

**Behaviour of elliptical concrete-filled steel tube (CFT)
columns under axial compression load**

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Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

The University of Leeds
School of Civil Engineering

October, 2011

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Abstract

This thesis describes a research of the behaviour of the elliptical CFT columns under axial loading. The most substantial part of this research is experimental works conducted on twenty-seven specimens including the hollow stub columns as references. Parameters such as slenderness ratio, uni-axial compressive strength of concrete infill and the aspect ratio were considered to investigate their influence on the behaviour on these columns. The results presented are the first member buckling tests on elliptical CFT columns. Key results from the tests have been presented and discussed. Parallel with the experimental works, numerical analyses were carried out and verified with the experimental results. Parametric studies were performed following the validation of the numerical models.

As there is no design guidance seems to be available in any standard, thus this research provides a review of the existing design standards of Eurocode 4 (EC4) and American Specifications (AISC). The design expressions from these current design provisions for circular, square and rectangular concrete-filled tubes design strengths were used to predict the capacities of elliptical CFT columns. The influences of concrete enhancement, steel reduction due to biaxial effects and column slenderness were all incorporated in design rules of EC4. Based on the experimental, numerical findings the evaluations were made on the design rules of the codes. This investigation was aimed at providing reliable design guidelines for practising engineers to employ the elliptical concrete-infill columns in the construction industry.

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Chapter 1

Introduction

1.1 Background

The composite structure of steel-concrete columns is not new to the construction industry. The columns have been used for over 100 years with the concrete material was initially used as insulation that was required to fulfil the fire-rating requirement.

In the case of its early application, the contribution of composite action, which is in the structure, was not taken into consideration. The composite action exists when two different materials are joined together so strongly that, from a structural perspective, together, they are able to act as a single unit. Owing to the composite action, the composite member is stiffer and stronger than the sum of the individual members. However, these structural benefits were only established in the middle of the 20th century when the increment of stiffness and strength were observed in another type of composite structure namely encased composite beam (Vrcelj and Uy, 2002). In 1948, British Standard has taken into account the increase of stiffness due to the concrete encasement in the design application (Grauers, 1993).

Composite columns possess many significant advantages over conventional reinforced concrete and steel structures. Its growing usage in the case of structural and architectural applications is predominantly owing to the

significant advantages of the structure, such as high load-carrying capacity owing to the blend of properties of differing materials in the structure. Steel is the most versatile traditional construction material and well known to provide high reliability in terms of its consistent quality and full efficiency when placed under tension whereas concrete is efficient in compression.

The composite structures are commonly used when the conventional structure is unable to develop sufficient resistance associated with design loading or in the case where more specialised applications were needed (Nethercot, 2004). This form of structure can be utilised in different configurations; whether the steel structure is used externally, known as concrete-filled tube column or the steel section is encased in the concrete material. Concrete-filled tubes column, hereafter referred to as CFT, is being increasingly used as a structural element, especially in seismic zones, as it offers a number of significant advantages. The structure exploits the characteristics and overall configuration of the structure elements; steel offers high tensile strength, ductility and construction speed, whereas concrete provides high compressive strength, stiffness and cost reduction. Another notable advantage associated with the use of composite columns is construction cost saving, as the steel tube can serve as a formwork to the concrete core. With the concrete-filled column profile, the steel frame can be erected after filling in the concrete material, without waiting for the concrete to harden provides the advantage of saving both time and cost.

1.2 Concrete-filled Tube (CFT) Composite Column

1.2.1 Functional principle

CFT composite columns can be introduced in various forms. The hollow steel tubes can be filled with various types of concrete and strength, whilst the columns can be erected with various shapes of hollow steel sections. The most common types of composite columns are shown in Figure 1.1; namely steel-encased concrete column, concrete-filled circular hollow section (CHS), concrete-filled square (SHS), or rectangular hollow section (RHS). The steel-encased column comprises I or H steel cross-section placed within a traditional reinforced concrete or plain concrete. This structure is the earliest type of composite cross-section. A CFT column, on the other hand, is simply constructed by filling concrete into the hollow section, which is used as a casting mould to the concrete.

