Advances in Steel Structures (ICASS 2020)

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Siu-Lai Chan
*Department of Civil and Environment Engineering, The Hong Kong Polytechnic University*

Zhi-Xiang Yu
*School of Civil Engineering, Southwest Jiaotong University*

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## Table of Contents

**Preface**

**Volume I**

### Keynote Lectures

- SEISMIC DESIGN AND ANALYSIS OF STEEL PANEL DAMPERS FOR STEEL FRAME BUILDINGS  
  K.C. Tsai* and C.H. Hsu
  2
- THE CONTINUOUS STRENGTH METHOD - REVIEW AND OUTLOOK  
  L. Gardner*, X. Yun and F. Walport
  15

### Assembled Structure

- A NEW TYPE OF ASSEMBLED THERMAL INSULATION DECORATIVE WALL SYSTEM FIRE RESISTANCE STUDY  
  C.L. Wang*, S.R. Jiang, B.C. Li and S. Li
  28
- RESEARCH ON SEISMIC BEHAVIOR OF ASSEMBLED BEAM-COLUMN JOINTS WITH C-SHAPED CANTILEVER SECTION  
  38
- EXPERIMENTAL STUDY AND NUMERICAL ANALYSIS ON SEISMIC BEHAVIOR OF ASSEMBLED BEAM-COLUMN JOINTS WITH C-SHAPED CANTILEVER SECTION  
  59
- RESEARCH ON DYNAMIC LOAD CARRYING CAPACITY OF ASSEMBLED INTERNAL STIFFENING WIND TURBINE TOWER BASED ON MULTI-SCALE MODELING  
  F.W. Wang*, K.M. Zhou and S.T. Ke
  82

### Bridge

- SOUND RADIATION OF ORTHOTROPIC STEEL DECKS SUBJECTED TO MOVING VEHICLE LOADS  
  Y.C. You and X. Zhang*
  93
- POWER FLOW ANALYSIS OF BRIDGE U-RIB STIFFENED PLATES BASED ON THE CONCEPT OF STRUCTURAL INTENSITY  
  D.R. Kong and X. Zhang*
  102
VIBRO-ACOUSTICAL PERFORMANCE OF A STEEL BEAM OF GROOVE PROFILE: FIELD TEST AND NUMERICAL ANALYSIS
Z.Q. Liu and X. Zhang*

PERFORMANCE OPTIMIZATION OF A STEEL-UHPC COMPOSITE ORTHOTROPIC BRIDGE WITH INTELLIGENT ALGORITHM
Z. Xiang*, Z.W. Zhu, J.Y. Cai and J.P. Li

LOAD-CARRYING CAPACITY OF DAMAGED STEEL GIRDER
E. Yamaguchi*, T. Amamoto, D. Nakashima and K. Shiraishi

Cold-Formed

EXPERIMENTAL STUDY ON MECHANICAL PROPERTIES OF STRAW BALE
H.S. Sun, B.Z. Cao*, Z.H. Chen

A SURROGATE MODEL TO ESTIMATE THE AXIAL COMpressive CAPACITY OF COLD-FORMED STEEL OPEN BUILT-UP SECTIONS
S.R. Kho*, A.L.Y. Ng, D.T.W. Looi

LOCAL BUCKLING BEHAVIORS OF COLD-FORMED CIRCULAR HOLLOW SECTIONS HIGH STRENGTH STEEL STUB COLUMNS BASED ON A HIGH-FIDELITY NUMERICAL MODEL
C. Yang, L. Ying* and Y.N. Zhao

BEHAVIOR OF WEB PERFORATED COLD-FORMED STEEL BEAMS UNDER COMBINED BENDING AND SHEAR ACTION
L.P. Wang*, J. Li, X.X. Cao and H.B. Wang

OVERHANG EFFECT ON WEB CRIPPLING CAPACITY OF COLD-FORMED AUSTENITIC STAINLESS STEEL SHS MEMBERS: AN EXPERIMENTAL STUDY
K.J. Zhan, C. Chen, Y. Cai and H.T. Li*

Composite

CALCULATION METHOD OF ULTIMATE LOAD BEARING CAPACITY OF CONCRETE FILLED STEEL TUBULAR LATTICE COLUMNS
J.J. Qi*, X. Hu, W.B. Zhou, W.H. Shi and Z. Huang

AXIAL COMPRESSION BEHAVIOR OF SQUARE THIN-WALLED CFST COLUMN TO RC BEAM JOINTS
D. GAN*, Z.X. Zhao, X.H. Zhou and Z. Zhou*
NUMERICAL SIMULATION ANALYSIS OF TEMPERATURE FIELD OF BOX-TYPE COMPOSITE WALL
Q.Q. He, R. Li, C. Xue, T. Lan and G.C. Qin

