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LIST OF ABBREVIATION

CFDST	Concrete-Filled Double Skin Steel Tubular
CFRP	Carbon Fiber Reinforced Polymer
CFST	Concrete-Filled Steel Tubular
DI	Ductility Index
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
HSC	High Strength Concrete
HSS	Hollow Structural Section
NSC	Normal Strength Concrete
RSI	Residual Strength Index
SEI	Strength Enhancement Index

LIST OF SYMBOLS

$\Delta_{0.85}$	Displacement at 0.85 ultimate strength
Δ_u	Displacement at ultimate strength
N_{eS}	Ultimate strength of repaired CFDST columns
N_{eU}	Ultimate strength of unrepaired CFDST columns
N_u	Ultimate strength of CFDST column at ambient temperature
$N_u(t)$	Ultimate strength of CFDST column after fire
t_0	Thickness of outer steel tube

KEBERKESANAN KAEDAH PEMBAIKAN MENGGUNAKAN POLIMER GENTIAN HIBRID KE ATAS TIANG KELULI DWI LAPISAN BERISI KONKRIT PASCA KEBAKARAN

ABSTRAK

Tiang keluli dwi lapisan berisi konkrit (CFDST) menjadi semakin popular pada masa kini di sebabkan oleh prestasinya yang tinggi berbanding dengan tiang komposit konvensional dan tiang keluli berisi konkrit (CFST). Walau bagaimanapun, penggunaan tiang jenis ini terhad kepada pembinaan luar seperti jambatan dan menara penghantaran (*transmission tower*) di mana api bukan merupakan satu kebimbangan utama. Tambahan pula, kajian sedia ada mengenai tiang CFDST hanya memberi tumpuan kepada prestasi tiang terhadap api dan kajian mengenai kekuatan sisa tiang CFDST pasca-kebakaran adalah terhad. Kekuatan sisa boleh digunakan untuk menentukan kaedah pembaikan yang paling sesuai supaya tiang tersebut kembali berfungsi seperti sediakala. Oleh itu, kajian ini bertujuan untuk mengkaji kesan parameter yang berbeza terhadap kekuatan sisa tiang CFDST. Antara parameter yang di bincangkan ialah ketebalan tiub keluli luar dan masa pendedahan kepada api. Kajian ini juga menilai keberkesanan kaedah pembaikan menggunakan polimer gentian (FRP) tunggal dan Hibrid terhadap prestasi tiang CFDST yang rosak akibat api. Tiang CFDST dibakar mengikut ASTM E119-11: Standard Test Methods for Fire Tests of Building Construction and Materials sehingga mencapai suhu 600°C. Selepas itu, suhu dimalarkan untuk dua jangka masa yang berbeza, iaitu, 60 minit dan 90 minit. Spesimen itu kemudian dibiarkan menyejuk pada suhu bilik di dalam relau sebelum ia dibawa keluar dan dibaiki sama ada dengan menggunakan FRP tunggal atau Hibrid. Spesimen dikategorikan kepada 3 kumpulan iaitu (1) spesimen tidak dibakar atau kawalan, (2) dibakar dan tidak dibaiki dan (3) dibakar dan dibaiki. Semua spesimen dibebankan dengan beban mampatan paksi sehingga gagal. Kategori pertama dan kedua spesimen gagal disebabkan oleh lengkokan tempatan ke arah luar daripada tiub keluli luar, kehancuran konkrit dan lengkokan tempatan daripada tiub keluli dalaman; manakala, spesimen daripada kategori ketiga gagal disebabkan oleh kegagalan FRP diikuti oleh lengkokan tempatan dan kehancuran konkrit seperti kategori pertama dan kedua. Kekuatan, kekukuhan sekan dan Indeks Kemuluran (DI) berkurang apabila suhu specimen meningkat. RSI dan