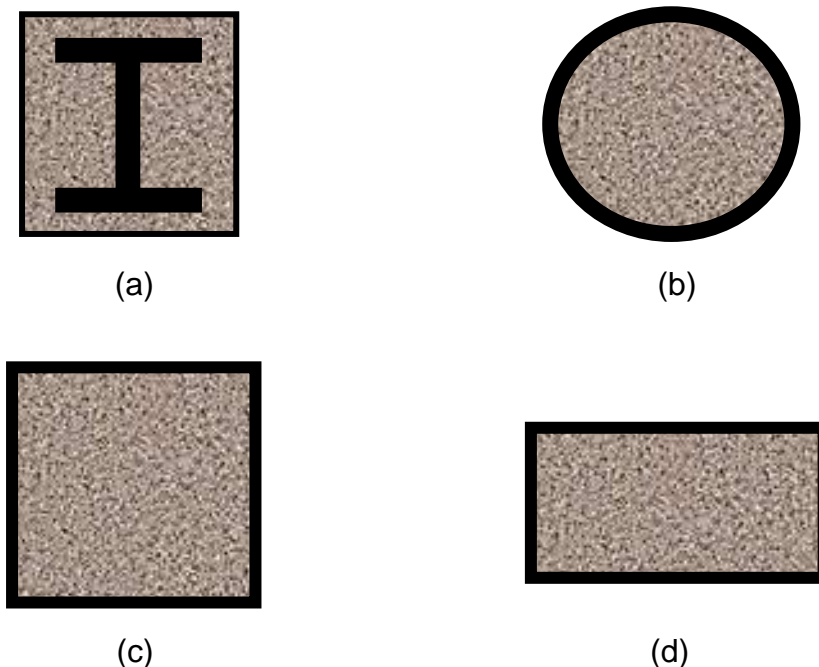


Figure 1.1: Typical cross-section of composite columns

The orientation of the steel and concrete member in the CFT column cross-section has a significant role in terms of enhancing the strength and stiffness of the structure. The steel section is located at the outer perimeter, where it performs most effectively in tension and bending moment. Furthermore, the stiffness of the CFT column is enhanced as the steel section has a greater modulus of elasticity compared with concrete members and a greater moment of inertia owing to the fact that the steel section is situated farthest from the centroid of the cross-section (Gourley et al., 2001). The concrete core, which acts as the inner structure (EFNARC, 2002), is considered to be ideal in terms of withstanding the compression loading, and is often found to prevent or delay the occurrence of local buckling in the steel section, particularly in rectangular CFTs (Gourley et al., 2001). The concrete core also prevents inward local buckling; thus, the steel tube can only buckle outwards, which therefore leads to an increase in ultimate strength and local buckling strength of the composite column (Liang et al., 2006). The CFT column is also popular as a structural member, as it has a number of significant advantages, such as higher strength and improved ductility (Ellobody et al., 2006, Ellobody and Young, 2006). Notably, saving construction time and labour costs is another keen advantage associated with the use of CFT column, as the steel column has the ability to eliminate the need of formwork since the steel section can also act as permanent formwork. Notably, longitudinal reinforcement and finished structure, including surface treatment, can be effectively achieved at the same time.

Recently, elliptical hollow sections (EHS) were introduced, drawing the attention from engineers and architects due to its aesthetic appearance and structural efficiency, predominantly owing to its major and minor axis. The

elliptical hollow sections also have greater bending capacity compared to circular hollow sections of the same area and weight, owing to its strong and weak axis directions (Packer, 2008). As a mark of acceptance, EHS have been employed in a number of applications, such as Terminal 5 Heathrow Airport in the UK, and the Legend Centre in Canada.

1.2.2 Composite Column Materials

The typical forming of hot-rolled hollow steel tubes is commonly utilised in the case of CFT columns. However, the cold-formed steel tube manufacturing and build-up steel section can also be found in the market. The build-up steel tube is formed by the welding of plates or channel sections. Moreover, the concrete member of the composite columns can be either normal strength concrete or high strength concrete. Notably, they should be designed and produced in accordance with relevant norms with at least 25 N/mm^2 cube strength and 2400 kg/m^3 concrete density. According to BS EN 1994-1-1:2004 the clause to design composite compression members only applies for normal weight concrete of cube strength classes C25 to C60. The typical density for the normal concrete is 2400 kg/m^3 .

