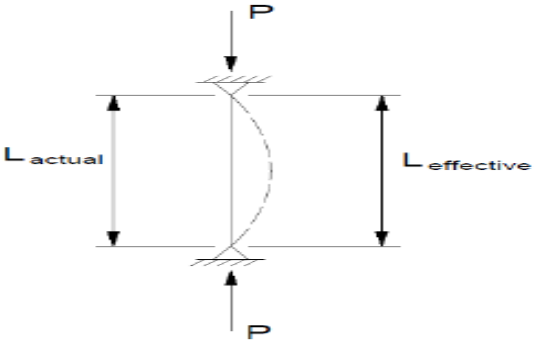
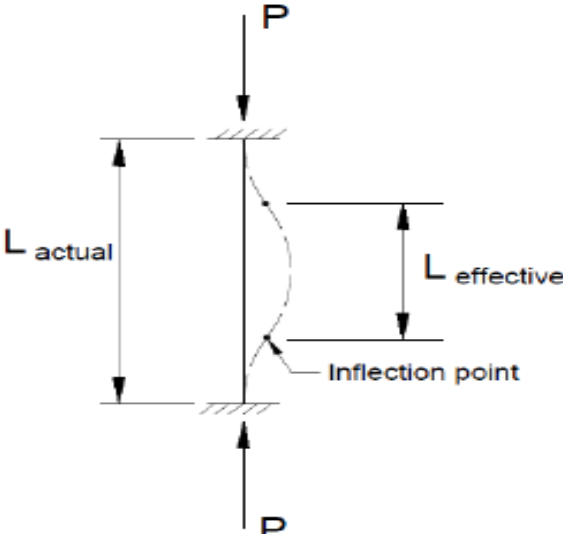
I_s, I_c : moment of inertia of steel and concrete on the buckling axis respectively

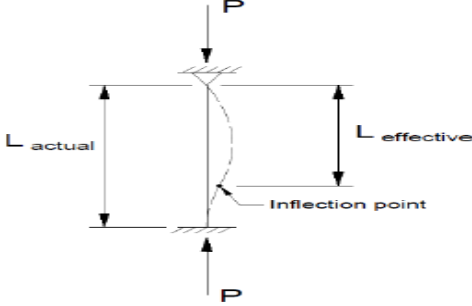
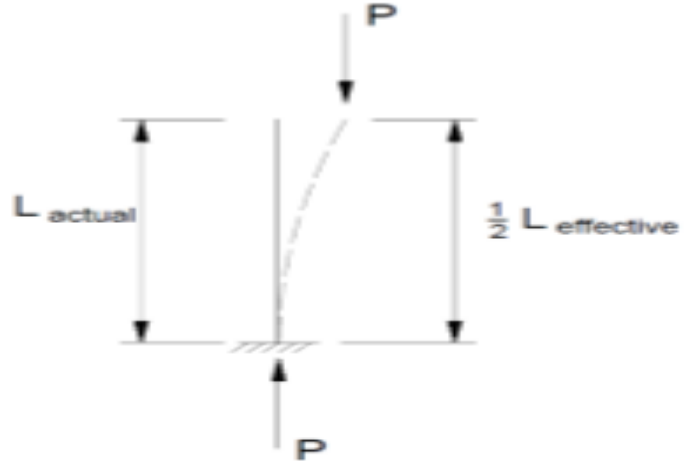
E_s, E_{cm} : elastic modulus of steel and concrete respectively.

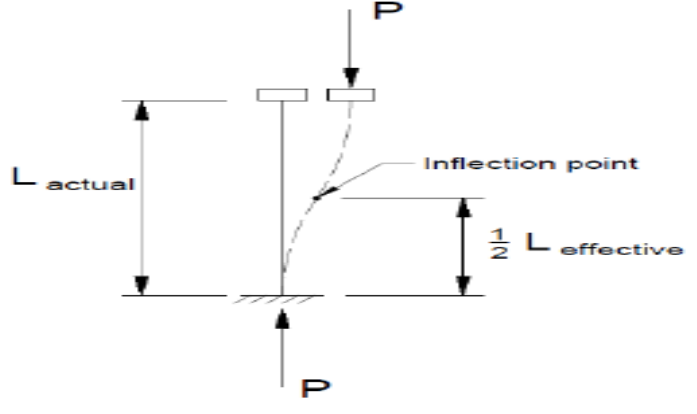
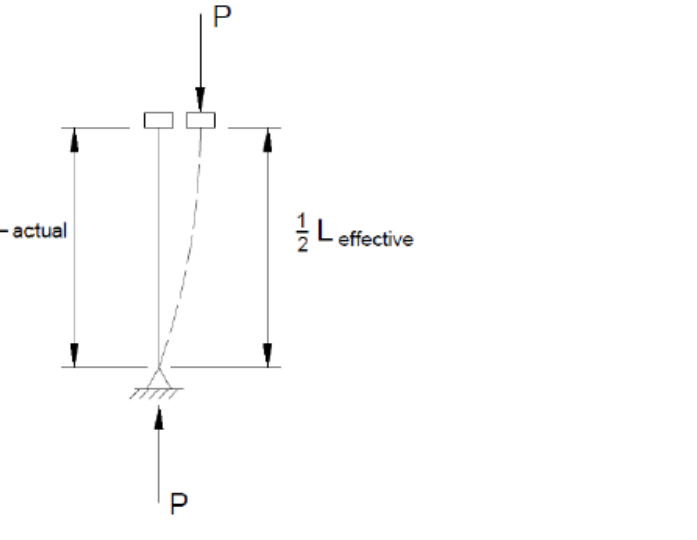
4.3.2 **Effective length of CFST column**

It is the length of an equivalent pin-ended column having the same load-carrying capacity as the member under consideration. Effective length of a column is the distance between inflection points in the column when it bends and/ or buckles. The effective length of a member under consideration depends upon its end support conditions. The following table is the recommended effective length factor, values for steel structures in accordance to Eurocodes 1991 which has been also used for composite steel and concrete structure.

Table 8 Qualitative and quantitative discription of effective length of CFST column

Cases	End conditions	Numerical Description	Qualitative Description
Case 1	Both ends are pinned	<p>The structure is adequately braced against lateral forces (e.g. wind and earthquake forces).</p> <p>Theoretical K-value: $K = 1.0$</p> <p>Effective length: $L_e = L$</p> <p>$P_{critical} = \pi^2 EI_{eff, min} / L^2$</p>	
Case 2	Both ends are fixed.	<p>The structure is adequately braced against lateral forces (e.g. wind and earthquake forces).</p> <p>Theoretical K-value: $K = 0.5$</p> <p>Effective length: $L_e = 0.5 L$</p> <p>$P_{critical} = \pi^2 EI_{min} / (0.5L)^2 = 4\pi^2 EI_{eff, min} / L^2$</p>	

<p>Case 3</p>	<p>One end is pinned, and one end is fixed.</p>	<p>The structure is adequately braced against lateral forces (e.g. wind and earthquake forces).</p> <p>Theoretical K-value: $K = 0.7$</p> <p>Effective length: $L_e = 0.707 L$</p> <p>$P_{critical} = \pi^2 E I_{eff, min} / (0.707L)^2 = 2\pi^2 E I_{eff, min} / L^2$</p>	
<p>Case 4</p>	<p>One end is free, and one end is fixed</p>	<p>Theoretical K-value: $K = 2.0$</p> <p>Effective length: $L_e = 2.0 L$</p> <p>$P_{critical} = 4\pi^2 E I_{eff, min} / L^2$</p>	

<p>Case 5</p>	<p>Both ends are fixed with some lateral translation</p>	<p>Theoretical K-value: $K = 1.0$ Effective length: $L_e = 1.0 L$ $P_{critical} = \pi^2 E I_{eff, min} / L^2$</p>	
<p>Case 6</p>	<p>The base is pinned, and the top is fixed with some lateral translation.</p>	<p>Theoretical K-value: $K = 2.0$ Effective length: $L_e = 2.0 L$ $P_{critical} = \pi^2 E I_{eff, min} / (2L)^2 = \pi^2 E I_{min} / 4L^2$</p>	

4.3.3 Critical Buckling load Calculation

The critical load is the maximum load which a column can bear while staying straight. It is given by the formula represented herein above by equation 3.

