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Application of Steel-tubed Concrete Structures in High-rise Buildings

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Abstract

Making full use of material strength, maintaining sufficient ductility of structural components, and ensuring simple and robust connections are crucial to the development of steel-concrete composite structures. The steel-tubed concrete structure uses thin-walled steel tube to provide confinement, so that the strength and ductility of the concrete core are improved. Meanwhile, the thin-walled steel tube is terminated at the beam-column joint to avoid the local buckling problem and simplify the connections between steel tube and RC members. A brief overview of the development of steel-tubed concrete structures is presented. Through the discussion on the structural behavior of steel-tubed concrete and the introduction of typical practical projects, the prospects for future research are highlighted.

Keywords: Steel-tubed concrete, Composite structure, Confinement, Structural behavior

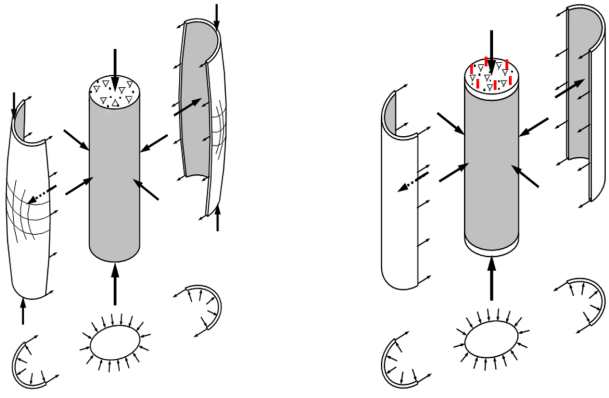
1. Introduction

Steel-Tubed Concrete (STC) is an innovative steel-concrete composite structure that uses steel tubes as transverse confinement rather than for directly carrying longitudinal loads. The main difference between a STC column and a traditional concrete filled steel tube (CFST) column lies in the end condition. As shown in Fig. 1, the axial load of a CFST column is carried by both the concrete and the steel tube, while in a STC column, the axial load is only applied to the concrete core at the column end with the steel casing sustaining no direct loads. As a result, the susceptibility to local buckling in STC is eliminated. It is worth noting that the confinement effect of STC columns is more effective compared to that of CFST columns. In practical projects, the steel tube in a STC column is disconnected at the beam-column joint to avoid sharing direct axial load, thus the concrete core generally needs to be reinforced by steel bars or structural steel sections to guanrantee the flexural stiffness and bending strength. The STC with reinforcing bars and steel sections are respectively known as steel-tubed reinforced concrete (STRC) and steel-tubed steel reinforced concrete (STSRC), as shown in Fig. 2. Since the steel carrying the axial load is embedded in the concrete, STC members also have excellent fire resistance. During a fire scenario, the frame column is not in the ultimate state of bearing capacity and the confining stress of the steel tube is relatively small. Even if the steel tube fails in fire, the load-carrying capacity of the infilled reinforced concrete or steel reinforced concrete still exists. Therefore, for a reasonably designed STC column, no additional fire protection measures are required for the steel tubes.

Owing to the special configurations and load-carrying mechanism, the STC can solve some of the problems in the development of composite structures, and has significant advantages considering following aspects:

(1) Simplification of column-beam connections

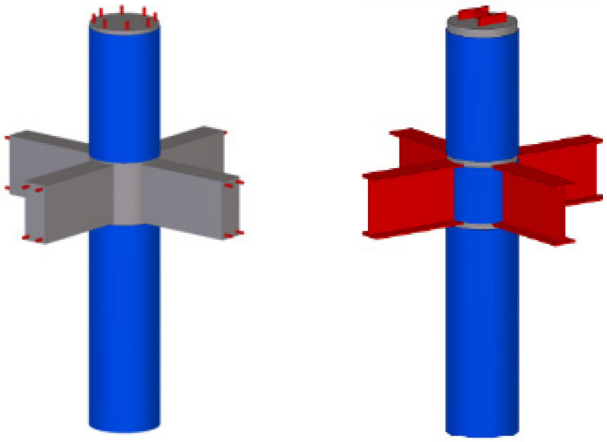
In the STC system, the design of connections is significantly simplified and much flexible since the steel tube does not need to be used for transferring axial loads in the beam-column connections, and the embedded steel can be configured into different forms. When connecting with RC beams, it is better to use STRC columns accompanied with the same construction process as pure RC structure. The STSRC columns are preferred when connecting with steel beams,



(a) CFST (b) STC

Figure 1. Load-carrying mechanism of CFST and STC.