Importantly, the development and application of high-performance materials have greatly increased all over the world. The materials have several advantages over ordinary strength materials. For example, the use of high-strength concrete (HSC) and high-strength steel (HSS) are proven to enhance the load-carrying capacity of structures and also significantly benefit in terms of saving material costs.

In the case of traditional reinforce high concrete strength columns, stirrup spacing is often reduced to prevent the brittle failure associated with the

characteristic of the high strength concrete and to obtain a higher ductility. However, the stirrups may create a form of natural plane separation between the confined concrete core and the unconfined concrete cover, and increases the risk of a premature spalling of the concrete cover (Johansson and Gylltoft, 2002). Nevertheless, this problem can be overcome with the use of composite columns consisting of concrete-filled steel tubes, CFT.

1.3 Research Significance

There has been a notable increase in the use of composite columns in engineering structures, especially in seismic zones. The presence of elliptical sections adds more choice for engineers and architects when employing such sections in numerous structures for aesthetic purposes. However, as with the newest section shape, there are many issues which are not well understood owing to a lack of knowledge in relation to its behaviour.

At this moment, there is limited understanding of structural performance on the section. The results on elliptical hollow sections are currently insufficient, and very limited experimental information can be found concerning elliptical CFT columns. Most of the researches on elliptical CFT columns focused on short columns such as work done by Dai and Lam (2010). The confinement effect is an issue which needs to be addressed, particularly in consideration of how it affects to the steel section. The interaction between local and global buckling also needs to be investigated, especially for long, slender columns. The works presented in this thesis highlight the study of mechanical behaviour in elliptical CFT columns. In order to comprehend the behaviour of elliptical CFT columns, it is first necessary to understand the

response of elliptical tubes in the composite structure and the interactions between individual materials in structure. Furthermore, the potential and advantages associated with the use of HSC in the composite column have been established. Thus, the knowledge gained from the experiments and FE analysis and the failure process in the columns are vital in order to add information which fundamentally benefits both the researcher and engineers.

1.4 Thesis Aims and Objectives

The study is mainly divided into experimental studies and Finite Element (FE) Modelling. The work emphasise on the investigation of behaviour and performance of concrete filled elliptical steel tube. Experiments were performed on both short and long columns tests and the results were used to verify the FE models. In this thesis, a long column is defined as a member whose length is considerably larger than any of its cross-sectional dimensions.

The principle aim of this research project is to gain an understanding into the behaviour of this form of constitution. Since the shape is relatively new and also as the data for this type of column is currently insufficient with very limited understanding, it therefore deserves further investigation. The objective of this project is mainly concerned with investigating the 2, capacity and failure patterns both up to and beyond the ultimate load of this cross-sectional shape of composite column. This is owing to the fact that the behaviour associated with such a shape is relatively unknown, especially in the case of long columns. The other objectives are to investigate the effects of the use of normal concrete strength and high concrete strength, the influence of slenderness on column strength, and the confinement provided

by the shape of steel tube, all of which are addressed in order to investigate the effects on CFT columns.

The main objectives of this study are outlined as follows:

1. To conduct an experimental investigation of elliptical CFT columns under axial load;
2. To investigate the influence of parameters such as column slenderness and concrete strength on load-bearing capacity;
3. To give an experimental base of information for the design of elliptical columns consisting of concrete filled hollow steel sections
4. To develop a numerical model in order to simulate the behaviour of the elliptical CFT columns under axial loading
5. To propose new equations for this form of structural sections.

1.5 Research Scope

In this study, tests concerning elliptical CFT columns were conducted on twenty-seven specimens, including two hollow stub columns, for the purpose of comparison. Parameters considered in this study include column slenderness (L/D), width-to-thickness ratio (D/t) and concrete strength. Reviews from previous studies have further highlighted that such parameters affect the behaviour and strengths of CFT columns. Moreover, experiments were carried out and studied in order to determine their influences on the ultimate strength of elliptical concrete-filled steel tube column. The results of the axial compression test on the specimens reflect the influences of such

parameters on the strength and behaviour of elliptical CFT columns. The experiments only considered concrete-filled elliptical hollow steel sections without the use of any mechanical connectors or reinforcement.