Since the column cross section shown table 1 was selected for base modeling analysis, first the critical load shall be determined directly by Euler formula by taking effective length factor directly from the recommended values of the available code. Hence, the critical load was calculated for each cross section and support conditions. For simplicity, the support conditions are labeled as cases (case1 to case 6) described on table 2 above. According to the Euler's critical load formula and theoretical values of effective length factor, the critical buckling load has been calculated and tabulated as follows;

Table 9 Critical Buckling load of selected CFST columns according to EC4

Steel tube	End conditions	Dimension in mm						P _{cr} , kN
		B	b	D	d	t	L	
Square section	Case 1	400	380	400	380	10	6000	31040
	Case 2	400	380	400	380	10	6000	124160
	Case 3	400	380	400	380	10	6000	63347
	Case 4	400	380	400	380	10	6000	7760
	Case 5	400	380	400	380	10	6000	31040
	Case 6	400	380	400	380	10	6000	7760
Rectangular section	Case 1	400	380	300	280	10	6000	15095
	Case 2	400	380	300	280	10	6000	60378
	Case 3	400	380	300	280	10	6000	30806
	Case 4	400	380	300	280	10	6000	3773
	Case 5	400	380	300	280	10	6000	15095
	Case 6	400	380	300	280	10	6000	3773
Circular	Cases	Dimension in mm				t	L	P _{cr} , kN
		Dia Outer		Dia inner				
	Case 1	400		386		7	6000	16602
	Case 2	400		386		7	6000	66407
	Case 3	400		386		7	6000	33881
Case 4	400		386		7	6000	4150	

Buckling Load and Effective Length of CFST Columns

	Case 5	400	386	7	6000	16602
	Case 6	400	386	7	6000	4150

As it is clearly tabulated above on table 9, the critical buckling load of the CFST columns were determined by current Euro codes formula for further comparisons of the FE software output. After determining the critical buckling load by FEM, ABAQUS 6.13, effective length factor would be determined accordingly which is clearly presented on the next chapter.

5. FINITE ELEMENT MODELING AND ANALYSIS

5.1 Introduction

This chapter describes the development of the finite element models of 18 different CFST (6 circular, 6 rectangular and 6 square) columns as a base model. And then 216 models by varying different parameters of CFST column were modelled. The purpose of the finite element models is to envisage the critical buckling load of the base models and then to determine effective length factor of slender concentrically loaded isolated CFST columns. A parametric study was also conducted to assess the effects various parameters on the buckling behavior of the CFST columns.

5.2 Development of the Finite Element Model

In conducting the literature study, it was found that some work was conducted on finite element modelling of composite sections and that ABAQUS, a finite element (FE) program, was commonly used. The modelling techniques developed by Han to model the behavior of CFST stub columns was also used by other authors to model the axial behavior of CFST columns. It was used by Li to model CFST stub columns with a pre-load on the steel tubes and showed good correlation when compared to experimental results published by different authors. For this reason, that the stress-strain relationship of the concrete core developed by Han was used in the development of the FE model in this study.

5.2.1 Geometry

A total of 18 (6 circular, 6 rectangular and 6 square) columns with different end support were modelled as a base model to predict the critical buckling load and to determine the effective length factor. Then the geometric properties were varied namely thickness of steel tube (D/t or H/t ratio), steel grade and concrete grade of the CFST. For a base model the geometric property described on table 1 was used.

5.2.2 Elements selection

5.2.2.1 Shell element

This section provides information on the shell element properties used in ABAQUS. Figure 9 shows a schematic view of a typical shell element with 6 degrees of freedom at each node.

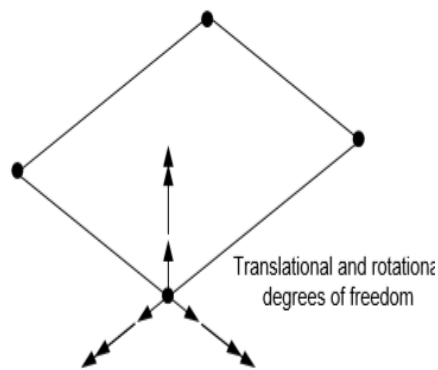


Figure 9: 4-node shell element

Shell elements are used to model structural parts in which the thickness dimension is significantly smaller than the other dimensions. Conventional shell elements in ABAQUS use this condition to discretize a body by defining the geometry at a reference surface. Thus, the element thickness is defined in the section property definition. The conventional shell elements in ABAQUS have displacement and rotational degrees of freedom. In contrast ABAQUS also has continuum shell elements, which discretize the entire three-dimensional body. Thus, the thickness is determined from the node geometry. Continuum shell elements only have translational degrees of freedom. Therefore, continuum shell elements look like continuum solid elements but has a behavior like shell elements.

It was decided to use the S4R shell element, a 4-node general-purpose shell element with reduced first-order integration, hourglass control, finite membrane strains and second order accuracy to model the steel tubes. Reduced integration is used to form the element stiffness matrix; however, the mass and distributed loadings are still integrated exactly. Reduced integration significantly reduces computation time, especially in the analysis of three-dimensional models. The element accounts for finite membrane strains and arbitrarily large rotations; therefore, it is suitable for large-strain analyses.

5.2.2.2 Solid element

This section provides information on the solid element's properties used in ABAQUS. Figure 10 shows a schematic view of a typical solid element with 6 degrees of freedom at each node.

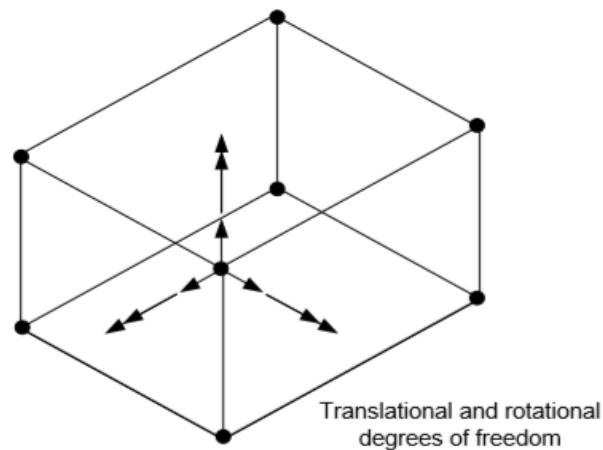


Figure 10: 8-node solid element

The solid elements in ABAQUS can be used for linear analysis and for complex nonlinear analysis involving contact, plasticity and large deformations. ABAQUS includes first order/linear interpolation elements and second order/quadratic interpolation. Reduced integration is also available for solid elements.

Reduced integration for solid elements is the same as for shell elements, i.e. it uses a lower order integration to form the element stiffness matrix, but the mass matrix and distributed loadings still use full integration. Second-order reduced integration elements in ABAQUS generally yield more accurate results than their full integration counterparts. However, for first order elements the accuracy achieved is largely dependent of the nature of the problem. The solid elements used to model the concrete infill was C3D8R, an 8-node solid element with reduced first-order integration.

5.2.3 Material Modeling

5.2.3.1 Concrete material model

Under low confining pressures concrete behaves in a brittle manner. The main failure mechanism is cracking in tension and crushing in compression. The brittle behavior of concrete becomes more ductile when confining pressures are significantly large to prevent crack propagation. Under these circumstances' failure is initiated by consolidation and collapse of the concrete microporous microstructure leading to macroscopic response that resembles a ductile material. In finite element modelling, the strength improvement observed at a state of triaxial loading can be achieved by the proper definition of the

yielding surface and the description of the plastic behavior of the equivalent stress-strain relationships of the core concrete (Han, et al., 2007). The plasticity of core concrete increases due to passive confinement in the following manner (Han, et al., 2007)

- The strain corresponding to maximum stress increases.
- The descending branch of the stress-strain curves trend to the horizontal.

The increase in the plastic behavior depends on the level of confinement which is related to the confinement factor given below as:

$$\xi = \frac{A_{so} \cdot f_{syo}}{A_{c,nominal} \cdot f_{ck}} \dots \text{Eq 4, Concrete confinement formula}$$

The equivalent stress strain model proposed by Han showed good agreement to experimental test conducted on CFST stub columns. The model has also been verified by Li Therefore, the same confinement model was used to verify if it is applicable to concentrically loaded slender columns. The model can be described:

$$\frac{\sigma}{f'c} = \left\{ 2 * \left(\frac{\epsilon}{\epsilon_0} \right) - \left(\frac{\epsilon}{\epsilon_0} \right)^2 \text{ for } (\epsilon/\epsilon_0 \leq 1) \right.$$

$$\left. \frac{\sigma}{f'c} = \left\{ \left(\frac{\epsilon}{\epsilon_0} \right) / \mathcal{B}o \left(\left(\frac{\epsilon}{\epsilon_0} - 1 \right)^2 \text{ for } (\epsilon/\epsilon_0 > 1) \right. \right.$$

$$\text{Where } \epsilon_0 = \epsilon_c + 800\xi^{0.2} \times 10^{-6}$$

$$\epsilon_c = (1300 + 12.5f'c) \times 10^{-6} \text{ and}$$

$$\mathcal{B}o = (2.36 * 10^{-5})^{[0.25+(\xi-0.5)^7]} (f'c)^{0.5} * 0.5 \geq 0.12$$

In the equations the term $f'c$ is the cylinder strength of the concrete with units of MPa. The cylindrical strength of concrete typically falls between 0.7 and 0.9 of the cube strengths. A cylinder strength of 0.8 of the cubes crushing strength is widely accepted and the confinement factor (ξ) obtained as 0.951.