THERMO-MECHANICAL COUPLING RESPONSE ANALYSIS OF THE BOX-PLATE PREFABRICATED STEEL STRUCTURE UNDER FIRE
C. Xue, R. Li, G.C. Qin and T. Lan*

STUDY ON FIRE RESISTANCE OF BOX-TYPE COMPOSITE WALLS
Y.Q. Fu, Q.Q. He, G.C. Qin, T. Lan* and R. Li

NUMERICAL SIMULATION AND RESEARCH ON WELDING RESIDUAL STRESS OF BOX-TYPE STEEL STRUCTURE
R. X. Gao, Men J. J., Lan T* and Li. R

STUDY ON SHEAR BEHAVIOR OF BOX – TYPE STEEL STRUCTURE CONSIDERING WELDING EFFECT
S. Wang, C. Xue, T. Lan* and J.J. Men

STUDY ON LOCAL BEARING CAPACITY OF COMPOSITE I-GIRDER WITH CONCRETE-FILLED TUBULAR FLANGE AND CORRUGATED WEB
C.J. Wu, L.X. Deng* and Y.B. Shao

PERFORMANCE OF STUD SHEAR CONNECTIONS IN COMPOSITE SLABS WITH VARIOUS CONFIGURATIONS
M.H. Shen, K.F. Chung* and X.D. Wang

STUDY OF INITIAL IMPERFECTION OF CONCRETE-FILLED CIRCULAR STEEL TUBE COLUMNS FOR DIRECT ANALYSIS
Z.J. Zhang, J.L. Xing, Y.P. Liu* and G.C. Li

Connections

SEISMIC PERFORMANCE OF THREE-DIMENSIONAL STEEL BEAM-COLUMN CONNECTIONS
Y.L. Xu*, Y.F. Shang and Y.X. Su

EXPERIMENTAL STUDY ON TRUSS TYPE STEEL REINFORCED CONCRETE JOINTS
T. Chen*, X.L. Gu, W.R. Fu, Q.H. Huang and B. Peng

EXPERIMENTAL INVESTIGATION ON THE STRUCTURAL BEHAVIOR OF CORRODED SELF-DRILLING SCREW CONNECTIONS IN COLD-FORMED STEEL STRUCTURES
ULTIMATE STRENGTH, DUCTILITY AND FAILURE MODE OF HIGH-STRENGTH FRICTIONAL BOLTED JOINTS MADE OF HIGH STRENGTH STEEL
Z.C. Qin*, H. Moriyama, T. Yamaguchi, M. Shigeishi, Y. Xing and A. Hashimoto

EXPERIMENTAL STUDY ON BOLTED CONNECTIONS IN COLD-ROLLED ALUMINIUM PORTAL FRAMES
H.C. Nguyen and C.H. Pham*

EXPERIMENTAL STUDY ON BEHAVIOR OF THE GUSSET-PLATE JOINT OF ALUMINUM ALLOY PORTAL FRAME
J. Liu*, X.N. Guo and Y.F. Luo

PARAMETRIC STUDIES ON SCF DISTRIBUTION OF THREE-PLANAR TUBULAR Y-JOINTS UNDER IN-PLANE BENDING MOMENT
S.L. Bao*, Y.T. Tai, Y. Tian, X.Y. Zhao and R.N. Li

PARAMETRIC STUDIES ON THE MOMENT RESISTANT BEAM-COLUMN CONNECTION BEHAVIOR OF CONCRETE FILLED DOUBLE STEEL TUBULAR COLUMNS AND I STEEL BEAMS
M. Sulthana*, T. Supritha

LOAD TRANSFER MECHANISM OF STEEL GIRDER-RC PIER CONNECTION IN COMPOSITE RIGID-FRAME BRIDGE
H.X. Liu*, Xianlin Wang, MaoFeng Yu, BinQiang Guo and Yuqing Li

COMPARISON OF MECHANICAL BEHAVIOR BETWEEN LONGITUDINAL LAP-WELDED JOINTS AND TRANSVERSE FILLET WELDED JOINTS OF HIGH STRENGTH STEEL
S.H. Jiang, M.M. Ran*, F. Xiong and Y.C. Zhong

