RGC Ref.: N_PolyU520/16 NSFC Ref. : 51661165016
(please insert ref. above)

The Research Grants Council of Hong Kong
NSFC/RGC Joint Research Scheme
Joint Completion Report

(Please attach a copy of the completion report submitted to the NSFC by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

Square Concrete-Filled Steel Tubular Columns with Internal High-Strength Steel Confinement

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. Jin-Guang TENG	Prof. Peng FENG
Post	Chair Professor of Structural Engineering	Professor
Unit / Department / Institution	Civil and Environmental Engineering / The Hong Kong Polytechnic University	Civil Engineering / Tsinghua University
Contact Information	cejgteng@polyu.edu.hk	fengpeng@tsinghua.ed.cn
Co-investigator(s) *(with title and institution)*	Dr Guan LIN	Dr Shi CHENG

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	1 Jan 2017		
Project Completion date	31 Dec 2020	30 Jun 2021	18 Dec 2020
Duration *(in month)*	48	54	18 Dec 2020
Deadline for Submission of Completion Report	31 Dec 2021	30 Jun 2022	18 Dec 2020

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1) To optimise the combinations of materials in square CCFST columns to achieve excellent performance in both strength and ductility;
2) To establish stress-strain models for the two regions of confined concrete in square CCFST columns;
3) To develop theoretical models and a design procedure for square CCFST columns.

5.2 Revised Objectives

N.A.

6. Research Outcome

Major findings and research outcome
(maximum 1 page; please make reference to Part C where necessary)

Findings Related to Objective 1:

(1) HSSS-confined concrete columns fail by the rupture of steel spiral near the column mid-height; the presence of an internal HSS spiral significantly enhances both the ductility and strength of concrete columns.
(2) None of the existing stress-strain models is able to accurately predict the stress-strain behaviour of HSSS-confined concrete with practically wide ranges of parameters, suggesting the need for the development of a more robust and reliable stress-strain model for HSSS-confined concrete.
(3) The square CCFST columns tested in the present study experienced large axial deformation; several instances of rupture of the internal steel spiral occurred after the peak load, accompanied by slight drops in the axial load. The presence of an internal HSS spiral significantly enhances both the load-carrying capacity and ductility of a CFST column.
(4) The load-carrying capacity of a CCFST column is much larger than the algebraic sum of the load-carrying capacities of the HST, the HSSS-confined concrete core, and the sandwiched concrete between the two in an isolated state.

Findings Related to Objective 2:
(1) The developed 3D and 2D FE models employing Yu et al.'s constitutive model (2010)

provided reasonably accurate predictions for the HSSS-confined concrete columns tested in the present study. A uniform confinement region (UCR), in which the axial stresses are generally uniformly distributed, in an HSS-confined concrete column section was identified based on the results of the 2D FE model employing Yu et al.'s constitutive model (2010). In addition, the 3D and 2D FE models employing the newly developed plasticity constitutive model also provided reasonably accurate predictions for the HSSS-confined concrete columns tested in the present study.

(2) The proposed analysis-oriented stress-strain models provided reasonably accurate predictions for the stress-strain curves, the peak axial stresses and the corresponding strains, and the ultimate axial strains of all tested HSSS-confined concrete columns.

(3) The proposed design-oriented stress-strain model was demonstrated to perform the best among the existing models of the same type for HSS-confined concrete.

(4) The 3D FE model employing Yu et al.'s constitutive model (2010) for the core concrete and Tao et al.'s model (2013) for the sandwiched concrete was found to provide reasonably accurate predictions for the tested CCFST columns. In addition, the 3D FE model employing the newly developed plasticity constitutive model was also found to provide reasonably accurate predictions for the tested CCFST columns without the need to use the empirical model of Tao et al. (2013).

Findings Related to Objective 3:

(1) The developed 3D FE model employing Yu et al.'s constitutive model (2010) for the core concrete and Tao et al.'s model (2013) for the sandwiched concrete was demonstrated to be reasonably accurate in predicting the behaviour of the CCFST columns under monotonic eccentric compression tested at Tsinghua University.