5.2.3.2 Incorporation to ABAQUS

The concrete damaged plasticity model in ABAQUS was used to model the concrete infill. A description of the model is presented below.

5.2.3.3 Concrete damage plasticity in ABAQUS

The concrete damaged plasticity (CDP) model in ABAQUS is a modification of the Drucker-Prager model. The CDP model in ABAQUS was used to model the concrete core. The model is a continuum, plasticity-based, damage model for concrete. It assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material. The evolution of the yield surface is controlled by two hardening variables, the tensile and compressive equivalent plastic strains. These variables are linked to failure mechanisms under tension and compression loading respectively. The following parameters are used to describe the concrete's performance under multiaxial loading:

- **Elastic modulus E_c :** The empirical equation recommended in ACI 318 (2011) was adopted to calculate E_c , as a function of f'_c where f'_c is in MPa.

$$E_c = 4700(f'_c)^{0.5} \dots \text{Eq 5, Concrete elastic modulus}$$

- **K_c :** The failure surface in the deviatoric cross section is governed by K_c . The parameter K_c can be interpreted as the ratio of the distances between the hydrostatic axis and the compression and tension meridians, respectively. This must always be larger than 0.5 and smaller than 1.0. Yu et al. (2010a), formulated the following equation by deducing different literatures and experiment data for CFST column during nonlinear buckling analysis input variable;

$$K_c = \frac{5.5}{5+2(f'_c)^{0.075}} \dots \text{Eq 6, Ratio of distance b/n hydrostatic axis}$$

Hence, the values of K_c were determined and take 0.725 which is in the range of 0.5 to 1 as a base model.

- **Plastic potential eccentricity:** The eccentricity parameter (ϵ) changes the shape of the meridians of the plastic potential surface in the stress space. In the CDP model the plastic potential surface in the meridional plane assumes the form of a hyperbola. The eccentricity parameter is a small positive value which expresses the rate of approach of the plastic potential hyperbola to its asymptote. It is defined as the distance, measured along the hydrostatic axis, between the center of the hyperbola and its vertex. The center of a hyperbola is where the asymptotes intersect. Figure 11 shows the plastic potential surface in the meridional plane.

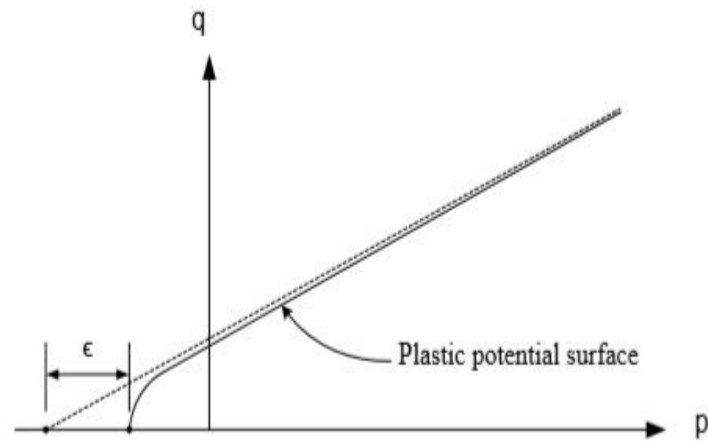


Figure 11 Hyperbolic plastic potential surface in the meridional plane (SIMULIA, 2013)

The eccentricity parameter (ϵ) can be calculated as a ratio of tensile strength to compressive strength (Jankowiak, et al., 2005). The CDP model recommends a value of $\epsilon = 0.1$. When $\epsilon = 0.0$, the plastic potential surface in the meridional plane becomes a straight line.

- **f_{b0}/f'_c :** Is a ratio of the strength in biaxial state to the strength in the uniaxial state. This parameter describes the point at which the material undergoes failure under biaxial compression. This parameter describes the point at which the material undergoes failure under biaxial compression. The CDP model uses $\frac{f_{b0}}{f'_c}=1.16$. And, based on test data collected from 14 references, Papanikolaou and Kappos (2007) proposed the following equation to predict the ratio of f_{b0}/f'_c and adopted the equation for this paper:

$$\frac{F_{b0}}{f'_c} = 1.5(f'_c)^{-0.075} \dots \text{Eq 7, Ratio of strength in biaxial state}$$

Hence, the values of f_{b0}/f'_c was determined and take 1.16 using the compressive strength 30Mpa which is equal to the recommended value.

- **Dilation angle:** The dilation angle (ψ) is the angle of inclination of the failure surface to the hydrostatic axis measured in the meridional plane. The angle is interpreted as the concrete internal friction angle. In an analysis a value of $\psi = 30^\circ$ or $\psi = 40^\circ$ is usually assumed (Kmieciak & Kaminski, 2011). Furthermore, A linear regression analysis was devised by Lee and Fenves which yields an equation to estimate the constant plastic dilatancy angle as a function of the concrete compressive strength and is:

$$\psi = [0.117f'c + 28.965]^0 \dots \text{Eq 8, Dilation angle}$$

Hence, the values of ψ was determined and take 32° which in the range of 0° to 50°

- Viscosity parameter:** Convergence issues may arise when full nonlinearity of the concrete material with gradual degradation under increased stress is assumed, especially with tensile stress. Reducing the size of the increment or increasing the maximum number of steps when solving the problem using Newton-Raphson may prove to be insufficient. The CDP model uses the viscosity parameter (μ) to allow the model to slightly exceed the plastic potential surface in certain, sufficiently small solution steps. In other words, μ is used for the viscoplastic regularization of the constitutive equations. It is necessary to use a trial and error approach to find the correct viscosity parameter since the minimum value of μ should be used.

5.3 Validation of finite element software (ABAQUS 6.13)

In order to confirm that the FEM gives a better result for critical buckling load and effective length of the CFST column, the FE software should be verified its certainty before going to modeling and giving any conclusion and recommendation. For this reason, through an extensive literature search, 6 circular, 6 square and 6 rectangular specimens with the different end support were collected and used to verify the proposed FE model. The parameters and the corresponding buckling loads of these specimens are summarized in the following table for circular and rectangular specimens, as specified on the following table tabulated herein below;

Table 10 Critical Buckling load according to FEM for tested CFST columns

CFST Column	End conditions	Dimension in mm						Pcr, kN
		B	b	D	d	t	L	Pcr
Square section	Case 1	100	95.42	100	95.42	2.29	1500	1973
	Case 2	100	95.42	100	95.42	2.29	1500	7703
	Case 3	100	95.42	100	95.42	2.29	1500	3939
	Case 4	100	95.42	100	95.42	2.29	1500	493
	Case 5	100	95.42	100	95.42	2.29	1500	1973
	Case 6	100	95.42	100	95.42	2.29	1500	493

Rectangular section	Case 1	130	121	98	79	4.5	1300	4838
	Case 2	130	121	98	79	4.5	1300	18115
	Case 3	130	121	98	79	4.5	1300	9522
	Case 4	130	121	98	79	4.5	1300	1175
	Case 5	130	121	98	79	4.5	1300	4838
	Case 6	130	121	98	79	4.5	1300	1175
Circular	Cases	Dimension in mm						
		Dia Outer	Dia inner	t	L	Pcr, kN		
	Case 1	114	105	4.5	1400	2954		
	Case 2	114	105	4.5	1400	21404		
	Case 3	114	105	4.5	1400	10812		
	Case 4	114	105	4.5	1400	1340		
	Case 5	114	105	4.5	1400	5282		
	Case 6	114	105	4.5	1400	1340		

As described on table 10 above, the critical buckling load was determined using numerical simulation software (ABAQUS 6.13). For the determination of the critical buckling load of the sampled CFST column, all the parameters which were used during experimental test was adopted and default values on FE analysis for ABAQUS software were adopted. For development of finite element modeling, detail explanation of each parameter described on the next sections for base model and other models.

Table 11 Critical Buckling load according to FEM, EN 1994-1-1 for the tested CFST columns

CFST column		Ultimate load (P_{ult}) in Kn due to							Remark
		Test (1)	EC41-1 (2)	FEM (3)	Error from EC4 1-1 (1-2)	Error in %	Error from FEM (1-3)	Error in %	
Square	Case 1	1983	1838	1973	145	7.90%	10	0.51%	The Critical Buckling load taken from the FEM software is almost the same as the results which have been taken from previous test specimen for buckling loads. Whereas the Critical Buckling load calculated by using EN 1994-1-1 is slightly lower than both test result and FEM output.
	Case 2	7752	7352	7703	400	5.44%	49	0.63%	
	Case 3	3952	3751	3939	201	5.36%	13	0.34%	
	Case 4	496	459	493	37	8.06%	3	0.66%	
	Case 5	1983	1838	1973	145	7.90%	10	0.51%	
	Case 6	496	459	493	37	8.06%	3	0.66%	
Rectangular	Case 1	4878	4504	4838	374	8.31%	40	0.83%	
	Case 2	18259	18018	18115	241	1.34%	145	0.80%	
	Case 3	9595	9193	9522	402	4.37%	72	0.76%	
	Case 4	1186	1126	1175	60	5.37%	11	0.94%	
	Case 5	4878	4504	4838	374	8.31%	40	0.83%	
	Case 6	1186	1126	1175	60	5.37%	11	0.94%	
Circular	Case 1	2975	2795	2954	180	6.44%	21	0.70%	
	Case 2	21607	19988	21404	1619	8.10%	203	0.95%	
	Case 3	10900	10198	10812	702	6.88%	88	0.81%	
	Case 4	1347	1249	1340	98	7.88%	8	0.59%	
	Case 5	5319	4997	5282	322	6.44%	37	0.7%	
	Case 6	1347	1249	1340	98	7.88%	8	0.59%	

As we clearly observed on the table 11, the buckling loads of each column for different end conditions are analyzed and tabulated in three different methods (i.e. test results taken from previous researches, currently available code EN 1994-1-1 and FEM, ABAQUS 6.13). According to the result, the critical buckling loads calculated by the FEM software and the test result are most likely the same (0.71% error in average). Hence, we concurred that the finite element software could give good result during critical load determination for further course of action.