The experiments involved short and long elliptical columns. The stub columns tests were performed in order to establish the squash load of the structure. Meanwhile, in the case of long columns, the tests were carried out on various lengths for the purpose of studying the behaviour and influences of global buckling on the structure's capacity. It is noteworthy to state that there is limited research work available in the literature concerning long concrete-filled steel columns and none involved elliptical sections. Thus, the experiment was performed over a range of length where local buckling and overall flexural buckling were involved. Moreover, long columns tests were carried out on three different lengths in a range of 1500 mm to 2500 mm in order to study the reduction in strength and behaviour with increasing slenderness. Different typical concrete cube strength 30 N/mm^2 , 60 N/mm^2 and 100 N/mm^2 are used in this study and in the form of self-compacting concrete (SCC). Self-compacting concrete is facilitating the highly efficient filling of composite columns by offering reliable and segregation-free techniques for filling up to significant heights without additional compaction. The use of high-strength concrete is included in this study as it benefits the structures in terms of both strength and stiffness (O'Shea and Bridge, 2000). Numerical modelling was carried out in parallel with the experimental programme. This analysis provides better behavioural understanding of the structural. In the numerical study, models were developed in order to predict the response of elliptical CFT column subjected to axial compression load.

Initial geometric imperfections were considered in the three-dimensional non-linear finite element models of long columns.

1.6 Dissertation Structure

This thesis presents the study of elliptical concrete-filled tube columns which involves reviews from related literatures, procedure of non-linear finite element models, the design of self-compacting concrete, and subsequent analysis from both experimental and FE results. The work developed in this thesis has been organised into eight chapters. The first chapter is the introduction of the research background. Research aims and the principles of CFT columns have been highlighted in this chapter.

Chapter 2 presents a review of the existing research work related to the area of interest covered in the thesis. This section discusses on the related findings in relation to investigations conducted on hollow and composite CFT columns.

Chapter 3 describes about the self-compacting concrete that has been chosen as concrete infill. This chapter covers the design and concreting procedure of the particular types of concrete.

Chapter 4 outlines the methodology used for the purpose of conducting the experimental work. This section explained in detail the procedure of specimen's preparation, the rig-frame setting-up and the tests involved in this study.

Chapter 5 encompassed the results of current study. Observation made from the experimental of elliptical columns under axial loading was highlighted in this chapter.

Chapter 6 discusses the numerical method performed in ABAQUS. It covers the procedure of modelling and verification of the results obtained throughout the FE analysis phase. A series of parametric study was also conducted.

Chapter 7 covers the analysis from the experimental results and numerical analysis. The influences of parameters involved in this study were discussed. The indicators such as strength enhancement index, SI and ductility index, DI were used to assess the compressive capacity and the ability of non-linear deformation respectively. Comparison of the results from both methods with current design codes are also highlighted in this chapter.

Chapter 8 is the final chapter that encompasses the conclusion drawn from the project analysis and its corresponding results. Significant findings were highlighted and recommendations for further research have been made.

Chapter 2

Literature Review

2.1 Introduction

This chapter is aimed towards providing an overview of the background literature. Key research findings relating to the experimental works, numerical modelling and design guide of the concrete infill columns structures are also covered.

Originally, the composite column started with a steel-encased concrete column type; however, the main disadvantage of this type of composite columns was that the structure required complete formwork and a reinforcement cage, which was needed in order to prevent the concrete core from spalling. On the other hand, the CFT column had the advantage of preventing such problems owing to the configuration of the structure.

As mentioned in the previous chapter, the combination of concrete and steel in the column structure was initially aimed towards achieving fire resistance. The composite action which occurred owing to the bonding between these materials was later found to have an effect on the structure's strength. As a result, an extensive study concerning the assessment of the composite action in the columns was conducted.