(2) The proposed design equations were shown to be reasonably accurate in predicting the load-carrying capacities of CCFST columns under concentric or eccentric compression.

References:

Yu, T., Teng, J. G., Wong, Y. L., & Dong, S. L. (2010). Finite element modeling of confined concrete-II: Plastic-damage model. *Engineering structures*, 32(3), 680-691.

Tao, Z., Wang, Z. B., & Yu, Q. (2013). Finite element modelling of concrete-filled steel stub columns under axial compression. *Journal of Constructional Steel Research*, 89, 121-131.

Potential for further development of the research and the proposed course of action
(maximum half a page)

A demonstration project of a building or a bridge using the proposed CCFST columns is of great importance to the future development of CCFST columns.

7. The Layman's Summary

(describe <u>in layman's language</u> the nature, significance and value of the research project, in no more than 200 words)

Concrete-filled steel tubular (CFST) columns have been extensively studied and widely used in practice. Existing research has shown that rectangular CFST columns are much less ductile than their circular counterparts, particularly when high-strength concrete (HSC) and thin/high-strength steel (HSS) tubes are used, which is a major concern in structures designed to resist seismic loading. This project was undertaken to develop a new form of high-performance rectangular CFST columns through the use of HSS spirals with a yield stress greater than 1,000 MPa to provide strong confinement to the infilled concrete; this new form of columns, referred to as rectangular confined concrete-filled steel tubular (CCFST) columns, was expected to be far superior to CFSTs in both load-carrying capacity and ductility. A systematic experimental study including monotonic concentric compression tests, cyclic concentric compression tests, monotonic eccentric compression tests, and cyclic lateral loading tests was carried out on CCFST columns through a collaborative research programme between The Hong Kong Polytechnic University and Tsinghua University. The test results demonstrated that the presence of an internal HSS spiral significantly enhances both the load-carrying capacity and the ductility of a CFST column. Advanced finite element modelling and theoretical analyses were conducted to extrapolate the test results, based on which design equations for the load-carrying capacity of CCFST columns were developed.

Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research project

(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

*Please fill in the following table for **each** publication.*

i. **The Latest Status of Publication**	**Published**	**Accepted but not yet published^**	**Under Review^**	**Under Preparation^** (optional)
	√			
^ For not-yet-published publication, items (vi) to (xxvi) can be left blank if information is not yet available.				
ii. **Author(s)** *(denote the corresponding author with an asterisk*)*	J.G. Teng*, J.J.Wang, Guan Lin, J. Zhang and P. Feng			
iii. **Contact information of the corresponding author(s)**	Name	ORCID (if any)	Email	
	J.G. Teng	0000-0001-5161-4502	cejgteng@polyu.edu.hk	
iv. **Title (in published language)**	Compressive behavior of concrete-filled steel tubular columns with internal high-strength steel spiral confinement			
v. **Title in other language (if any)**				
vi. **Full name of journal/book**	Advances in Structural Engineering			
vii. **Volume**	24			
viii. **Issue number**	8			
ix. **Pages**	1687-1708			
x. **Article Number**				
xi. **Other necessary publishing details (if any)**				
xii. **Year of publication / Year of acceptance**	2021/2020			
xiii. **Original language of the publication**	English			
xiv. **Publisher or equivalent**	SAGE			
xv. **Digital object identifier (DOI)**	10.1177/1369433220981656			