5.4 Formulating of base model

As clearly explained above on table 11, the FE method has been verified and validated for the next course of action. Hence, the following values were chosen for the parameters discussed earlier for the base model.

Table 12 Concrete damage plasticity parameter

Material	Concrete
Compressive Strength	30Mpa
Tensile Strength	10% of Compressive strength
Elastic Modules	25700Mpa
Poissons Ratio	0.2
Initial Elastic Strain	0
Density	2450kg/m ³
Dilation Angle	32°
Kc	0.725
f_{b0}/f_c	1.16

The stress-strain model was used as an input parameter in ABAQUS in two stages namely, the elastic stage and the plastic stage. The elastic stage is entered using two variables, namely:

- The elastic modulus of the concrete
- The initial Poisson's ratio of concrete

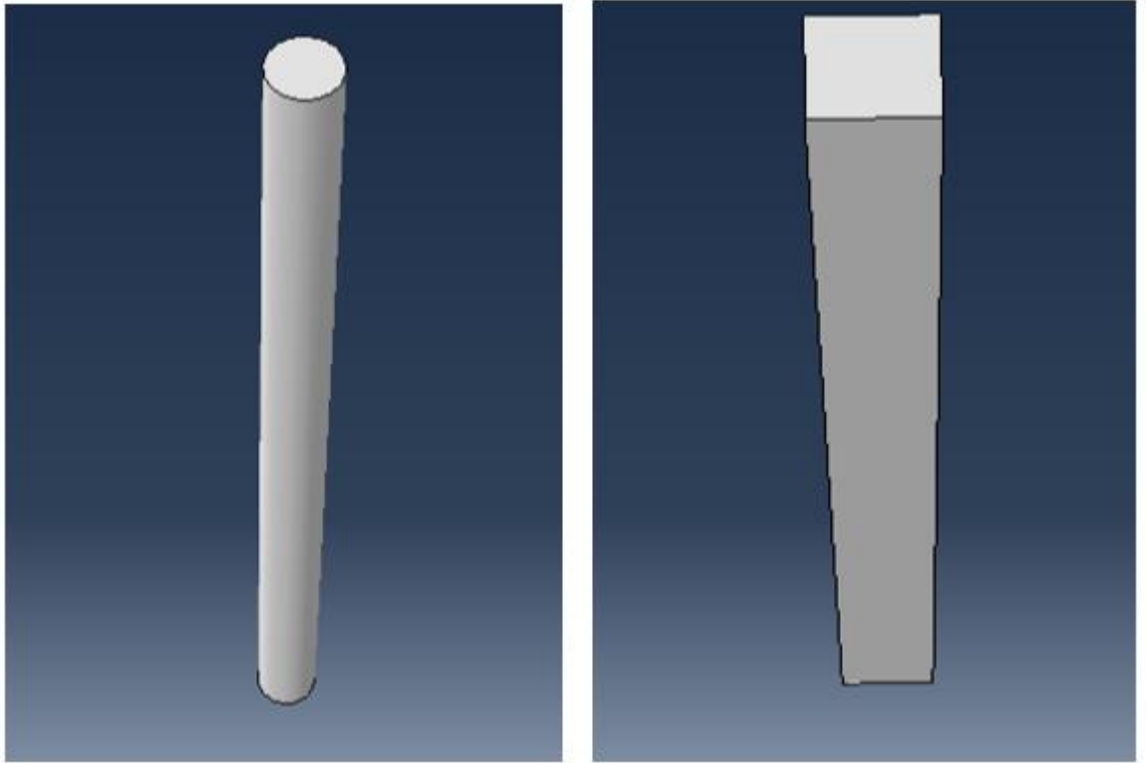


Figure 12 Sample concrete part of CFST column

5.4.1.1 Steel material modeling

The material model for structural steel proposed by Liang (Liang, 2009) was used. The transition from the elastic to the plastic region is represented by a smooth curve described by the following equation;

$$\sigma_s = f_{sy} \left(\frac{\epsilon_s - 0.9\epsilon_{sy}}{\epsilon_{st} - 0.9\epsilon_{sy}} \right)^{\frac{1}{45}} \dots \text{Eq 9, Steel material modeling formula}$$

$$(0.9\epsilon_{sy} < \epsilon_s \leq \epsilon_{st})$$

Where, σ_s is the stress in the steel, ϵ_s is the strain in the steel, f_{sy} is the yield stress, ϵ_{sy} is the yield strain and ϵ_{st} is the hardening strain taken as 0.005.

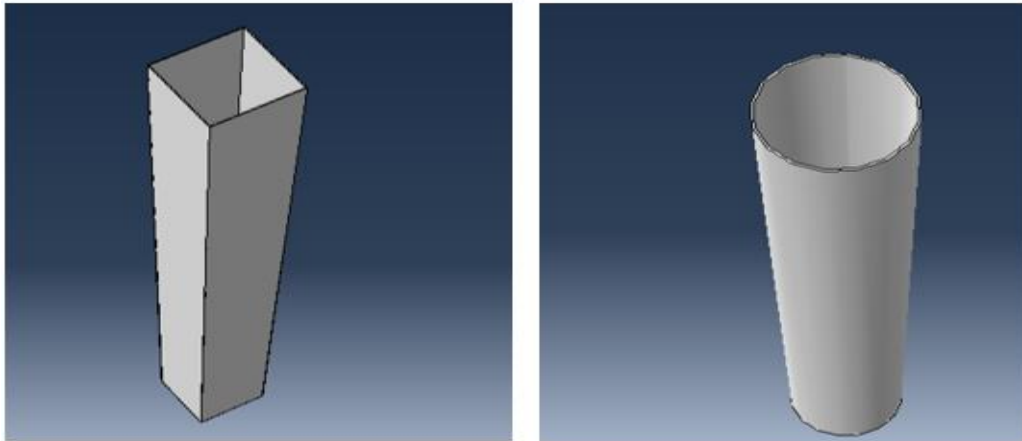


Figure 13 Sample steel part CFST columns

5.4.2 Meshing

Meshing can be done on individual parts and then assembled or vice-versa. In this analysis parts were individually meshed and then assembled for further process. The mesh size of the parts was based on the mesh convergence studies and hence element size across the cross-section was chosen as $D/15$ for a circular column or $B/15$ for rectangular column, where D and B are the overall diameter of the circular tube and the overall width of the rectangular tube, respectively. The FE method discretizes the CFST column as per the given discretization value by itself. Some of representative mesh for the assembled CFST columns are shown below for both rectangular and circular cross section

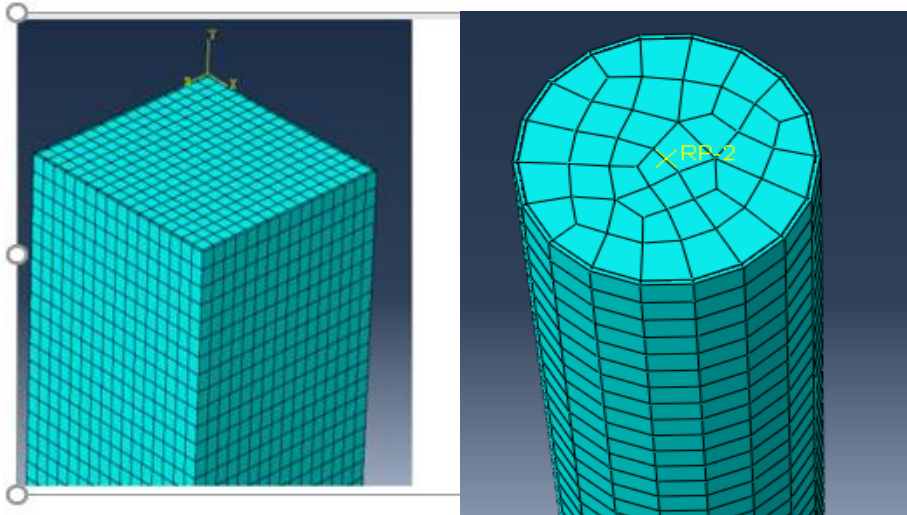


Figure 14 Sample mesh of rectangular and circular CFST column

5.4.3 Steel-concrete interaction

Where two surfaces are in contact, they transmit shear forces as well as a normal force across their interface which results in a relationship between the two forces. In ABAQUS it is possible to define a shear stress limit $\bar{\tau}_{max}$. This implies that sliding will occur if the magnitude of the equivalent shear stress reaches $\bar{\tau}_{max}$, regardless of the magnitude of the contact pressure. The specified value of $\bar{\tau}_{max}$ cannot be zero. Figure 10 illustrates the shear stress limit.