STUDY ON THE STATIC BEHAVIOR OF COLD-FORMED STEEL FABRICATED BEAM-COLUMN JOINT
L.P. Wang*, A. Abubakar B* and J. Li

NUMERICAL STUDY OF THE PRELOAD FORCE LOSS OF CORRODED HIGH-STRENGTH BOLTS
Y. Jin, X. Zhang and Z.Y. Kong*

Corrosion, Fracture & Collapse

ANTI-WIND CAPACITY CHECK AND COLLAPSES ANALYSIS OF EXISTING TRANSMISSION TOWER
W.T. Zhang*, Y.Q. Xiao, C. LI and Q.X. Zheng
DYNAMIC ANALYSIS OF LONG-SPAN TRANSMISSION TOWER-LINE SYSTEM UNDER DOWNBURST
D.K. Zhang*, H.Z. Deng and X.Y. Hu

APPLICATION RESEARCH OF V CONTAINING HIGH STRENGTH WEATHERING STEEL IN STEEL STRUCTURE BUILDING
Z.R. Li*, K.Y. Cui, C.W. Wang and S. Chen

EFFECT OF VARIOUS BOUNDARY CONSTRAINTS ON THE COLLAPSE BEHAVIOR OF MULTI-STORY COMPOSITE FRAMES
Z. Tan, W.H. Zhang*, X.Y. Song, B. Meng, C.F. Li, and S.C. Duan

Design & Analysis

STRENGTHENING DESIGN AND MECHANICAL BEHAVIOR ANALYSIS OF THE MAIN STRUCTURE FOR AN INDUSTRIAL WORKSHOP WHEN EQUIPMENT CHANGED
B. Jiang*, L. Jiang, S.C. Sang, Y.Y. Li, Y.G. Wu

ENHANCEMENT OF ANTI-COLLAPSE CAPACITY OF STEEL FRAME WITH OPENINGS IN BEAM WEB
B. Meng*, W.H. Zhong and J.P. Hao

INNOVATION AND PRACTICE IN BUILDING STRUCTURE DESIGN
Y.Q. Zhang*, J.M. Ding and Z. Zhang

CORRELATION BETWEEN RANDOM LOCAL MECHANICAL PROPERTIES OF STRUCTURAL STEEL
A. Machowski, M. Maslak* and M. Pazdanowski

RESEARCH ON CALCULATION METHOD OF LOADED COMPRESSION MEMBER OF SINGLE-LIMB FIRE-CURVED EQUILATERAL DOUBLE SPLICING T-SHAPED ANGLE STEEL
X.D. Li*, Z.G. Fang, J.Q. Ye, D.H. Sun and W. Yao

ROTATIONAL STIFFNESS MODEL FOR SHALLOW EMBEDDED STEEL COLUMN BASES
X.X. Xu*, X.Z. Zhao and S. Yan

STUDY ON MECHANICAL PROPERTIES OF SIMPLIFIED STEEL FRAME MODEL WITH EXTERNAL WALL PANELS
Y.Z. Liu* and W.Y. Zhang

INTEGRATED DESIGN OPTIMIZATION FOR LONG SPAN STEEL TRANSFER TRUSS
AT REDEVELOPMENT OF HONG KONG KWONG WAH HOSPITAL
X.K. Zou, Y. Zhang, Y.P. Liu*, L.C. Shi and D. Kan

**Direct Analysis**

SECOND-ORDER DIRECT ANALYSIS FOR STEEL H-PILES ACCOUNTING FOR POST-DRIVING RESIDUAL STRESSES

*W.H. Ouyang, L. Chen and S.W. Liu*

**Fatigue**

RECONSTRUCTION METHOD OF FATIGUE DAMAGE STATE OF IN-SERVICE STEEL BRIDGE WITHOUT LOAD INFORMATION

*L.T. Da*, Q.H. Zhang, M.Z. Li and C. Cui

Fatigue Performance of rib-to-deck joints strengthened with internal welding

*M.Z. Li*, Q.H. Zhang, J. Li, L.T. Da and C. Cui

Experimental investigation on residual stress distribution and relaxation effect at double-side welded rib-to-deck joints of orthotropic steel decks

*Y. Ma*, C. Cui, Q.H. Zhang and W.L. Lao

Fatigue behaviour of titanium-clad bimetallic steel plate with different interfacial conditions

*C.Y. Huang*, H.Y. Ban, L.T. Hai and Y.J. Shi

Mechanical properties and simulation method of structural steel after high cycle fatigue damage

*Q. Si, Y. Ding, L. Zong* and *H. Liu*

Experimental study on welding residual stress of two-way stiffened steel plates

*Z. Shao, Y.X. Li, S.Y. Song, W.L. Jin, Y.Q. Liu*

**Volume II**

**Fire**
BENDING MECHANICAL PROPERTIES OF STEEL - WELDED HOLLOW SPHERICAL JOINTS AT HIGH TEMPERATURES
L. Wang, H.B. Liu*, H. Dong, and X.N. Liu