xvi. **Abstract (as set out in the journal article)**	Concrete-filled steel tubular (CFST) columns have been extensively studied and widely used in practice. Existing research has shown that non-circular CFST columns is much less ductile than their circular counterparts, particularly when thin/high strength steel (HSS) tubes and high-strength concrete are used. To address this problem, a new form of CFST columns has recently been proposed by the first author. The new column consists of a steel tube filled with concrete that is confined with HSS spiral reinforcement typically with a yield stress exceeding 1000 MPa. These columns, referred to as confined concrete-filled steel tubular (CCFST) columns, also maintain the ease for connection to CFST or steel beams. This paper presents the results of a series of concentric axial compression tests on such columns of square cross-section to demonstrate their advantages. The experimental program included 13 CCFST columns, four CFST columns without internal spiral confinement, two hollow steel tube (HST) columns, and 11 circular HSS spiral-confined concrete columns. Three different compressive strengths and three HSS spiral pitches were examined in the experimental program. The CFST columns, HST columns, and HSS spiral-confined concrete columns were all tested under axial compression to gain a good understanding of the confinement mechanism in a CCFST column. The test results show that the new columns possess much greater ductility than those without internal spiral confinement, although the use of HSS spirals increases the steel volume by only a small percentage. It is also shown that the axial load-axial strain curve of a CCFST column can be conservatively predicted by summing the axial load-axial strain curves of the hollow steel tube without local buckling, the HSS spiral-confined concrete core, and the sandwiched concrete between the two.
xvii. **Open access status** *(Immediate open access / Embargoed open access / Non-open access)*	Non-open access
xviii. **Embargo end date (month, year) (if any)**	
xix. **Accessible from the institutional repository** *(Yes or No)*	No
xx. **Hyperlink to the publication (the link to institutional repository if preferred) (if any)**	https://journals.sagepub.com/doi/full/10.1177/1369433220981656
xxi. **Other affordable means for access (if any)** *(Individual article purchase offered by the publisher / Access through the university libraries (on membership) / Contacting the corresponding author(s))*	Individual article purchase offered by the publisher / Access through the university libraries (on membership) / Contacting the corresponding author(s)
xxii. **Article Processing Charge (APC) for publishing the article in an open access journal*** *(Required / Not required / Not applicable)*	Not applicable
xxiii. **Total amount of associated APC* (in Hong Kong dollars, if any)**	
xxiv. **Amount of associated APC paid by university* (or universities, in case it is borne by more than one university) (in Hong Kong dollars, if any)**	
xxv. **Copyright retained by author(s)** *(Yes or No)*	Yes
xxvi. **Number(s) and jurisdiction(s) of the granted patents associated with the article (if any)**	
xxvii. **Submitted to RGC (indicate the year ending of the relevant progress report)**	No

xxviii. **Attached to this report** *(Yes or No)*	Yes
xxix. **Acknowledged the support of RGC** *(Yes or No)*	Yes

<table>
<tr><td rowspan="2">i. The Latest Status of Publication</td><td>Published</td><td>Accepted but not yet published^</td><td>Under Review^</td><td>Under Preparation^ (optional)</td></tr>
<tr><td>√</td><td></td><td></td><td></td></tr>
<tr><td colspan="5">^ For not-yet-published publication, items (vi) to (xxvi) can be left blank if information is not yet available.</td></tr>
<tr><td>ii. Author(s)
(denote the corresponding author with an asterisk*)</td><td colspan="4">B.T. Zheng and J.G. Teng*</td></tr>
<tr><td rowspan="2">iii. Contact information of the corresponding author(s)</td><td>Name</td><td colspan="2">ORCID (if any)</td><td>Email</td></tr>
<tr><td>J.G. Teng</td><td colspan="2">0000-0001-5161-4502</td><td>cejgteng@polyu.edu.hk</td></tr>
<tr><td>iv. Title (in published language)</td><td colspan="4">A plasticity constitutive model for concrete under multiaxial compression</td></tr>
<tr><td>v. Title in other language (if any)</td><td colspan="4"></td></tr>
<tr><td>vi. Full name of journal/book</td><td colspan="4">Engineering Structures</td></tr>
<tr><td>vii. Volume</td><td colspan="4">251</td></tr>
<tr><td>viii. Issue number</td><td colspan="4"></td></tr>
<tr><td>ix. Pages</td><td colspan="4"></td></tr>
<tr><td>x. Article Number</td><td colspan="4">113435</td></tr>
<tr><td>xi. Other necessary publishing details (if any)</td><td colspan="4"></td></tr>
<tr><td>xii. Year of publication / Year of acceptance</td><td colspan="4">2022/2021</td></tr>
<tr><td>xiii. Original language of the publication</td><td colspan="4">English</td></tr>
<tr><td>xiv. Publisher or equivalent</td><td colspan="4">Elsevier</td></tr>
<tr><td>xv. Digital object identifier (DOI)</td><td colspan="4">10.1016/j.engstruct.2021.113435</td></tr>
</table>