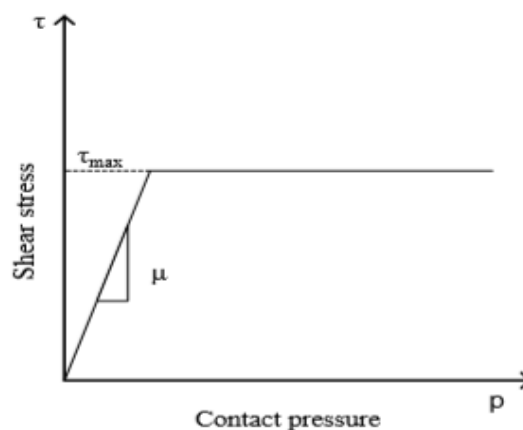


Figure 15 Shear stress limit at interface (SIMULIA, 2013)

It was decided to use hard-contact to model the normal behavior of the steel-concrete interface and the default friction model of ABAQUS. The friction coefficient was chosen as 0.20 which is the same magnitude used by Ellobody. To decide on a shear stress limit,

it was assumed that the contact behavior between the steel tube and concrete would be like the contact behavior between a normal R-bar (smooth reinforcing steel).

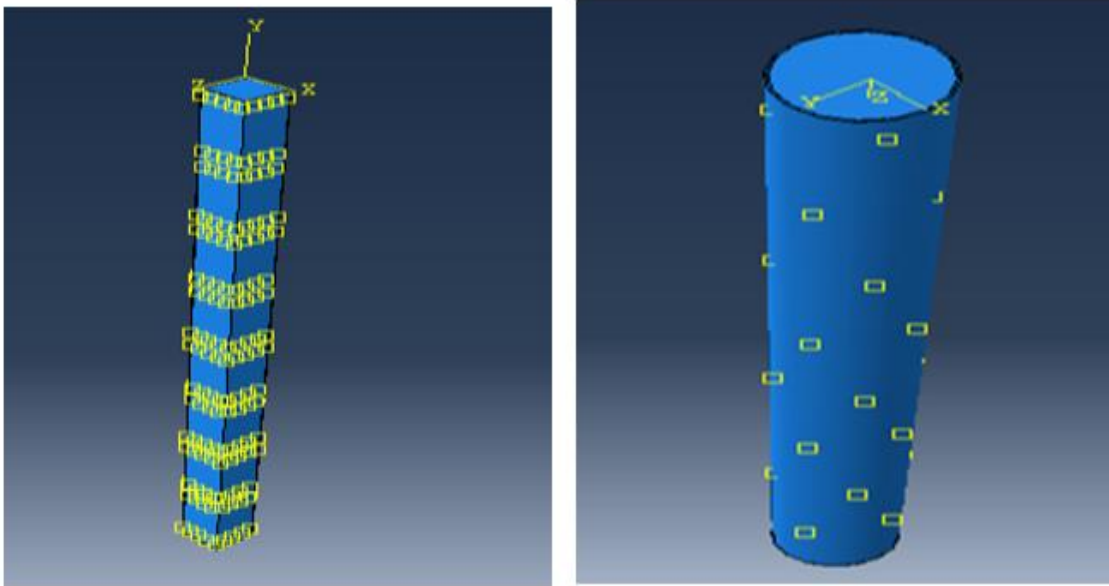


Figure 16 Sample hard contact between surfaces

5.5 Finite element result

Base models were developed to get the critical buckling load for determination of effective length factor where after individual parameters were independently varied to determine the effect on the critical buckling load and effective length factor of the CFST columns.

5.5.1 Description of base model

The following parameters were used to obtain load versus displacement curves for the various CFST columns by varying support conditions:

Concrete material: The stress-strain model has the following parameters:

$$f_{cu} = 30 \text{ MPa} \text{ Cube strength of concrete.}$$

$$\nu = 0.2 \text{ Initial Poisson's ratio.}$$

$$E = 25.7 \text{ GPa Elastic modulus.}$$

$$f_{ctm} = 1.19 \text{ MPa Tensile strength}$$

Steel material: The stress-strain model has the following parameters:

$f_{sy} = 275 \text{ MPa}$ Yield strength.

$f_{su} = 360 \text{ MPa}$ Ultimate strength.

$\nu = 0.3$ Poisson's ratio.

$E = 210 \text{ GPa}$ Elastic modulus.

Steel-concrete interface: The steel-concrete interface has the following parameters.

$\mu = 0.20$ Friction coefficient.

$\bar{\tau}_{max} = 1.93 \text{ MPa}$ Shear stress limit.

$e_s = 1.0 \times 10^{-5}$ Elastic slip.

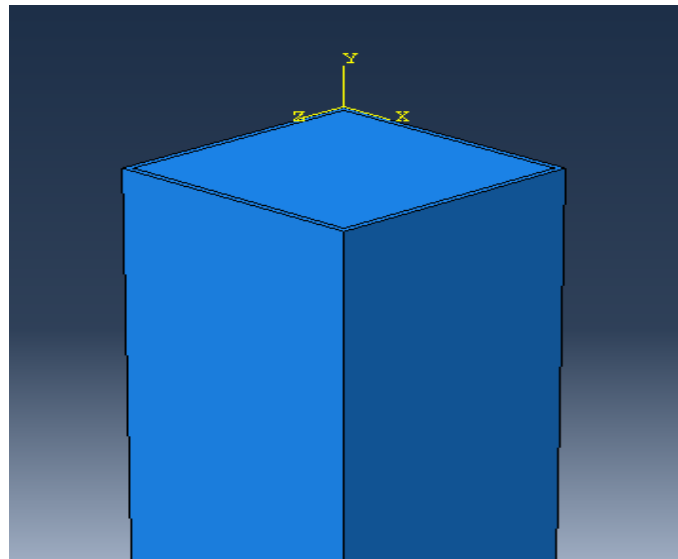


Figure 17 Sample assembled CFST column

5.5.2 Load and boundary conditions

Loads and boundary conditions must be applied to the geometry of model accurately to get the precise result. In this analysis for each of the two ends, two different types of boundary conditions were used. Load and boundary conditions for each column has been conducted as the sample of the same listed herein below;

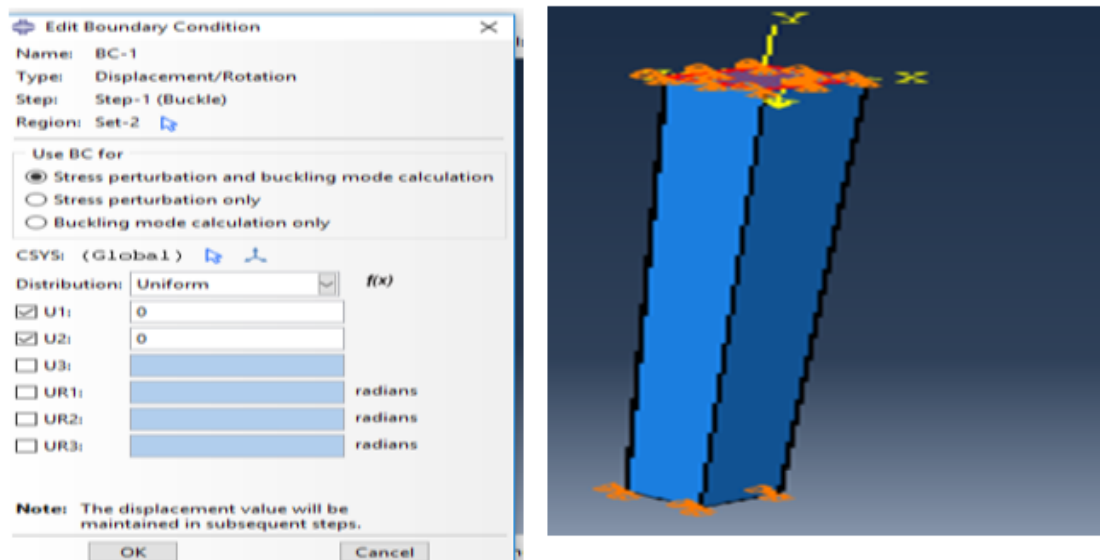


Figure 18 Sample load and boundary condition configuration

Some of the parameters are taken as default value since many of researchers use such parameters and their value determination is scarce and some of the values investigated by different authors are not the same. Those default values adopted for this paper are taken from the recommended values as default.