Studies on CFT columns have been on-going for many decades (Giakoumelis and Lam, 2004, Zeghiche and Chaoui, 2005). The use of CFT columns was first recorded and published by Sewell in 1901 (Johansson, 2002), and the earliest complete test on CFT columns was conducted in 1957 by Kloppel and Goder (Han, 2002). The aim of the concrete infill in the Sewell study was to protect the internal hollow tube from rusting. The enhancement of the structure stiffness was noticeable after some of the columns were accidentally overloaded. The development in studying the axial strength of the CFT columns continued since the columns first tested by Kloppel and Goder were various cross-sections structures, such as circular, square, and rectangular (Han, 2002).

Recently, the elliptical tube section was introduced in the hollow tube family. Since it is the newest steel section, only a handful of investigations on the application of this column structure shape had been undertaken. However, most of the researchers conducted so far have involved elliptical hollow sections and stub elliptical composite columns. Therefore, it is considered that further investigations and experimental data are needed in order to develop a better understanding of the elliptical CFT columns particularly on slender columns behaviour.

2.2 Behaviour of CFT Column

A column is a structural element which primarily loads in compression along its length. It can be either subjected to compression forces or combined with eccentric load or bending moment. The failure of short compression columns is the result of compression axial force, whereas in the case of longer

columns, compression members are affected by the strength and stiffness of the material, as well as the geometry of the members.

The steel hollow section is known to be a very efficient structure in terms of resisting compression loads, and has been widely used in the case of framed structures in industrial buildings. However, it is nevertheless recognised that the material is vulnerable to heat, and the potential of exposed steel section to be used in design might therefore be compromised. In spite of this, as the development in the steel industry has moved forward, there have been many approaches to fire protection offered for exposed steel columns. Furthermore, as the construction technology advances, concrete infill in the hollow section are not only expected to increase the capacity of the structure, but also to increase its overall fire resistance.

There are several factors which may have a considerable effect on the ultimate strength of CFT columns, such as slenderness ratio, thickness, cross-section shape, and the mechanical properties of steel and concrete (Shakir-Khalid and Zeghiche, 1989, Romero et al., 2005). Generally, the compression axially loaded CFT members can fail in two principal ways: in terms of slenderness and material properties. In the case of short columns, mechanical properties play an important role in their behaviour. The failure state is attained when the steel tube reaches the limit state of yielding and concrete crushing, which is known as a strength criterion. On the other hand, stability will essentially govern the ultimate load capacity of slender CFT columns, where the members are more likely to fail as a result of buckling and second-order effects becoming more critical (Gourley et al., 2001, Sakino, 2006); therefore, the critical buckling load, P_{ct} , which represents the

load at which slender column buckles is more crucial for the column. It can be seen that the stiffness fundamentally influences the column's strength more in slender columns, but that this is not the case for short columns where the strength is mainly depends on the material strength and cross-sectional area.

The shape of the column has also contributed to the strength and behaviour of CFT column. Comparing the open section and the hollow tube, the latter is considered to be the most efficient shape for the compression member owing to its material distribution, which is further away from the centre of the cross-section. However, the disadvantage remains that the structure member is difficult in terms of connection.

Nowadays, there are many types of hollow tubes available in the market. Amongst them, the circular hollow section is evidently the most efficient for compression members, as it has an equal second-moment of area and stiffness in all directions. The effect of the cross-section shape and thickness on the ultimate axial strength of CFT columns has been acknowledged from research carried out by Schneider (1998), Shams and Saadeghvaziri (1997), Huang et al., (2002). From the study, it was concluded that the short axially loaded circular CFT columns have an elastic-perfectly plastic behaviour, and also offer more post-yield axial ductility when compared with the square or rectangular CFT column. This was further exhibited by the significant strain-hardening behaviour of the circular column, whilst various post-yield behaviour—depending on the tube wall thickness of the tube column, were exhibited in the case of square and rectangular tubes.