Kekukuhan Sekan meningkat apabila masa pendedahan meningkat. Menariknya, RSI tertinggi yang dicapai hanya 22% yang bermaksud, spesimen masih mampu membawa lebih daripada 70% daripada beban asal selepas terdedah kepada api selama 90 minit dengan hanya 3 mm ketebalan tiub keluli luar. Pembaikan tiang CFDST yang rosak akibat api dengan menggunakan FRP tunggal dan Hibrid berjaya menambahkan kekuatan muktamad tiang. Peningkatan kekuatan muktamad adalah lebih ketara apabila spesimen dibaiki dengan kaedah Hubrid FRP bersama spesimen yang mempunyai ketebalan tiub keluli luar yang nipis. Walau bagaimanapun, kenaikan dalam Kekukuhan Sekan dan Indeks Kemuluran (DI) spesimen yang dibaiki tidak mencapai nilai asal.

EFFECTIVENESS OF REPAIR METHOD USING HYBRID FIBER REINFORCED POLYMER FABRIC ON CONCRETE-FILLED DOUBLE SKIN STEEL TUBULAR COLUMNS EXPOSED TO FIRE

ABSTRACT

Concrete-filled double skin steel tubular (CFDST) column is becoming more popular nowadays due to its superior performance compared to conventional composite column and concrete-filled steel tubular (CFST) column. However, the use of this type of column is still limited to outdoor construction such as bridge piers and transmission tower where fire is not a main concern. Moreover, existing research studies on CFDST column only focused on fire performance and limited research studies can be found on residual strength of the CFDST column. Residual strength can be used to determine the most suitable repair method needed in order to retrofit the column. Therefore, this study aims to study the effect of different parameter towards residual strength of CFDST column. Among discussed parameter is thickness of outer steel tube (t_0) and fire exposure time. In addition, this study is also aim to determine the effectiveness of repair method using Single and Hybrid fiber reinforced polymer (FRP) of fire-damaged CFDST columns. CFDST columns were heated in accordance of ASTM E119-11: Standard Test Methods for Fire Tests of Building Construction and Materials until the temperature reached 600°C. Afterwards, the temperature was kept constant for two different durations, i.e., 60 minutes and 90 minutes. The specimen was then left to cool down to room temperature inside the furnace before it was taken out and repaired by Single and Hybrid FRP. The specimens were categorized into the following three groups: (1) unheated or control specimens, (2) heated and unrepaired and (3) heated and repaired. All specimens were subjected to axial compression loading until failure. The first and second category specimens failed by local outward buckling of outer steel tube, crushing of concrete and local buckling of inner steel tube; whereas, specimens in third category failed by rupture of FRP followed by similar local buckling and concrete crushing as those observed in first and second category specimens. Ultimate strength, secant stiffness and Ductility Index (DI) decreased as temperature of the specimen increased. The lost in secant stiffness of thinner CFDST

specimens exposed to 60 minutes of fire exposure time is similar to thicker CFDST specimens exposed to 90 minutes of fire exposure time regardless of its diameter. In addition, CFDST specimens exposed to 90 minutes of fire exposure time were more ductile than control specimen. RSI and secant stiffness increased with the increased in fire exposure time. Interestingly, the highest RSI achieved is only 22% which means the specimens were still able to carry more than 70% of its initial load after being exposed to 90 minutes of fire exposure time with only 3 mm thickness of outer steel tube. Repairing the fire-damaged CFDST columns with Single and Hybrid FRP are proven to improve ultimate compressive strength significantly. The increment in ultimate compressive strength is more pronounced in specimen with Hybrid FRP and thinner outer steel tube. The secant stiffness and Ductility Index (DI) of repaired specimens were however not able to be restored to those of control specimen.