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(a) STRC (b) STSRC

Figure 2. Two types of STC using in practice.

which avoids the complexity of arrangement of reinforcing bars and steel sections. What's more, through some simple methods, such as increasing the stirrups, thickening the steel tube in the joint zone, etc., the strength of the connection can be effectively enhanced to meet the design principle of "strong joint".

(2) Improvement in seismic behavior of short RC columns

Short RC columns are sometimes unavoidable in structural design, which are vulnerable to brittle shear failure during earthquake. By contrast, the seismic behavior of short STC columns is significantly improved because of the external steel tube. On one hand, the shear strength of the short column is enhanced by direct shearing of the steel tube. On the other hand, the confinement of the steel tube greatly improves the ductility of the concrete core and avoids brittle failure.

(3) Application of high-strength materials

In the potential plastic region of a STC column where the steel tube is disconnected, the longitudinal compressive stress of the steel tube is relatively small and the confinement induced by lateral tensile stress is maximized. In addition, free from local buckling of thin-walled steel tube in STC enables the application scope of steel tube with high yielding strength. Meanwhile, the effectiveness in confinement in STC columns significantly improves the ductility of the infilled concrete, which promotes the application of high/ultra-high strength concrete (HSC/UHSC) in buildings in seismic regions.

2. Development of STC

2.1. As a contrast specimen in CFST experiments

The prototype of STC can be traced back to the investigations on the bond behavior of CFSTs with different loading modes by Gardner et al (1967), in which the reference specimens loaded on the concrete core were STC columns. Some similar investigations were carried out by Prion (1994), Johansson (2002), Fam (2004), Han (2005), Xiong (2017) et al., and their studies showed that the end loading condition had little influence on the axial strength of CFST columns due to the friction between the concrete and the steel tube. To further enhance the tube confinement to the concrete core, Orito (1987), Lahlou (1999), O'shea (2000), Peter (2004) et al. focused on the behavior of unbonded STC columns where antifriction material was applied to the inner surface of the steel tube, and concluded that the unbonded STC specimens had higher axial compressive capacity and ductility than CFST specimens, but the elastic stiffness was greatly reduced. These investigations imply that the STC is an effective composite mode of steel tube and concrete that maximizes the potential strength and deformation capacity of materials. However, studies within this period mainly focus on STC members filled with plain concrete, which is not suitable for practical projects subjected to complex load conditions.

2.2. Retrofit for non-ductile RC piers or frame columns

One of the applications of STC concept is the retrofit for non-ductile RC piers or frame columns, which is also known as steel jacketed reinforced concrete (SJRC). In 1985, Priestley et al. (1985) studied the seismic behavior of RC bridge piles with continuous and discontinuous steel tubes, concluded that the piles with discontinuous steel tubes exhibited excellent seismic performance and their strength and stiffness had almost no reduction under cyclic loading. Since then, Priestley et al. (1994a; 1994b) further compared the seismic behavior of four circular RC piers and four retrofit piers with steel tubes not extending into the cap beam and foundation. The results showed that all the RC piers suffered from brittle shear failure and low ductility, while the steel jacketed piers exhibited good seismic performance with displacement ductility factors greater than 8. Aboutaha et al. (1996) combined drilling bolts with rectangular steel jackets to enhance the confinement effect of non-ductile RC columns. Xiao et al. (2003) developed a retrofit method using welded rectilinear steel jackets and stiffeners, which significantly improved the strength and ductility of square and rectangular RC columns. Lubiewski et al. (2006) proposed a method to increase the ductility of column-bent cap connections of Alaska bridges by disconnecting the semi-embedded steel tubes with a 51mm wide gap from the bent cap and enlarging the bent caps in the joint region. It can be seen that the jacketing retrofit using steel tube is an effective method to provide additional transverse confinement to increase the load-carrying capacity and to improve the ductility of an existing deficient RC column.