HIGH STRENGTH STEEL BEAM BEHAVIOR UNDER FIRE EXPOSURE CONSIDERING CREEP
H. Al-azzani*, W.Y. Wang and A. Sharhan

EXPERIMENTAL INVESTIGATION ON MECHANICAL PROPERTIES OF GRADE 1670 STEEL WIRES AT AND AFTER ELEVATED TEMPERATURE

FINITE ELEMENT SIMULATION FOR ULTRA-HIGH-PERFORMANCE CONCRETE-FILLED DOUBLE-SKIN TUBES EXPOSED TO FIRE
A.H.A. Abdelrahman*, M. Ghannam, S. Lotfy, and M. AlHamaydeh

High-Strength Steel

EXPERIMENTAL INVESTIGATION OF RESIDUAL STRESS IN WELDED T-SECTION BY DOMESTIC Q460 HIGH STRENGTH S
X.L. Xiong*, F.R. Nkuichou, T. Wang, M. Ma and K. Du

CORROSION EFFECTS ON MECHANICAL PROPERTIES OF Q620 HIGH-STRENGTH STEEL
N. Wang, J.M. Hua, X.Y. Xue*, Q.Q. Huang, F. Wang

Impact and protection

TENSILE BEHAVIOR OF T-STUB SUBJECTED TO STATIC AND DYNAMIC LOADS
H. Huang, L.M. Ren, K. Chen, X.J. Li, L. Wang and B. Yang*

Intelligent Construction

APPLICATION OF HYDRAULIC SYNCHRONOUS LIFTING TECHNOLOGY IN CONSTRUCTION OF LONG-SPAN HYBRID STEEL STRUCTURES
M.L. Zhang*, W. Liu, Z. Lei, D.G. Wang, J.Y. Wang, L.Y. Zhou* and X.P. Shu

TESTING OF ADDITIVELY MANUFACTURED STAINLESS STEEL MATERIAL AND CROSS-SECTIONS
R.Z. Zhang*, L. Gardner and C. Buchanan

EMBODIED CARBON CALCULATION AND ASSESSMENT FOR STEEL STRUCTURE PROJECT
D. Chan, W. Sun and Y.Y. Wang*
COMPLETE SET CONSTRUCTION TECHNOLOGY OF LARGE OPENING CABLE DOME STRUCTURE BASED ON INTEGRATED
Y.Y. Shang*, Z.S Xing, C.Q. Wu, F.S. Lu and B. Luo

COMPLETE SET ROTATION-LIFTING CONSTRUCTION TECHNOLOGY FOR FREE-FORM SURFACE ROOF STRUCTURES WITH LARGE ELEVATION DIFFERENCE
Z.S. Xing, S.R. Jia, Z.H. Zhang and D.C. Ye

**New Materials**

FINITE ELEMENT ANALYSIS ON BEHAVIOR OF HCFHST MIDDLE LONG COLUMNS WITH INNER I-SHAPED CFRP UNDER AXIAL LOAD
G.C. Li, R.Z. Li* and Z.J. Yang

STUDY ON THE MECHANICAL BEHAVIOR OF GFRP PLATE-CONE CYLINDRICAL RETICULATED SHELL
X. Wang, L. Chen, Y.H. Huang, F. Wang* and X. Zhang

EXPERIMENTAL STUDY ON MECHANICAL PROPERTIES AND OPTIMIZATION OF CHOPPED BASALT FIBER REINFORCED CONCRETE
Q. Liu, Z.X. Yu and R. Guo*

STUDY ON MECHANICAL PROPERTIES OF STAINLESS STEEL PLATE SHEAR WALL STRENGTHENED BY CORRUGATED FRP
Y.P. Du* and L. Zhong

DESIGN OF THE DEPLOYABLE-FOLDABLE ACTUATOR AND VIBRATION CONTROL DEVICE BASED ON THE SHAPE MEMORY ALLOYS WITH A TWO-WAY EFFECT
D. Song*, Y.J. Lu, and C.Q. Miao

**Seismic Resistance**

FEASIBILITY STUDY OF VISCOELASTIC HYBRID SELF-CENTERING BRACE (VSCB) FOR SEISMIC-RESISTANT STEEL FRAMES
Y.W. Ping, C. Fang* and Y.Y. Chen