xvi. **Abstract (as set out in the journal article)**	Structural members with confined concrete are becoming increasingly popular in civil engineering applications because of their superior strength and ductility. In these structural members, the concrete is subjected to dilation-induced (passive) lateral compressive stresses from the confining device (e.g., a steel tube). Existing research has led to theoretical models that predict closely the stress–strain behavior of concrete under uniform confinement (e.g., concrete in circular steel tubes under concentric axial compression), but theoretical models with a similar capability have not been achieved for the more common situation of concrete under non-uniform confinement (e.g., concrete in rectangular steel tubes). This paper presents a three-dimensional (3D) plasticity constitutive model that is accurate in predicting the stress–strain behavior of concrete in various scenarios of confinement. In the proposed model, a well-established open strength surface with associated open yield surfaces is combined with a hardening/softening rule compatible with both plastic volumetric compaction and dilation. In addition, a novel potential surface with a triangle-like deviatoric trace is proposed and calibrated with available experimental data of non-uniformly confined concrete. The implementation of the constitutive model in finite element analysis with an enhanced stress-return algorithm suitable for the novel potential surface is explained. While the focus of the present work is on monotonic compression-dominated loading, the model can be combined with fracture and damage theories to depict the behavior of concrete under tension-dominated and cyclic loading conditions. The performance of the proposed model is evaluated by comparing its predictions with a wide range of experimental data covering uniform active, uniform passive, and non-uniform passive confinement conditions, which demonstrates the capability and high accuracy of the proposed model.
xvii. **Open access status** *(Immediate open access / Embargoed open access / Non-open access)*	Embargoed open access
xviii. **Embargo end date (month, year) (if any)**	2024-01-15
xix. **Accessible from the institutional repository** *(Yes or No)*	Yes
xx. **Hyperlink to the publication (the link to institutional repository if preferred) (if any)**	https://ira.lib.polyu.edu.hk/handle/10397/91612?mode=simple
xxi. **Other affordable means for access (if any)** *(Individual article purchase offered by the publisher / Access through the university libraries (on membership) / Contacting the corresponding author(s))*	Individual article purchase offered by the publisher / Access through the university libraries (on membership) / Contacting the corresponding author(s)
xxii. **Article Processing Charge (APC) for publishing the article in an open access journal*** *(Required / Not required / Not applicable)*	Not applicable
xxiii. **Total amount of associated APC* (in Hong Kong dollars, if any)**	
xxiv. **Amount of associated APC paid by university* (or universities, in case it is borne by more than one university) (in Hong Kong dollars, if any)**	
xxv. **Copyright retained by author(s)** *(Yes or No)*	No
xxvi. **Number(s) and jurisdiction(s) of the granted patents associated with the article (if any)**	

xxvii. **Submitted to RGC (indicate the year ending of the relevant progress report)**	No
xxviii. **Attached to this report** *(Yes or No)*	Yes
xxix. **Acknowledged the support of RGC** *(Yes or No)*	Yes

* *This information will be for the Secretariat's reference only and not be disclosed to the public.*

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

Month/Year/Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
12/2016/Hong Kong	Concrete-filled steel tubular columns with Internal confinement by high strength steel spirals	Eighth International Conference on Steel and Aluminium Structures	No	Yes	No	No
12/2021/Online	A 3D plasticity model for concrete and its application to concrete under non-uniform FRP confinement	10th International Conference on FRP Composites in Civil Engineering	No	Yes	Yes	No

10. Student(s) trained *(Please attach a copy of the title page of the thesis.)*

Name	Degree registered for	Date of registration	Date of thesis submission
Jiji Wang	PhD	08-2013	04-2020

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*

N.A.

12. Statistics on Research Outputs *(Please ensure the summary statistics below are consistent with the information presented in other parts of this report.)*

	Peer-reviewed journal publications	Conference papers	Scholarly books, monographs and chapters	Patents awarded	Other research outputs (Please specify)
No. of outputs arising directly from this research project [or conference]	2	2			