2.2.1 Confinement

Confinement has a significant relation to the ductility of CFT columns besides providing a significant advantage in term of the column's ultimate strength. In the columns, compressive confining stress on the concrete core is induced via a passive confinement provided by the hollow steel tube (Johansson and Akesson, 2002). The confining effect, however, basically depends on a variety of factors, such as the dimension of the steel tube, concrete strength, tube thickness, the yield stress of the steel tube and the overall shape of the column cross-section (Ellobody and Young, 2006, Ellobody et al., 2006). The development of confinement at the steel-concrete interface is initiated partly from the difference in Poisson's ratios between materials in the structure. Concrete has a smaller Poisson's ratio, ν_{conc} (0.15-0.25) than steel, (0.3) during the elastic stage, which therefore leads to lateral separation of the steel tube and concrete core. Notably, however, ν_{conc} becomes higher than steel, particularly when the concrete core begins to crack or crush; thus, lateral deformation of the concrete reinitiates interactive contact with the steel tube (Gourley et al., 2001). Further loading results in the development of radial pressure and setting up a hoop tension in the tube. During this stage, the steel shell provides confining pressure to the concrete expansion of the concrete core, which subsequently puts the concrete under tri-axial stress and the steel in biaxial. Accordingly, it is expected that the steel tube in the CFT enhances the concrete core in axial compressive strength by its lateral confinement. The tri-axial compression concrete in the columns can withstand higher strains and stress (Grauers, 1993).

The section's shape effect on confinement was investigated by Nardin and El Debs (2007) and Fujimoto et al. (2004). As has been ascertained from the study, the confinement is found to be superior in circular and octagonal CFT columns, but not in CFT columns with a square steel section. This is owing to the uniformed lateral pressure in the circular tube which confines the concrete core; in the case of the square section, however, higher confining pressure only occurs at the centre and corner of the section compared to the other side. Further investigation also demonstrates that the thickness of the tube influences the ductility behaviour of the square section.

The investigation carried out by Shanmugam and Lakshmi (2001) on rectangular tubes, shows that the tension hoop developed along the side of the tube was not constant, and therefore seems to be the reason as to why a confinement effect was not present except in the corner of the steel tube. The same conclusion was drawn from the non-linear analysis conducted by (Hu et al., 2003). The nonlinear finite element program, *ABAQUS* in their study had been performed on circular section, square section, and square section stiffened by reinforcing ties. Thus, it is suggested that confinement is considered to be more significant in the case of circular CFT columns rather than square CFT columns, where the column only shows a small increment in axial strength (Fujimoto et al., 2004). As can be determined from the study of Nardin and Debs (2007), the confinement in the square section was found to be more effective than the rectangular section, which was represented by greater ductility in the post-peak behaviour. Notably, the circular section was still established as being more ductile compared with other shapes in their studies. CFT columns with circular sections provide a good confining effect; however, when the width-to-thickness ratio is small ($D/t < 40$), it was

established that the square section did not provide a large confining effect especially when the width-to-thickness ratio was large ($B/t > 30$). The effects of concrete confinement for columns with large plate slenderness ratios were also found to be less pronounced, as local buckling may occur (Uy, 1998).

The confining effect was noted to have enhanced considerably the strength of a short column; however, the effect was found to be insignificant in the case of slender columns (Oehlers and Bradford, 1995). This is primarily due to the fact that the column with large L/D ratios was generally found to fail owing to columns buckling before it reached the strain necessary to cause an increase in concrete volume (Han, 2002). From a numerical investigation carried out by Neogi *et al.* (1969), it was established that there was a gain in strength owing to a triaxial effect for columns with L/D ratios less than 15. In their study, complete interaction between steel and concrete was assumed; thus, triaxial and biaxial effects were not considered. The columns were subsequently analysed by tangent-modulus approach and compared with experimental results.

2.2.2 Axial Buckling

Buckling is one of the structural behaviour and an instability form which should be considered primarily for compression members, such as columns. Its presence obviously reduces the capacity of the structure. Eurocode 4 (EC4), for instance, has imposed some restrictions on the allowable diameter-to-thickness ratio, D/t in order to prevent local buckling from influencing structure capability as indicated in Table 6.3 in BS EN 1994-1-1:2004.