2.3. Steel-tubed reinforced concrete (STRC) in building structures

In 1985, Tomii et al. (1985) firstly proposed the concept of STRC (also known as tubed RC or super RC) and applied it to building structures to prevent shear failure and to

improve the ductility of short columns in RC frame structures or boundary columns of shear walls. Sun et al. (1997) conducted both experimental and theoretical investigations on the earthquake-resisting performance of square STRC columns, in which the influences of axial load ratio, wall thickness of steel tube and shear span ratio were discussed. Another study of Sun et al (2004). on the cyclic response of STRC columns using the HSC indicated that the confinement from the steel tube could greatly improve the ductility of HSC columns. Aboutaha (1999) investigated the cyclic response of rectangular STRC columns and concluded that the rectangular STRC columns exhibited higher lateral strength and ductility than traditional RC columns. Fukuhara and Sun (2008) tested 8 one-bay, one-story square STRC frames using the HSC and concluded that the tube confinement effectively improved the seismic behavior of HSC frames.

Over the past 15 years, the STRC column has attracted a broad attention in China due to its superior structural behavior. Zhang et al. (2008) focused on the axial and seismic behavior of square steel tube confined reinforced concrete columns, in which the confining mode of the tube was discussed and an analytical fiber model was developed. Han et al. (2009) also conducted a test on thin-walled steel tube confined concrete column to RC beam joints subjected to cyclic loading, which showed good seismic performance. Yang et al. (2015) investigated the post-fire behavior of slender STRC columns and proposed a simplified design method for predicting the residual load bearing capacity. Since 2010, Zhou and Liu et al. have conducted a series of experimental and theoretical investigations on the behavior of STRC members (Zhou et al., 2010a; Wang et al., 2015; Zhou et al., 2016) and their beam-to-column joints (Zhou et al., 2017) and proposed a design theory. Moreover, their study outcomes have been utilized in more than 20 different construction projects in China.

2.4. Steel-tubed steel reinforced concrete (STSRC) in building structures

To provide more effective confinement to the concrete core and simplify the construction of traditional steel reinforced concrete (SRC) columns, Zhou et al. (2009) proposed the steel-tubed steel reinforced concrete (STSRC) by replacing the reinforcing cage in the SRC column with an outer thin-walled steel tube. The seismic behavior of STSRC columns was investigated and compared with SRC columns by Zhou and Liu (2010b). The results indicated that the shear strength, ductility, plastic deformation capacity, and energy dissipating capacity of STSRC columns were much higher than those of SRC columns. Gan et al. (2011) tested four STSRC and two SRC slender columns under combined constant axial compression and lateral cyclic loads. Their test results indicated that the ultimate storey drift ratio of STSRC columns was nearly four times as that of SRC columns due to the effective confinement provided by the steel tube. Qi et al. (2011) studied the behavior and strength of axially loaded STSRC columns, indicating that the effect of height to diameter/width ratio of the separated tubes on the failure mode and strength of the columns was insignificant. Liu and Zhou et al. (Liu et al., 2015; Zhou et al., 2015; Wang et al., 2016) studied the behavior of STSRC columns subjected to eccentric compression and established the axial load versus moment interaction diagrams for these columns. They also found that the ultimate compressive strain of the confined concrete was improved. More recently, the effects of shear studs on the seismic behavior of STSRC columns failed in flexural mode have been studied (Zhou et al., 2017; Liu et al., 2018). It was found that the shear studs attached on the steel shape had limited influence on the peak lateral load, ductility, and deformation capacity of STSRC columns. In addition, Zhou et al. (Zhou et al., 2019; Chen et al., 2019) have proposed some innovative beam-column connections for STSRC structures and examined their static and seismic performances.