5.5.3 Analysis type

FE provides various analysis procedures to analyze the behavior of different models catering different needs. There are basically two types of step analysis:

- Linear perturbation, buckle analysis type and
- General, static, Riks analysis type

The “General, Static, Riks’ is the convended type of analysis and used to analyze linear or non-linear response. Whereas the analysis type “Linear Perturbation, Buckle” can be used only to analyze linear analysis problems. Linear analysis always considered to be linear perturbation analysis about the state at the time when the linear analysis procedure is introduced and gives eigenvalue of the CFST columns. This analysis is simply the calculation of eigenvalues for buckling prediction.

5.6 Determination of critical load and effective length factor

5.6.1 Finite element analysis output

The analysis of the critical buckling load of each column was conducted and determined using the ABAQOS 6.13 software output by linear and nonlinear buckling analysis. After detail analysis and calculation, the critical buckling load of the columns are tabulated herein below,

Table 13 Summaries of P_{cr} as per the FE modeling

Steel tube	End conditions	Dimension in mm						
		B	b	D	d	t	L	P _{cr} , kN
Square section	Case 1	400	380	400	380	10	6000	37854
	Case 2	400	380	400	380	10	6000	139865
	Case 3	400	380	400	380	10	6000	76985
	Case 4	400	380	400	380	10	6000	8862
	Case 5	400	380	400	380	10	6000	37854
	Case 6	400	380	400	380	10	6000	8862
Rectangular section	Case 1	400	380	300	280	10	6000	18345
	Case 2	400	380	300	280	10	6000	69012
	Case 3	400	380	300	280	10	6000	39521
	Case 4	400	380	300	280	10	6000	5013
	Case 5	400	380	300	280	10	6000	18345
	Case 6	400	380	300	280	10	6000	5013
Circular	Cases	Dimension in mm					P _{cr} , Kn	
		Dia Outer		Dia inner	t	L		
	Case 1	400		386	7	6000	19524	
	Case 2	400		386	7	6000	75685	
	Case 3	400		386	7	6000	37985	
	Case 4	400		386	7	6000	4857	
	Case 5	400		386	7	6000	19524	
	Case 6	400		386	7	6000	4857	

The buckling loads of each column are shown on table 14. After modeling and analysis of the columns, the critical buckling load obtained from the Eurocode formula have been

compared with the buckling loads of the same columns obtained from ABAQUS 6.13 FE software for further discussion. Some of the sample shape of the CFST column has been described herein below.

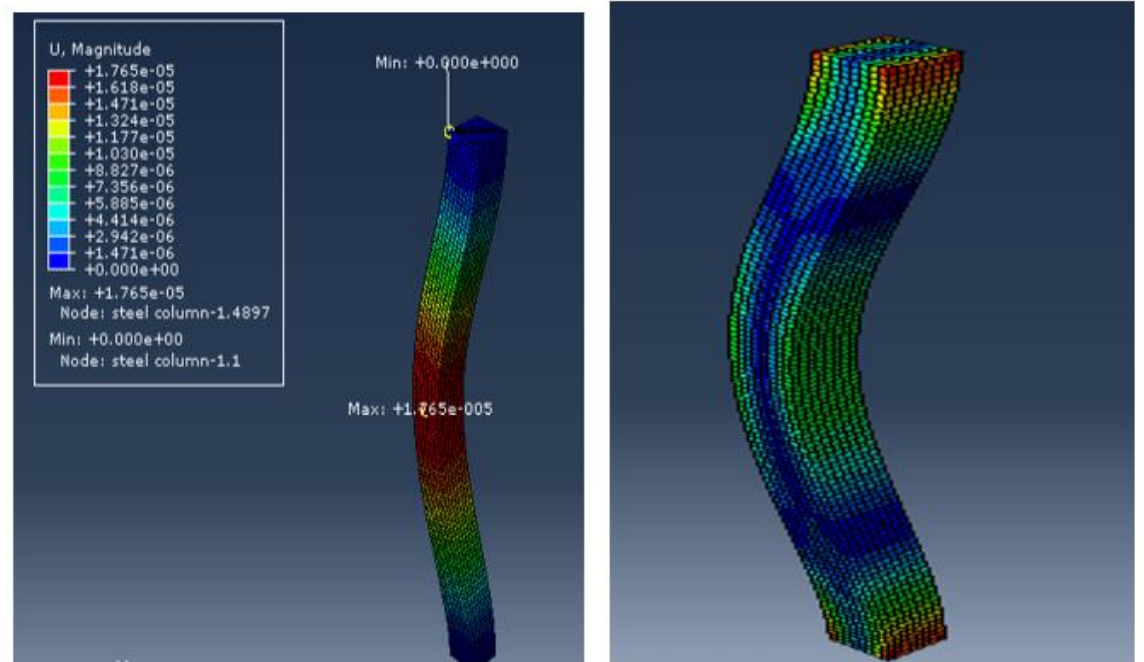


Figure 19 Sample buckled shapes of CFST column after FE analysis

5.6.2 Actual buckling load and effective length factor

As we have seen on the table below, the buckling loads of the CFST column for each case (support conditions) on both EC4 and FEM analysis are different. The difference in magnitude for each case among the above methods are tabulated below;

Table 14 Comparison of buckling loads of CFST between EC4 and FEM

Steel tube	End conditions	Critical Buckling load (kN)		Difference in kN (B-A)	% of load increment (B-A)/(A)
		(A) EC4	(B) FEM		
Square section	Case 1	31040	37854	6814	18.00%
	Case 2	124160	139865	15705	11.23%
	Case 3	63347	76985	13638	17.72%
	Case 4	7760	8862	1102	12.44%
	Case 5	31040	37854	6814	18.00%

	Case 6	7760	8862	1102	12.44%
Rectangular section	Case 1	15095	18345	3250	17.72%
	Case 2	60378	69012	8634	12.51%
	Case 3	30806	39521	8715	22.05%
	Case 4	3773	5013	1240	24.74%
	Case 5	15095	18345	3250	17.72%
	Case 6	3773	5013	1240	24.74%
Circular	Case 1	16602	19524	2922	14.97%
	Case 2	66407	75685	9278	12.26%
	Case 3	33881	37985	4104	10.80%
	Case 4	16602	19524	2922	14.56%
	Case 5	4150	4857	707	14.97%
	Case 6	4150	4857	707	14.56%

It is clearly shown on the above table 14 that the critical buckling load of each column with different end conditions of the FE output is higher than that of critical buckling loads determined by the currently available EC4. Since the critical buckling load is inversely proportional to the square of effective length of the column, which leads that the actual effective length factor is lower than the recommended values stipulated under EC3 steel structure.

Accordingly, the effective length factor K , was determine in accordance with the FE output by arc length method. During analysis of the model, the FE computes the critical load and the arc length of the deflected shape of the column (from points of inflection). Hence, the effective length of the column is a multiple of original length and effective length factor, the factor can be determined directly as follows.

Table 15 Determination of effective length factor according to FEM output

Steel tube	End conditions	Length and effective length factor		
		OL (mm)	AL (mm)	Effective length factor, $K=OL/AL$
Square section	Case 1	6000	5460	0.91
	Case 2	6000	2700	0.45
	Case 3	6000	3720	0.62
	Case 4	6000	11220	1.87
	Case 5	6000	5460	0.91
	Case 6	6000	11220	1.87
Rectangular section	Case 1	6000	5520	0.92
	Case 2	6000	2820	0.47
	Case 3	6000	3780	0.63
	Case 4	6000	11280	1.88
	Case 5	6000	5520	0.92
	Case 6	6000	11280	1.88
Circular section	Case 1	6000	5400	0.90
	Case 2	6000	2640	0.44
	Case 3	6000	3660	0.61
	Case 4	6000	11100	1.85
	Case 5	6000	5400	0.90
	Case 6	6000	11100	1.85

OL: Original Length

AL: Arc Length from the points of inflection

Furthermore, the effective length factor K , could be determine by setting the critical buckling load of the column by using Euler’s formula and obtained the same result as described above on table 15. To this effect, the effect of different parameters on effective length factor and buckling loads of the CFST column has been conducted and presented on the next chapter.