2.2.2.1 Local Buckling

There are two types of buckling: local buckling and overall buckling. Local buckling occurs when the thin steel elements are compressed in their planes (Oehlers and Bradford, 1995). With this in mind, and in order to fully utilise the steel strength, the failure mode should be prevented before the steel reaches its yield stress. In the case of thin walled steel tubes, the influence of local buckling is significant to its strength. This type of failure is indicated by the growth of bulges, waves or ripples. In the case of CFT columns, the presence of concrete infill has an effect in prolonging the local buckling of the tube wall (Baig et al., 2006, Schneider, 1998). Furthermore, the resistance in a local buckling of steel owing to the presence of concrete was first identified by Matsui (Uy, 1998). Other than delaying the presence of local buckling, the concrete core in CFT columns has also been established to significantly increase the structure's ductility. It also adds stiffness to the steel tube by preventing inward buckling, as the concrete core only forces the buckling modes outward, consequently increasing the stability and strength of the structure (Hu et al., 2003, Nardin and El Debs, 2007, Hu et al., 2005). As a result of the prevention of inward buckling by concrete core, it was found that the increment of buckling capacity was approximately 50% more when compared with the hollow steel column, as highlighted in (Shanmugam and Lakshmi, 2001). The contribution of concrete core in delaying the occurrence of inward local buckling could ensure that the steel would reach its longitudinal yield strength before buckling took place (Zeghiche and Chaoui, 2005). The other advantage of having only outward mode failure mechanism is the prevention of significant decreases in the section modulus. This is owing to the fact that the distance between the top

and bottom flanges of the steel increases rather than decreases (as without) the concrete core when local buckling occurred. The presence of local buckling is also known to affect the confinement in concrete-filled columns when failure occurs prior to concrete crushing where the effect of confinement is limited as the tube sections were prevented from providing a continuous restraint on the concrete for confinement. However, if the local buckling is inelastic, then the confinement of concrete can nevertheless develop (Uy, 1998).

The experiment conducted by Schneider (1998) proved that very similar local buckling behaviour was established in rectangular and square section results. The square tube has buckling effects occurring equally on each face, whereas the rectangular CFT has extensive local buckling owing to the fact that it has a wider face. In circular CFT, the wall buckling was found to be owing to a radial expansion of the tube. Generally, a tube with larger D/t ratios has more local buckling capability with higher apparent distortion compared to the sections with small D/t ratios.

2.2.2.2 Overall Buckling

Overall buckling generally occurred in the case of long or slender columns. The failure is illustrated by sideways bending where, for the particularly columns, the global stability is more vulnerable, as the columns tend to fail owing to flexural buckling (Oehlers and Bradford, 1995). This failure occurs when the condition of a stable equilibrium between the internal and external forces in the structure is no longer possible (Shanmugam and Lakshmi, 2001). The behaviour of these columns is influenced by the slenderness ratio, with the slenderness also contributing to the so-called second order effects.

2.2.3 Modes of Failure

A short or stocky columns failure mechanism is characterised by the yielding of steel and crushing of concrete, whilst the medium length CFT columns behave inelasticity and therefore fail owing to the partial yielding of steel, the crushing of concrete in compression, and the cracking of concrete in tension (Shanmugam and Lakshmi, 2001). Finally, slender columns are bound by the elastic limit. As the capacities of short columns are dominated by the strength limit of the material thus, the structures are known as material-dependent.

The type of buckling mode of stub CFT columns is also significantly influenced by the method of loading conditions. Study by Johansson and Gyltoft (2002) on the columns subjected to axial loading include various different loading conditions, namely loading on the steel tube, loading on the concrete core, and simultaneous loading of the steel and concrete. From the study, for those columns with the load applied to the entire section and those columns with the load applied to the concrete core, the combination of local buckling and crushing was found to affect the stability of the columns. From the experiment, bond strength was found to have no effect on the behaviour of the columns when simultaneous loading was applied; however, in the case when the load was applied only on the concrete core, the bond strength was found to significantly affect the confinement effects; this condition also greatly influenced the overall strength and behaviour of the columns.

Axially-loaded long CFT columns with an L/D ratio of between 12.5 and 25.0, and lengths from 2-4 m were tested by Zeghiche and Chaoui (2005). The results showed that the columns failed after they reached the steel yield

strain with small-lateral mid-length deflections. Furthermore, there was no sign of local buckling, and the overall instability fundamentally dominated the column's failure mode. The removal of the steel envelope for some specimens revealed no sign of concrete-crushing at the mid-length of the sections. This study also highlighted that the enhancement owing to concrete strength is essentially more significant for short columns.