3. Applications of STC in China

During 1980s~1990s, the main application of STC was for the retrofit of existing structures in seismic regions, while it was rarely used in newly-built buildings. Since the 21st century, the concept of STC has received extensive attention in China. Researchers and engineers found that the STC column inherits the advantages of conventional CFST and SRC composite columns, e. g., high bearing capacity, good ductility, and excellent fire resistance, and using STC columns can effectively avoid the complexity of connecting traditional composite column to RC beam system. Therefore, STC has been well promoted in China and more than 40 projects in China have adopted the STC technique. Some typical application examples are introduced as follows.

(1) Dalian Petroleum Building

Dalian Petroleum Building is the headquarters of China National Petroleum Corporation in the northeast of China. It was completed in 2014. Its main tower reaches 176m in height with 4 basement floors and 43 stories above ground (Fig. 3). The lateral system of this building consists of a RC core and an external frame-truss hybrid structure where the underground 4 floors and the bottom 3 floors above ground are frames, and the 4th to 43th floors are cross trusses. In order to reduce the cost, the external truss system is required to use reinforced concrete. However, the cross-section of the truss inclined column is limited because of the facade requirements of the building, resulting in a very high axial load ratio of the RC truss members which cannot meet the design requirement. Considering the factors such as project cost and connection construction difficulties, the engineers of this project adopted STRC components to improve the bearing capacity of the external truss system. Some model tests were carried out to show the effectiveness

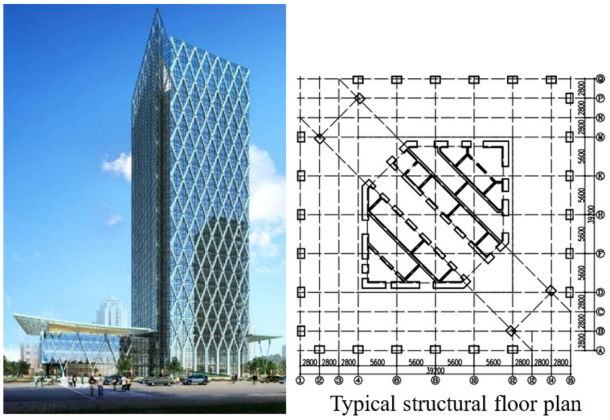


Figure 3. Dalian Petroleum Building.

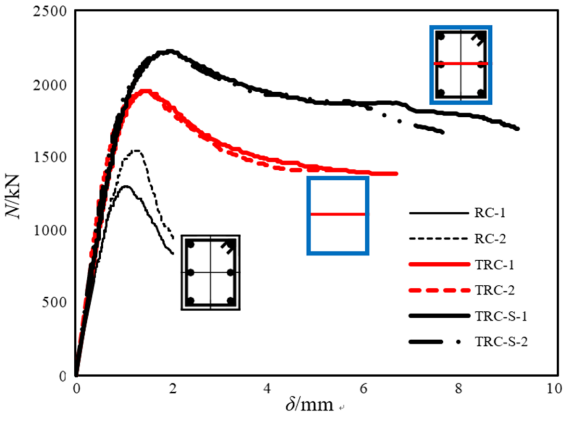


Figure 4. Model tests.

of STRC on structural performance improvement, as shown in Fig. 4.

(2) Qingdao Haitian Center Project (T1 and T3 towers)

Qingdao Haitian Center Project consists of three super-high-rise towers, podium houses and five basement floors, in which the first tower (T1) is 210m high with 42 floors above ground, the second tower (T2) is 369m high with 73 floors above ground, and the third tower (T3) is 245m high with 56 floors above ground (Fig. 5). All the towers adopt a frame-core wall system and some of the frame columns in T1 and T3 are STRC columns. Fig. 6 shows the STRC columns in construction. The application of STRC significantly reduced the amount of steel used in this project and improved the construction efficiency, resulting in a saving of direct and indirect costs.