Table 16 Determination of effective length factor according to FEM output

CFST	End conditions	Theoretical K factor	Critical Buckling load according to EC4	Effective length factor K	EFM Buckling load	Difference from recommended K value	In %
Square section	Case 1	1.0	31040	0.91	37854	0.0945	9.45%
	Case 2	0.5	124160	0.45	139865	0.0289	5.78%
	Case 3	0.7	63347	0.62	76985	0.0650	9.29%
	Case 4	2.0	7760	1.87	8862	0.1285	6.42%
	Case 5	1.0	31040	0.91	37854	0.0945	9.45%
	Case 6	2.0	7760	1.87	8862	0.1285	6.42%
Rectangular section	Case 1	1.0	15095	0.92	18345	0.0929	9.29%
	Case 2	0.5	60378	0.47	69012	0.0323	6.46%
	Case 3	0.7	30806	0.63	39521	0.0820	11.71%
	Case 4	2.0	3773	1.88	5013	0.2647	13.24%
	Case 5	1.0	15095	0.92	18345	0.0929	9.29%
	Case 6	2.0	3773	1.88	5013	0.2647	13.24%
Circular	Case 1	1.0	16602	0.90	19524	0.0779	7.79%
	Case 2	0.5	66407	0.44	75685	0.0316	6.33%
	Case 3	0.7	33881	0.61	37985	0.0389	5.56%
	Case 4	2.0	4150	1.85	4857	0.1512	7.56%
	Case 5	1.0	16602	0.90	19524	0.0779	7.79%
	Case 6	2.0	4150	1.85	4857	0.1512	7.56%

As we have seen from the result, the effective length factor is slightly lower than the theoretical value and much lower than the recommended K value. According to the Euro codes recommendation, the designer shall use the recommended K values conservatively during critical buckling load determination of an isolated composite column including CFST column. However, the actual effective length factor of the CFST column with possible end support combination is lower than the recommended values so that the section capacity of the CFST column to buckle is underestimated.

6. RESULT AND DISCUSSION

6.1 Result

The buckling load and effective length factor of the CFST column was determined on the selected parameters using FE method and investigated the critical buckling loads and effective length factors with different support conditions. Hence, the effective length factor taken from the EC4 during buckling analysis of CFST column was in conservative approach and hence the accurate effective length factor are shown below on tables 20 and 21. The effective length factor for different cross sections are almost the same and does not depend on parameters like thickness of steel tube, steel grade and concrete grade. On the other hand, the critical buckling load depends on the aforementioned parameters.

Table 17 Final Effective length factor

Cases	End conditions	Effective length factor			
		EC4	Sqr	Rec	Cir
1	Both ends are pinned	1.00	0.91	0.92	0.90
2	Both ends are fixed	0.50	0.45	0.47	0.44
3	One end is pinned, and one end is fixed	0.70	0.62	0.63	0.61
4	One end is free, and one end is fixed	2.00	1.87	1.88	1.85
5	Both ends are fixed with some lateral translation	1.00	0.91	0.92	0.90
6	The base is pinned & the top is fixed with some lateral translation	2.00	1.87	1.88	1.85

Where,

EC4: Euro code

Sqr: square CFST column

Rec: Rectangular CFST column

Cir: Circular CFST column

6.2 Discussion

As explained above, the effective length factor was determined, and the values taken from the FE analysis slightly lower than the specified values on EC4. Furthermore, the effective length factors for different cross sections (Square, Rectangle and Circular) are not exactly the same to each other whereas the EC4 recommends the same values for all sections. The possible reasons for which the current available codes underestimate the effective length factor;

1. The difference is mainly the analytic method in design code underestimate the critical buckling load based on some assumptions due to problems regarding to workmanship, material property and others.
2. The concrete core prevents the structural steel tube from lateral buckling and the outer structural steel tube increases the confinement of the concrete core in which the section capacity highly increases due to such interactions among the materials.
3. The effective length factor of the CFST columns taken from the available code depend only the support conditions and hence the Engineer (Designer) uses such values conservatively. However, the factors are overestimated for the sake of safety but not economical.

The increase in thickness of steel tube, concrete grade and steel grade of the CFST column increases the critical buckling load. This is because;

- The increase in thickness of the steel tube increases the stiffness of the column
- The initial stiffness of the columns increases slightly due to the use of comparatively strength concrete. Further, use of high strength concrete leads to increase in the load carrying capacity. Accordingly, the maximum concrete grade used for this paper is up to C45.
- The effective length factor determined from the FE analysis was slightly different from the recommended values. However, those factors are not dependent on steel grade and concrete grade but the increase in thickness of steel tube reduces the effective length factor in a little bit for some models but not have significant effect totally.

7. CONCLUSION AND RECOMMENDATION

7.1 Conclusion

From the results of this paper, the following conclusions are drawn with limitations which endures the designers (Engineers) to account during design and stability analysis.

1. A reasonable simplified FE model of the composite (concrete filled steel tube, CFST) isolated column by varying the end support conditions were developed to investigate the critical buckling load and the effective length factor by using FE software. Accordingly, considering the influence of geometrical nonlinearity with initial imperfection, the FEM model is much accurate and closer to actual situation for which the current available design codes underestimates the capacity of CFST columns which leads the designer being uneconomical.
2. Since the result obtained from the finite element analysis is verified by the test results conducted on previous researches, the effective length factor calculated by buckling analysis of an isolated CFST column is reasonable and acceptable.
3. The effective length factors of the CFST column depends on support conditions.
4. The effective length factors are slightly different each other for RHS and CHS sections.
5. Finally, the critical buckling load obtained from the code is uneconomical since it reduces the capacity of the CFST column so that the recommended effective length factor on EC4 is a conservative approach.

7.2 Recommendation

In accordance with the result of this paper, the following recommendations are forwarded for further detail investigation and future works.

1. Since currently there is no available special codes for design of CFST columns, the designers (Engineers) would use the finite element method for precise determination of critical buckling load and structural stability analysis for CFST column and other composite columns, rather than using the theoretical and recommended values of K stipulated on EC4.
2. Further studies to set the actual and precise effective length factor for determining critical buckling load for composite columns shall be conduct by increasing the other parameters such as length of column, rate of loading and other necessary parameters for ease reference of the designers in order to design cost effective and efficient structures.

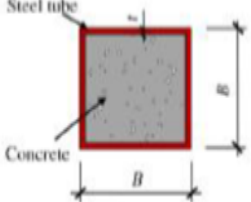
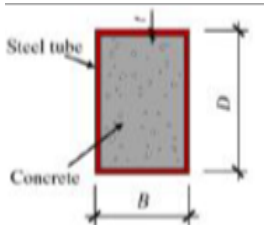
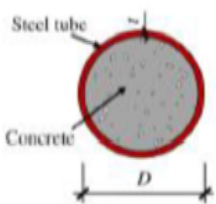
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APPENDIX A

Section properties of the base modeled CFST columns:

Type of section	Qualitative description	Dimension (mm)			Section property (cm ⁴)	
		B	B	t	I _{yy}	I _{zz}
Square		400	400	10	I _{yy}	I _{zz}
					2.13 x 10 ⁵	2.13 x 10 ⁵
					I _{sy}	I _{sz}
					3.95 x 10 ⁴	3.95 x 10 ⁴
					I _{cy}	I _{cz}
					1.73 x 10 ⁵	1.73 x 10 ⁵
Rectangular		400	300	10	I _{yy}	I _{zz}
					1.6 x 10 ⁵	9.0 x 10 ⁴
					I _{sy}	I _{sz}
					3.19 x 10 ⁴	2.05 x 10 ⁴
					I _{cy}	I _{cz}
					1.2 x 10 ⁵	6.95 x 10 ⁴
Circular		400		7	I _{yy}	I _{zz}
					1.26 x 10 ⁵	1.26 x 10 ⁵
					I _{sy}	I _{sz}
					1.67 x 10 ⁴	1.67 x 10 ⁴
					I _{cy}	I _{cz}
					1.09 x 10 ⁵	1.09 x 10 ⁵

APPENDIX B

linear-buckling analysis (400x400x10) CFST column input file

***Heading**

**** Job name: Job-1 Model name: Model-1**

**** Generated by: Abaqus/CAE 6.13-1**

***Preprint, echo=NO, model=NO, history=NO, contact=NO**

**** PARTS**

***Part, name=concrete**

***Node**

,

,

,

78,	-95.,	380.,	0.
79,	-190.,	380.,	0.
80,	-285.,	380.,	0.
81,	-380.,	380.,	0.
82,	380.,	-380.,	100.
83,	285.,	-380.,	100.
84,	190.,	-380.,	100.
85,	95.,	-380.,	100.
86,	0.,	-380.,	100.
87,	-95.,	-380.,	100.

,

,

,

1104, 2199, 2227, 2183, 2180, 2263, 2291, 2247, 2244
1105, 2200, 2228, 2227, 2199, 2264, 2292, 2291, 2263
1106, 2202, 2230, 2229, 2201, 2266, 2294, 2293, 2265
1107, 2202, 2203, 2231, 2230, 2266, 2267, 2295, 2294
1108, 2203, 2204, 2232, 2231, 2267, 2268, 2296, 2295
1109, 2206, 2220, 2182, 2178, 2270, 2284, 2246, 2242
1110, 2207, 2221, 2220, 2206, 2271, 2285, 2284, 2270
1111, 2209, 2223, 2222, 2208, 2273, 2287, 2286, 2272

1112, 2209, 2210, 2224, 2223, 2273, 2274, 2288, 2287

1113, 2210, 2211, 2225, 2224, 2274, 2275, 2289, 2288

***Nset, nset=Set-1, generate**

1, 3904, 1

***Elset, elset=Set-1, generate**

1, 1920, 1

**** Section: steel**

***Shell Section, elset=Set-1, material=steel**

,

***End Part**

**** ASSEMBLY**

***Assembly, name=Assembly**

***Instance, name=concrete-1, part=concrete**

***End Instance**

***Instance, name=steel-1, part=steel**

***End Instance**

***Node**

1, 0., 0., 0.