2.2.4 Creep and Shrinkage

Both creep and shrinkage in terms of concrete structure is categorised as time-dependent deformation. The concrete creep can be defined as the deformation which commonly occurring in the direction, in which the force is being applied—of the structure under a sustained load which can generally change the shape of the concrete structure.

The concrete shrinkage is the volumetric change of concrete structures owing to the evaporation of water from the hardened concrete. Tensile stresses will be generated, with the presence of cracks. There are three shrinkage categories: plastic shrinkage, chemical shrinkage, and drying shrinkage. The effect of plastic shrinkage occurs in the case of wet concrete, and may result in significant cracking throughout the setting process. Cracking occurs owing to capillary tension in the pore water. Since the bond between the plastic concrete and the steel tube in CFT columns has not yet developed, the steel section is ineffective in controlling such cracks. Moreover, drying shrinkage is the reduction in volume caused principally by the loss of water during the drying process, whilst chemical (or endogenous) shrinkage results from various chemical reactions within the cement paste and includes hydration shrinkage, which is related to the degree of hydration of the binder in a sealed specimen. The high-strength concrete of SCC is

ultimately more prone to plastic shrinkage and chemical shrinkage due to its low water content and silica fume. On the other hand, the drying shrinkage for the high-performance concrete is smaller than in normal-strength concrete due to the lower quantities of free water following hydration. However, the effects of shrinkage in CFT columns have been found to be smaller compared with plain concrete (Uy, 2001). Furthermore, the shrinking effect hardly has any effect on the load resistance of CFT columns (Shams and Saadeghvaziri, 1997). As the concrete core in CFT columns is confined in the steel tube and isolated from the environment, the tube can act as a barrier for a better curing system which prevents the loss of moisture, which subsequently minimises the presence of shrinkage.

2.3 Composite Column Materials and Structure

Strength and stiffness are the most important properties in a material. The strength of the material dominates the determination of the collapse load of a structure, whilst its stiffness ensures that the structure does not deflect significantly under the load (Seward, 1998).

2.3.1 Concrete Infill

The strength for the concrete infill can be in the form of normal concrete with a compressive strength of less than 60 MPa, or high strength concrete with a compressive strength of more than 60 MPa. Notably, concrete core with lower concrete strength may experience failure through concrete splitting, whilst in the case of higher concrete strength, concrete sliding may cause failure. A comparison between a low concrete strength and a higher concrete strength in terms of stress-strain curves indicates that the concrete which possesses a higher strength has large elastic rigidity as the initial

elastic modulus of concrete increases parallel with the increase in the concrete strength.

The use of high-strength concrete (HSC) offers several advantages over normal-strength concrete due to its greater stiffness. Increasing the concrete strength also results in a greater strength capacity and the reduction of the external dimension of the composite columns (Nardin and El Debs, 2007). Nevertheless, the majority of research conducted on CFT columns has focused on circular and square sections with lower concrete strength (Lue, 2007); thus, for this research, the high-strength concrete is included in order to experimentally investigate the elliptical CFT column behaviour which is subjected to axial loading. The major concern regarding the use of HSC is brittleness, which is associated with ductility. Accordingly, the use of the HSC column is limited in high seismic zones. However, the ductility of HSC in columns can be significantly improved by encasing the concrete core in a steel shell, which can provide shear resistance as well as improvements in overall ductility, as described by Aboutaha and Machado (1998). The study highlights various weaknesses concerning the use of CFT columns; however, such considerations will not be discussed here.

The use of HSC as concrete infill in CFT columns has been considered in a study by Giakoumelis and Lam (2004). The study involved various concrete strengths, i.e. 30, 60 and 100 N/mm², with the overall aim of examining the bond strength and confinement effect. However, from the load-strain graph of the normal concrete and the high concrete strengths, it has been concluded that, for high-strength CFT columns, peak load was achieved for small shortening, whereas for normal concrete, the ultimate load was gained

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