TEST ON RESILIENCE CAPACITY OF SELF-CENTERING BUCKLING RESTRAINED BRACE WITH DISC SPRINGS

MECHANICAL PROPERTIES OF KINKED STEEL PLATES AND THEIR APPLICATIONS IN FRAME STRUCTURES
X.J. Yang, F. Lin* and C.P. Liu
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEISMIC COLLAPSE AND DEBRIS DISTRIBUTION OF STEEL FRAME STRUCTURES WITH INFILL WALLS</td>
<td>889</td>
</tr>
<tr>
<td>Z. Xu and F. Lin*</td>
<td></td>
</tr>
<tr>
<td>ANALYSIS OF TRANSIENT STRUCTURAL RESPONSES OF STEEL FRAMES WITH NON-SYMMETRIC SECTIONS UNDER EARTHQUAKE MOTION</td>
<td>899</td>
</tr>
<tr>
<td>W.L. Gao, L. Chen and S.W. Liu*</td>
<td></td>
</tr>
<tr>
<td>SEISMIC RESILIENCE ASSESSMENT OF A SINGLE-LAYER RETICULATED DOME DURING CONSTRUCTION</td>
<td>911</td>
</tr>
<tr>
<td>T.L. Zhang and J.Y. Zhao*</td>
<td></td>
</tr>
</tbody>
</table>

**Stability**

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCAL BUCKLING (WRINKLING) OF PROFILED METAL-FACED INSULATING SANDWICH PANELS - A PARAMETRIC STUDY</td>
<td>930</td>
</tr>
<tr>
<td>M.N. Tahir* and E. Hamed</td>
<td></td>
</tr>
<tr>
<td>COMPARATIVE STUDY ON STABILITY OF WELDED AND HOT-ROLLED Q420 L300×30 COLUMNS</td>
<td>938</td>
</tr>
<tr>
<td>A.P. Chou and G. Shi*</td>
<td></td>
</tr>
<tr>
<td>ELASTIC BUCKLING OF OUTSTAND STAINLESS-CLAD BIMETALLIC STEEL PLATES SUBJECTED TO UNIAXIAL COMPRESSION</td>
<td>946</td>
</tr>
<tr>
<td>Y.X. Mei* and H.Y. Ban</td>
<td></td>
</tr>
<tr>
<td>IMPERFECTION SENSITIVITY OF NON-TRIANGULATED CYLINDRICAL SHELL CONFIGURATIONS</td>
<td>955</td>
</tr>
<tr>
<td>R. Kolakkattol*, K.D. Tsavdaridis, and A.S. Jayachandran</td>
<td></td>
</tr>
</tbody>
</table>

**Stainless Steel**

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATERIAL PROPERTIES AND LOCAL STABILITY OF WAAM STAINLESS STEEL PLATES WITH DIFFERENT DEPOSITION RATES</td>
<td>968</td>
</tr>
<tr>
<td>S.I. Evans* and J. Wang</td>
<td></td>
</tr>
<tr>
<td>A REEXAMINATION ON CALIBRATION OF CYCLIC CONSTITUTIVE MODEL FOR STRUCTURAL STEELS</td>
<td>980</td>
</tr>
<tr>
<td>FINITE ELEMENT MODELING OF CONCRETE-FILLED STAINLESS-CLAD BIMETALLIC STEEL SQUARE TUBES UNDER AXIAL COMPRESSION</td>
<td>992</td>
</tr>
<tr>
<td>Z.J. Chen*, H.Y. Ban, Y.Q. Wang</td>
<td></td>
</tr>
</tbody>
</table>
Structure Systems

INVESTIGATION OF CYCLIC BEHAVIOR OF FULL-SCALE TREE-LIKE HOLLOW STRUCTURAL SECTION COLUMNS WITH INFILLED CONCRETE
D. Gan*, Z.H. He, and H.H. Huang

ANALYSIS OF THE SEISMIC BEHAVIOR OF INNOVATIVE ALUMINIUM ALLOY ENERGY DISSIPATION BRACES
B. Jia*, Q.L. Zhang and T. Wu

SHAKING TABLE TEST OF NEW LIGHT STEEL STRUCTURE SYSTEM

Testing & Monitoring

THE CRACK DETECTION METHOD OF LONGITUDINAL RIB BUTT WELD OF STEEL BRIDGE BASED ON ULTRASONIC LAMB WAVE
D.K. Zhang*, Q.H. Zhang, C. Cui and S.J. Qiu

ON FIELD-MEASURED VERTICAL TEMPERATURE GRADIENT OF BOX GIRDER IN STEEL BRIDGES
Z.W. Zhu*, T. Qin, X.W. Chen
Preface

These proceedings contain the papers presented at the TENTH INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES (ICASS 2020) held in Chengdu, China, from 21 to 23 August 2022. The international conference series on Advances in Steel Structures was initiated in 1996 under the support of The Hong Kong Polytechnic University, which remains very active in fostering its continuation—joined a few years later by the Hong Kong Institute of Steel Construction.