CHAPTER ONE

INTRODUCTION

1.1 Background

Steel hollow structural section (HSS) are widely used in high rise building and as bridge pier because of their resistance to lateral movement in addition to its lighter weight compared with solid steel section and reinforced concrete columns (Lam & Williams 2004). HSS columns are also known to be very effective in resisting compression loads and are widely used especially in industrial building as framed structures (Kodur and Lie, 1995). Filling this hollow column with plain concrete leads to a number of benefits such as increasing the load bearing capacity of the columns, higher fire resistance compared with HSS without concrete filling, preventing spalling of concrete when subjected to fire due to existence of steel and finally, the presence of steel eliminates the need of formwork (Han et al. 2002; Han et al. 2003; Han et al. 2003) thus, leading to a rapid (Han et al. 2005; Yang et al. 2008) and economical construction (Tao et al. 2007). Over time, engineers began to use concrete-filled hollow steel column or also known as concrete-filled steel tubular (CFST) column to replace HSS due to the above mentioned advantages. Overalls, CFST column are proven to be more economical than HSS (Lam & Williams 2004).

The profile of concrete-filled double skin steel tubular (CFDST) column is similar to CFST except for the void in the middle of the column as shown in Figure 1. **1**. CFDST columns have been used bridge piers in Japan, owing to its good damping and energy absorption properties as well as light weight cross-section (Zhao et al. 2002). More recently, Han et al. (2014) reported that CFDST columns have been used as an electric pole in China (Figure 1.2). Unlike CFDST columns, CFST columns have been widely used in China for almost 50 years. Among the examples are 1) Ruifeng building in Hangzhou, 2) Zhaohua Jialing River Bridge and 3) Qianmen subway station in Beijing (Han et al. 2014). Furthermore, CFDST columns are used only in outdoor construction where fire is not the main concern.

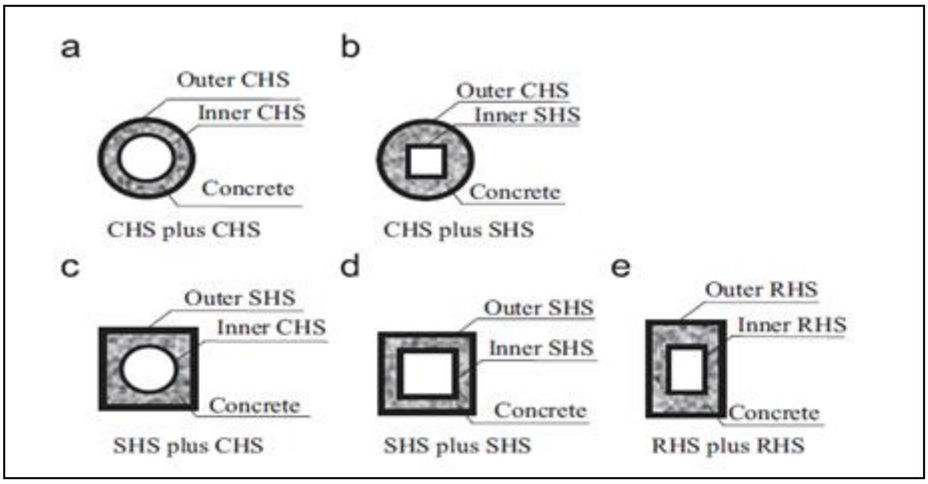

Figure 1. 1: Typical profile of concrete-filled double skin tubular column (Lu, Han, et al. 2010)

Figure 1.2: A CFDST pole in China (Han et al. 2014)

1.2 Problem Statement

Over the years, many types of composite columns have been proposed in order to keep up with advance and complex design of new buildings. However, the columns need to be tested for their fire endurance before they can be widely used and accepted in actual construction because fire is one of the primary design consideration in building construction (Chowdhury et al. 2007). So far, many literatures can be found on concrete-filled steel tubular (CFST) columns exposed to standard fire but very few focused on concrete-filled double skin tubular (CFDST) columns (Lu et al. 2010). Since there is increasing interest on the use of CFDST columns, the needs to study their behavior when exposed to fire and their behavior after exposure (i.e., post-fire behavior) has become very crucial. Understanding of the behavior under fire exposure is crucial for use by engineers not only for outdoor construction but also indoor construction with confidence.