4. Research trends for STC

4.1. Using high-performance materials in STC

The application of high-performance materials such as ultra high performance concrete (UHPC) and stainless steel in construction has received much attention owing to their superiority in mechanical properties and long-term

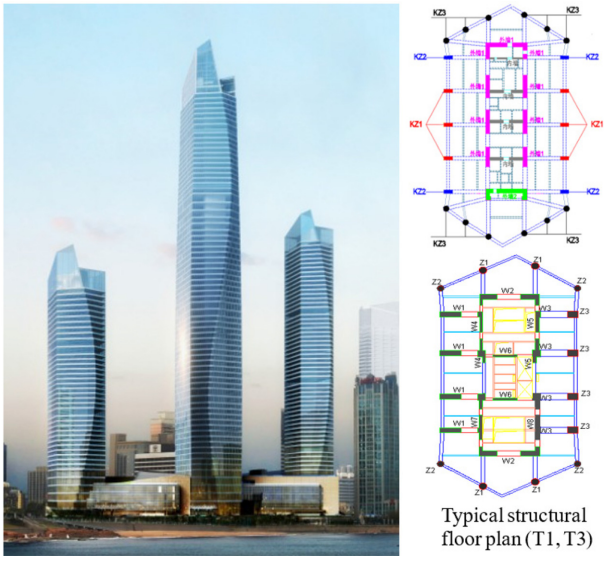


Figure 5. Qingdao Haitian Center Project.



Figure 6. STRC columns in construction.

performance over conventional materials. Using high-performance materials in STC will achieve even better results, since the strength of both the steel and concrete can be fully utilized in a ductile manner in this composite mode. Recently, Hoang et al. (2019) have conducted an experiment to study the structural performance of steel-tubed UHPC. The analysis of test results demonstrated that the addition of steel fibers had negligible effect on the response of axial load versus axial strain and the impact of steel tube thickness and the confinement index on the strength and ductility was more dominant. Guo et al. (2019) applied stainless steel in STC columns and compared them with CFST columns using stainless steel. The test results indicated that the confinement provided by stainless steel tube in STC columns was larger than that in CFST columns, and the compressive capacity of core concrete was improved significantly.

4.2. Innovations in STC cross sections

Until now, most of the investigations have focused on STC members with circular or square cross sections, and a few on rectangular section. However, in some specific projects, STC columns with innovative cross sections have greater advantages over those with conventional cross sections. The authors' research group has conducted some preliminary investigations on STC columns with circular hollow cross section and dumb-bell cross section.

(1) STRC columns with circular hollow cross section

Columns with hollow cross section have several benefits over the solid ones, including higher strength-to-mass and stiffness-to-mass ratios, reduction of vertical load and inertia actions applied to the foundation, saving of materials and equipment during construction. The hollow RC columns with single layer of reinforcement may fail in brittle mode due to insufficient confinement of concrete (Hoshikuma et al., 2000). Using two layers of longitudinal reinforcement connected by extensive stirrups and cross ties can result in an improvement of the ductility of hollow RC columns, but meanwhile, the densely arranged reinforcement also increases the construction time and cost. The hollow STRC column might be a good solution to these problems. As shown in Fig. 7, the hollow STRC column under axial compression fails in a ductile manner, regardless of using single or double layers of reinforcement. Although the peak load of the single-layer STRC specimen is reduced by about 9% than that of double layers specimen, it is still 32% higher than the nominal capacity of the hollow RC core. What's more, the stiffness and ductility of the single-layer specimen are similar to those of the double-layers specimen.

(2) STRC columns with dumb-bell cross section

The dumb-bell STRC (Fig. 8) is proposed in consideration of the following advantages: 1) the dumb-bell cross section has a large moment of inertia, and the RC cores at the two flanges are effectively confined by the steel tubes, resulting in high bearing capacity against axial compression and bending moment, as well as good rotation ability; 2) the steel web plates significantly improve the shear strength and energy consumption ability of short piers by forming a diagonal tensile stress field. Therefore, the dumb-bell STRC will be a promising application prospect in short piers or ultra-short piers that are subjected to a large amount of seismic forces during earthquakes. Fig. 9 shows the

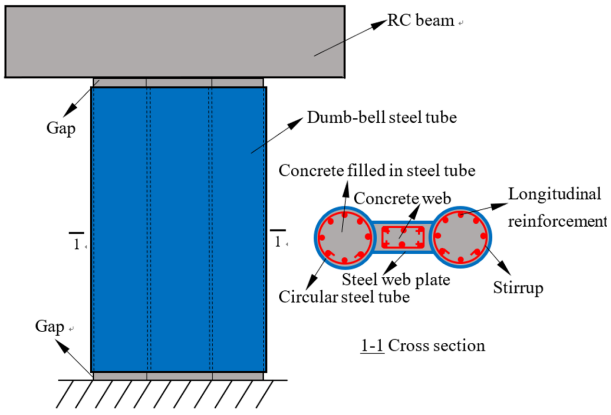


Figure 8. The dumb-bell STRC.