These proceedings bring together most recent findings in numerical, theoretical and experimental research, as well as its practical implementation in design practice in the areas of Assembled Structure, Bridge, Cold-formed Steel, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue, Fire, High-Strength Steel, Impact and Protection, Intelligent Construction, New Material, Seismic Resistance, Stability, Stainless Steel, Structure Systems, Testing & Monitoring. The papers presented in these proceedings come from a wide range of countries/regions and will be a great reference source.

Specially, the subject matter has been categorized under the broad heading of:

**Volume I:** Keynotes Lectures, Assembled Structure, Bridge, Cold-Formed, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue


Each of the papers was subjected to stringent review by a panel of experts in the respective area. This peer review began with an assessment of the submitted abstracts and following this, authors were invited to submit their full manuscripts. Each manuscript was then carefully reviewed by relevant experts, and their recommendations on accepting, rejecting or modifying the submissions were strictly adhered to, before inclusion in the conference proceedings.
FINITE ELEMENT ANALYSIS ON BEHAVIOR OF HCFHST MIDDLE LONG COLUMNS WITH INNER I-SHAPED CFRP UNDER AXIAL LOAD

Guochang Li, Runze Li* and Zhijian Yang

School of Civil Engineering, Shenyang Jianzhu University, Shenyang, China
E-mails: liguochang0604@sina.com, 694256429@qq.com, faemail@163.com

Abstract: In this paper, the behavior of high-strength concrete filled high-strength square steel tube (HCFHST) middle long columns with inner I-shaped CFRP profile under axial load was studied. The finite element analysis models were established by ABAQUS software based on reasonable material constitutive relationship models. The whole process curve of load-deformation was analyzed. In addition, effects of concrete strength, steel yield strength, slenderness ratio, steel ratio and configuration ratio of CFRP on mechanical behavior of middle long columns were studied. On the basis of the parametric analysis, the limit slenderness ratio of middle long columns was obtained. Results show that with the increase of steel yield strength, the bearing capacity increases gradually, but ductility decreases. The higher the concrete strength is, the greater the ultimate bearing capacity is. Effect of steel ratio on the ultimate bearing capacity and ductility is relatively obvious. The ultimate bearing capacity of HCFHST middle long columns with inner I-shaped CFRP profile decreases with the increase of slenderness ratio.

Keywords: High-strength concrete; High-strength square steel tube; I-shaped CFRP; Axial compressive behavior; Middle long column

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1 INTRODUCTION

In modern society, concrete-filled steel tube (CFST) is widely used in practical engineering due to its high bearing capacity, good seismic performance and excellent ductility [1]. For the mechanical properties of CFST, domestic and foreign scholars have done a lot of research on it. However, with the rapid development of the city, the super-high-rise buildings continue to increase, and the vertical load assumed by the structure also increases. The traditional CFST must increase the section size to meet the requirement of building performance. Therefore, new composite columns such as steel-reinforced concrete columns and steel-reinforced concrete filled steel tubular columns have been developed [2,3].

In recent years, fiber reinforced polymer (FRP) is a kind of excellent-performance materials with high strength, large specific modulus and good corrosion resistance which has been extensively studied and applied. Pecce [4] analyzed the mechanical properties, yielding and failure modes of FRP profiles subjected to axial compression. Linda [5] analyzed the bearing capacity of pultruded fiberglass profile columns. Laudiero [6] studied the buckling and post-buckling behavior of GFRP I-shaped columns with different flange widths under compression. Nunes [7,8] conducted experiments and finite element analysis on a variety of different parameters of the I-shaped FRP profile column. Therefore, many scholars combined the use of

The above studies show that the research and application of CFRP mainly used its tensile properties. Li [17,18,19,20] put the I-shaped CFRP profile into the CFST to form a new type of concrete-filled steel tubular composite column. The research indicates that the composite column has high stability bearing capacity and ductility due to the use of the I-shaped CFRP profile. The finite element analysis of mechanical behavior of HCFHST middle long columns with inner I-shaped CFRP under axial load was studied in this paper. The composite performance of three high-strength materials and the parameters of such as slenderness ratio, steel strength and concrete strength were investigated.

2 DESIGN OF FINITE ELEMENT MODEL

The main parameters are slenderness ratio, concrete strength, steel yield strength, wall thickness of steel tube and CFRP profile ratio. The specific parameters are shown in Table 1. The model section is 150×150 mm, and the cross-sectional dimensions of the embedded I-shaped CFRP profile are shown in Table 2.