In order to repair fire-damaged CFDST columns, engineer need to understand their residual strength after exposed to fire. Residual strength of damaged columns needs to be determined in order to predict the approximate strength gained after retrofitting the damaged columns. In the case of structural steel, the main concern of engineers is usually on residual deformation and distortion of steel members. According to Kodur et al. (2010), if the maximum temperature of steel do not exceed 550˚C, upon cooling steel retain almost 100% of its original room temperature strength. On contrary, 300˚C is taken as threshold temperature for concrete to start losing its compressive strength (Ingham 2009 and Liu 2009). Nevertheless, concrete in CFDST columns, acts as an insulator to inner steel tube. While outer steel tube is scarified during fire exposure, the load bearing capacity of the column shifts to concrete and inner steel tube. Therefore, in order to achieve this, temperature of inner steel tube needs to kept as low as possible.

There are many existing research studies on repairing or retrofitting of reinforced concrete columns and CFST columns with FRP, however, research study on CFDST columns is very limited. To date, only three research studies deals with repairing of fire-damaged CFST columns/beam-columns with FRP (Tao et al. 2008, Tao & Han 2007 and Tao et al. 2007). Two of them (Tao et al. 2008 and Tao & Han 2007) deals with repairing work using more than one layer of FRP. However, the above mentioned research studies used similar type of FRP which is CFRP and none of them is using Hybrid FRP. CFRP is known to increase the ultimate compressive strength; nevertheless GFRP can endure larger strain than CFRP (Talaeitaba et al. 2015). Combination of CFRP and GFRP will result in superior performance as repair method for fire-damaged CFDST columns. Therefore, there is an urgent need to study the post-fire behavior of CFDST columns for the purpose of repairing this kind of composite columns after being exposed to fire.

In CFDST columns, the thickness of the concrete is greatly reduced due to the presence of void in the middle of the columns. Therefore, it is expected that the temperature of the concrete is much higher than ordinary CFST or reinforced concrete columns. On the other hand, the presence of inner steel tube has proven to be of great benefit to CFDST column. Concrete acts as the insulator thus increases the fire resistance of CFDST column, enabling the steel to continuously resist loading even though the outer tube has already begun to lose its strength due to fire (Lu et al. 2011). Steel can withstand at least 15 to 20 minutes of load before reaching its critical temperature and starting to lose its strength (Schaumann et al. 2009). After that, the load will be transferred to concrete. In the case of CFDST, the load will be transferred to both concrete and inner steel tube. However, in depth study regarding the contribution of inner steel tube to the overall capacity of CFDST after fire exposure needs to be carried out. In addition to that, the role of concrete that acts as heat sink as well as insulator need to be understood.

There has been a contradictory finding concerning the role of thickness of outer steel tube of CFST when exposed to fire. Similar situation also applies to the case of CFDST. In a parametric study done by Kodur (1999), the influence of outer tube thickness was found to be very small to the point that it can be neglected. On the contrary, Yin et al.(2006) showed that thinner steel tube was able to slow down the heat transfer from the surface of exposure to concrete core. Therefore, this matter needs to be further investigated.

1.3 Research Objective

The aim of this research study is to investigate the residual strength of CFDST columns after exposure to fire. It is also aimed at investigating the performance of fire-damaged CFDST columns after repair. With these aims, the objectives of this research are established to be as follows:

1) To identify the relationship between thickness of outer steel tube and maximum temperature of concrete in concrete-filled double skin steel tubular (CFDST) columns exposed to fire
2) To determine the residual strength of concrete-filled double skin steel tubular (CFDST) columns exposed to fire
3) To determine the effectiveness of repair method using Single and Hybrid Fiber Reinforced Polymer (FRP) fabric on fire-damaged concrete-filled double skin steel tubular (CFDST) columns