***Node**

2, 0., 0., 6000.

***Nset, nset=Bottom, instance=concrete-1**

***Nset, nset=Bottom, instance=steel-1, generate**

1, 64, 1

***Nset, nset=Set-5**

1,

***Nset, nset=Set-6**

2,

***Nset, nset=Set-7**

2,

***Nset, nset=Top, instance=concrete-1**

***Elset, elset=_CP-4-steel-1_S5, internal, instance=steel-1, generate**

26, 1914, 32

```
*Surface, type=ELEMENT, name=CP-4-steel-1
_CP-4-steel-1_S6, S6
_CP-4-steel-1_S3, S3
_CP-4-steel-1_S5, S5
** Constraint: bottom
*Rigid Body, ref node=_PickedSet20, tie nset=Bottom
** Constraint: top
*Rigid Body, ref node=_PickedSet21, tie nset=Top
*End Assembly
**
** MATERIALS
**
*Material, name=concrete
*Elastic
21., 0.2
*Material, name=steel
*Elastic
210., 0.3
**
** INTERACTION PROPERTIES
**
*Surface Interaction, name="steel concrete"
1.,
*Friction, slip tolerance=0.005
0.25,
*Surface Behavior, pressure-overclosure=HARD
**
** BOUNDARY CONDITIONS
**
** Name: bottom Type: Symmetry/Antisymmetry/Encastre
*Boundary
Set-5, ENCASTRE
** Name: top Type: Displacement/Rotation
*Boundary
Set-6, 1, 1
Set-6, 2, 2
Set-6, 3, 3
**
** INTERACTIONS
**
```

```
** Interaction: CP-1-concrete-1-steel-1
*Contact Pair, interaction="steel concrete", type=SURFACE TO SURFACE
CP-1-steel-1, CP-1-concrete-1
** Interaction: CP-2-concrete-1-steel-1
*Contact Pair, interaction="steel concrete", type=SURFACE TO SURFACE
CP-2-steel-1, CP-2-concrete-1
** Interaction: CP-3-concrete-1-steel-1
*Contact Pair, interaction="steel concrete", type=SURFACE TO SURFACE
CP-3-steel-1, CP-3-concrete-1
** Interaction: CP-4-concrete-1-steel-1
*Contact Pair, interaction="steel concrete", type=SURFACE TO SURFACE
CP-4-steel-1, CP-4-concrete-1
** -----
**
** STEP: linear buckling
**
*Step, name=linear buckling, nlgeom=NO, perturbation
*Buckle
6, , 12, 300
**
** BOUNDARY CONDITIONS
**
** Name: bottom Type: Symmetry/Antisymmetry/Encastre
*Boundary, op=NEW, load case=1
Set-5, ENCASTRE
*Boundary, op=NEW, load case=2
Set-5, ENCASTRE
** Name: top Type: Displacement/Rotation
*Boundary, op=NEW, load case=1
Set-6, 1, 1
Set-6, 2, 2
Set-6, 3, 3
*Boundary, op=NEW, load case=2
Set-6, 1, 1
Set-6, 2, 2
Set-6, 3, 3
**
** LOADS
**
** Name: Load-1 Type: Concentrated force
```

```
*Cloud
Set-7, 3, -1.
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, variable=PRESELECT
*NODE FILE
U
*End Step
```

Nonlinear-buckling analysis (400x400x10) CFST column input file

```
*Heading
** Job name: Job-1 Model name: Model-1
** Generated by: Abaqus/CAE 6.13-1
*Preprint, echo=NO, model=NO, history=NO, contact=NO
**
** PARTS
**
*Part, name=concrete
*Node
,
,
,
78, -95., 380., 0.
79, -190., 380., 0.
80, -285., 380., 0.
81, -380., 380., 0.
82, 380., -380., 100.
83, 285., -380., 100.
84, 190., -380., 100.
85, 95., -380., 100.
```

86, 0., -380., 100.
 87, -95., -380., 100.

,
 ,
 ,

1104, 2199, 2227, 2183, 2180, 2263, 2291, 2247, 2244
 1105, 2200, 2228, 2227, 2199, 2264, 2292, 2291, 2263
 1106, 2202, 2230, 2229, 2201, 2266, 2294, 2293, 2265
 1107, 2202, 2203, 2231, 2230, 2266, 2267, 2295, 2294
 1108, 2203, 2204, 2232, 2231, 2267, 2268, 2296, 2295
 1109, 2206, 2220, 2182, 2178, 2270, 2284, 2246, 2242
 1110, 2207, 2221, 2220, 2206, 2271, 2285, 2284, 2270
 1111, 2209, 2223, 2222, 2208, 2273, 2287, 2286, 2272
 1112, 2209, 2210, 2224, 2223, 2273, 2274, 2288, 2287
 1113, 2210, 2211, 2225, 2224, 2274, 2275, 2289, 2288

*Nset, nset=Set-1, generate

1, 3904, 1

*Elset, elset=Set-1, generate

1, 1920, 1

** Section: steel

*Solid Section, elset=Set-1, material=steel

,

*End Part

**

**

** ASSEMBLY

**

*Assembly, name=Assembly

**

*Instance, name=concrete-1, part=concrete

*End Instance

**

*Instance, name=steel-1, part=steel

*End Instance

**

*Node

1, 0., 0., 0.

*Node

```
2, 0., 0., 6000.
*Nset, nset=Bottom, instance=concrete-1
*Nset, nset=Bottom, instance=steel-1, generate
1, 64, 1
*Nset, nset=Set-5
1,
*Nset, nset=Set-6
2,
*Nset, nset=Set-7
2,
*Nset, nset=Top, instance=concrete-1
*Elset, elset=_CP-4-steel-1_S5, internal, instance=steel-1, generate
26, 1914, 32
*Surface, type=ELEMENT, name=CP-4-steel-1
_CP-4-steel-1_S6, S6
_CP-4-steel-1_S3, S3
_CP-4-steel-1_S5, S5
** Constraint: bottom
*Rigid Body, ref node=_PickedSet20, tie nset=Bottom
** Constraint: top
*Rigid Body, ref node=_PickedSet21, tie nset=Top
*End Assembly
**
** MATERIALS
**
*Material, name=concrete
*Elastic
21., 0.2
*Material, name=steel
*Elastic
210., 0.3
**
** INTERACTION PROPERTIES
**
*Surface Interaction, name="steel concrete"
1.,
*Friction, slip tolerance=0.005
0.25,
*Surface Behavior, pressure-overclosure=HARD
**
```

**** BOUNDARY CONDITIONS**

**

**** Name: bottom Type: Symmetry/Antisymmetry/Encastre**

***Boundary**

Set-5, ENCASTRE

**** Name: top Type: Displacement/Rotation**

***Boundary**

Set-6, 1, 1

Set-6, 2, 2

Set-6, 3, 3

**

**** INTERACTIONS**

**

**** Interaction: CP-1-concrete-1-steel-1**

***Contact Pair, interaction="steel concrete", type=SURFACE TO SURFACE**

CP-1-steel-1, CP-1-concrete-1

**** Interaction: CP-2-concrete-1-steel-1**

***Contact Pair, interaction="steel concrete", type=SURFACE TO SURFACE**

CP-2-steel-1, CP-2-concrete-1

**** Interaction: CP-3-concrete-1-steel-1**

***Contact Pair, interaction="steel concrete", type=SURFACE TO SURFACE**

CP-3-steel-1, CP-3-concrete-1

**** Interaction: CP-4-concrete-1-steel-1**

***Contact Pair, interaction="steel concrete", type=SURFACE TO SURFACE**

CP-4-steel-1, CP-4-concrete-1

**** -----**

**

**** STEP: nonlinear_buckling**

**

***IMPERFECTION, FILE=linear_buckling, STEP=1**

1,0.21

***Step, name=nonlinear_buckling, nlgeom=YES, inc=1000**

***Static, riks**

0.01, 1., 1e-05

**

**** LOADS**

**

**** Name: Load-1 Type: Concentrated force**

***Cload**

Set-8, 3, -1.11113e+06

**

** **OUTPUT REQUESTS**

**

***Restart, write, frequency=0**

**

** **FIELD OUTPUT: F-Output-1**

**

***Output, field, variable=PRESELECT**

**

** **HISTORY OUTPUT: H-Output-1**

**

***Output, history, variable=PRESELECT**

***End Step**