<table>
<thead>
<tr>
<th>Number</th>
<th>B×t×L (mm)</th>
<th>λ</th>
<th>α</th>
<th>f_{cu} (MPa)</th>
<th>f_{y} (MPa)</th>
<th>A_{f} (mm²)</th>
<th>N_{u} (kN)</th>
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<td>150×5×1000</td>
<td>23.09</td>
<td>15.6</td>
<td>100</td>
<td>550</td>
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<tr>
<td>ACC-2</td>
<td>150×5×1500</td>
<td>34.64</td>
<td>15.6</td>
<td>100</td>
<td>550</td>
<td>1068</td>
<td>3357.03</td>
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<tr>
<td>ACC-3</td>
<td>150×5×2000</td>
<td>46.19</td>
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<td>100</td>
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<td>1068</td>
<td>3156.47</td>
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<td>ACC-4</td>
<td>150×5×2500</td>
<td>57.74</td>
<td>15.6</td>
<td>100</td>
<td>550</td>
<td>1068</td>
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<td>ACC-5</td>
<td>150×5×3000</td>
<td>69.28</td>
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<td>100</td>
<td>550</td>
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<td>2445.54</td>
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<td>ACC-6</td>
<td>150×4×1500</td>
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</tr>
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<td>34.64</td>
<td>15.6</td>
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<td>550</td>
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<td>3039.46</td>
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<td>3312.71</td>
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<td>550</td>
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<td>550</td>
<td>0</td>
<td>3176.77</td>
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</table>

Note: λ is the slenderness ratio, α is the steel ratio, f_{cu} is the compressive strength of concrete, f_{y} is steel yield strength, A_{f} is the cross-sectional area of CFRP, N_{u} is the ultimate bearing capacity of the model.
Table 2: The dimensions of CFRP I-shaped profiles.

<table>
<thead>
<tr>
<th>H(mm)</th>
<th>W(mm)</th>
<th>T(mm)</th>
<th>$A_f$(mm$^2$)</th>
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<tr>
<td>70</td>
<td>60</td>
<td>4</td>
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<tr>
<td>70</td>
<td>60</td>
<td>8</td>
<td>1392</td>
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</table>

### 3.1 Constitutive relationship of materials

The simplified idea elastic-plastic stress-strain curve model of high-strength steel proposed by Han is used. The modulus of the strengthen stage is $0.01E_s$.

The concrete damaged plasticity model provided by ABAQUS was used for simulation. The constitutive relationship of concrete was based on the core concrete equivalent stress-strain relationship model proposed by Liu [21]. At the same time, the fracture energy criterion was defined for concrete tensile behavior [22].

The pultruded CFRP profile is selected, which is mainly composed of a carbon fiber unidirectional fabric layer and a carbon fiber continuous fiber felt layer. The mechanical properties of each material are taken from the measured values of the material properties. Based on the ABAQUS secondary development subroutine USDFLD, the Tsai-Wu failure strength criterion is applied to judge the failure of CFRP.

### 3.2 Finite element model establishment

The CFRP profiles, concrete, steel pipes and endplates all used C3D8R solid elements. The endplates were set as rigid body. The elastic modulus was defined as $2.06 \times 10^{11}$ and the Poisson's ratio was defined as 0.

The “Tie” contact was adopted between the CFRP profile and the concrete. There is a slight
slip between concrete and steel tube, the normal direction is defined as hard contact, the tangential direction is Coulomb friction model, and the friction coefficient is 0.6. The contacts between endplate and concrete, CFRP were “Hard contact”. The endplate and steel tube were tied to together.

The displacement loading method with eccentricity of one thousandth column length proposed is applied in this paper, as shown in Figure 3.

![Figure 3: Model contact condition and Schematic diagram of loading mode.](image)

4 RESULTS OF FINITE ELEMENT ANALYSIS

4.1 Analysis of the whole loading process of typical model

Analysis on the whole process of the axial compressive behavior of high-strength concrete filled high-strength square steel tube middle long columns with inner I-shaped CFRP profile were carried out. The ACC-2 was selected as a typical column, and four feature points were defined. The load-displacement curve can be divided into four stages. The load-displacement curve of typical model is shown in Figure 4.