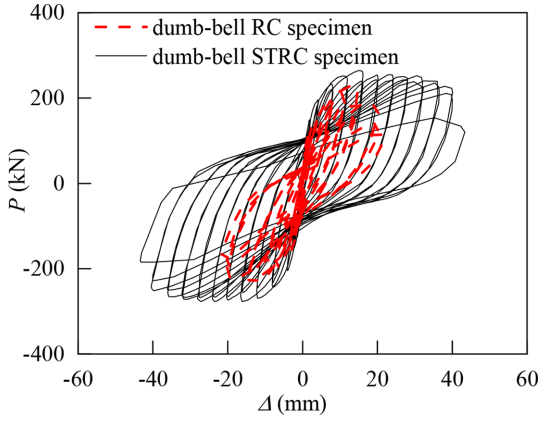


Figure 9. Comparison of dumb-bell RC and STRC.

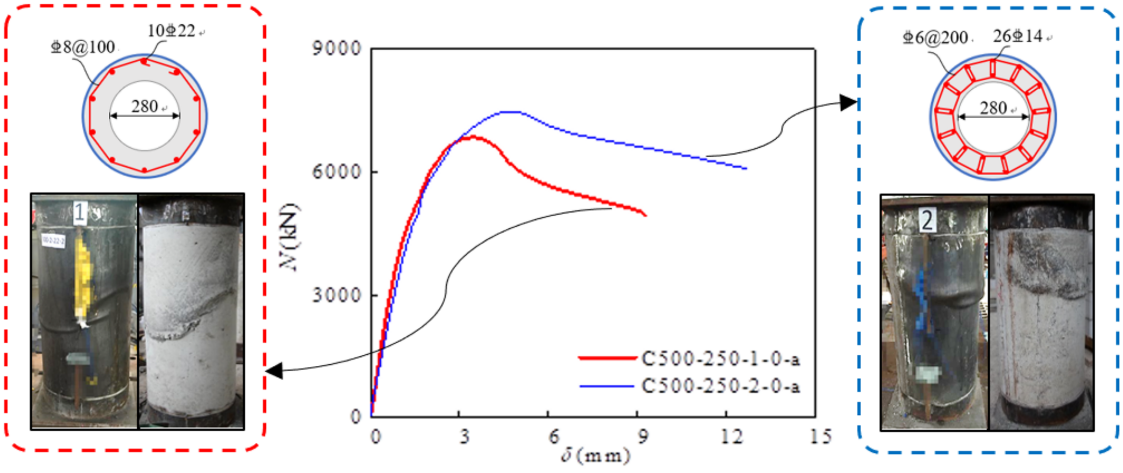


Figure 7. Test of hollow STRC columns.

comparison of test results for dumb-bell STRC and dumb-bell RC specimens. It can be concluded that the encasing dumb-bell steel tube effectively changes the failure mode of the inner RC core from shear failure to bending failure and significantly enhances the seismic performance of the specimens.

5. Conclusions

This paper presented an overview on previous research with respect to the steel-tubed concrete and introduced some typical projects in China, which intended to provide an outline of the characteristics and development of this composite structure. The followings can be summarized from the aforementioned:

(1) The STC is an effective composite mode of steel tube and concrete, characterized by high load-carrying capacity, sufficient ductility, good fire resistance, simple connection construction process, and reasonable costs.

(2) Numerous studies on STC components have been conducted and design theories have been developed accordingly. However, the research on STC connections and systems is still insufficient, and the corresponding design theory is also in urgent need.

(3) As an effective alternative to conventional RC structures or composite structures, the STC is suitable to be used in the high-rise buildings, heavy-load or large-span structures.

(4) It is promising to use high-performance materials and innovative cross sections in the STC structures.

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