![Figure 4: Load-displacement curve of typical model.](image)

a) Elastic stage OA. At the initial stage of loading, the steel tube, concrete and CFRP profiles worked individually, and the load and displacement increased linearly. At point A, the maximum fiber compressive stress of the steel tube reached the proportional limit. The load is about 44.17% of the peak load.
b) Elastoplastic stage AB. As the load continues to increase, the component entered the elastoplastic phase, and the curve grew nonlinearly. When reaching the point B, the steel began to yield. The restraining effect of the steel tube on the concrete is obvious. At this time, the concrete was in triaxial compressive stress state, and its strength was greatly improved, and the CFRP profile was not damaged.

c) Plastic strengthening stage BC. The steel entered into yielding stage and the deflection of the middle section increased. When the characteristic point C was reached, the component reached the ultimate bearing capacity.

d) Decent stage CDE. After the C point, the bearing capacity of the model decreased slowly. The load shared by steel tube and concrete reduced, and the load shared by the CFRP profiles continued to increase. After the characteristic point D, the bearing capacity of the model decreased sharply with the brittle failure of CFRP. The I-shaped CFRP that broke the section when it reached the characteristic point E completely withdrew from the work, but the I-shaped CFRP still assumed 1.59% of the load.

4.2 Stress distribution of characteristic points

Figure 5 shows the longitudinal stress distribution of the core concrete of ACC-2. At the initial stage of loading, the deformation of concrete was small and the whole section was under compression. At feature point A, the average compressive stress of concrete is 48.68 MPa. Near point B, the stress concentration of concrete appeared at corner because the concrete and the square steel tube were in contact at the corner area. When the point C was reached, the maximum stress is 1.16\(f_{cu}\) due to the restraining effect of the steel tube. When the load declined to point D, some part of the area changed from the compression zone to the tension zone, and the maximum concrete stress between the upper and lower flanges of the profile reached 103.88 MPa. It shows that the ultimate stress of concrete was improved due to the restraining effect of CFRP profiles. After the D point, the CFRP profile began to break. As it reached the point E, the CFRP profile broke brittle fracture, and the stress in the section of the concrete did not change too much.

Figure 5: Concrete stress contour of the middle section.
The Mises stress contour of steel tube is shown in Figure 6. Before point A, the whole section of the steel tube was in elastic state. The steel tube began to appear plastic deformation when it reached the characteristic point B. When loading to point C, most of the steel tube yielded, but the stress of tension side did not change much from point B, and the yield strength was not yet reached. When reaching point D, the stress of compressive side increased gradually, and the maximum stress was 593.0 MPa, while the stress of tension side decreased. At point E, the stress of steel tube on compressive side increased to 626.2 MPa.

Figure 6: Mises stress contour of steel tube.

Figure 7: Vertical CFRP profiles stress contour and coordinate system of CFRP.
Figure 7 is the vertical stress contour and coordinate system of CFRP profile in model ACC-2. It can be seen from the Figure 7 that the whole section of CFRP profile was under compression when the load reaches point A. At point C, the CFRP profile was not damaged and its maximum compressive stress was at the mid-span section. At feature point D, the load sharing of the profile reached the limit. Moreover, it can be found that the stress of CFRP profile at mid-span section was smaller than both ends, indicating that the middle portion was damaged. At point E, the CFRP appeared brittle failure in the middle of the span and withdrew from work.

5 PARAMETER ANALYSIS

5.1 Slenderness ratio

Figure 8 is the load-deflection curve of different slenderness ratio. It can be seen from the Figure 8 that the slenderness ratio has a greater influence on the bearing capacity of the model. As the slenderness ratio changed from 34.64 to 69.28, the bearing capacity of the members decreases by 4.95%, 5.97%, 9.91%, and 14.0%, respectively. The deflection increases with the increase of slenderness ratio, and the ductility is better.

5.2 Steel yield strength

Figure 9 is the load-deflection curve of different steel yield strength. Before the steel yield strength was reached, the curves are basically coincident. The steel yield strength has little effect on the mechanical properties of the model at elastic stage. When the steel yield strength is increased from 550MPa to 690MPa, 890MPa, the bearing capacity is increased by 14.01% and 31.30%, respectively. It can be seen that the steel yield strength has a great influence on the bearing capacity of the model.
5.3 Concrete strength

Figure 10 shows the load-deflection curves of different concrete strength. It can be seen from Figure 10 that the concrete strength has no significant effect on the stiffness of the models. When the concrete strength is increased from 80MPa to 120MPa, the bearing capacity is increased by 20.31%. The bearing capacity increases with the increasing of concrete strength, but the ductility is reduced.

5.4 Steel ratio

Figure 11 shows the load-deflection curves different thicknesses of steel tube. As the steel ratio increases from 4mm to 7mm, the bearing capacity of the model is increased by 8.08%, 7.51%, and 7.12%, respectively. The bearing capacity and stiffness increase with the increase of the steel ratio.

5.5 Configuration ratio of CFRP

Figure 12 the load-displacement curve of different CFRP profile thicknesses. As can be seen from the Figure 12, the bearing capacity of the model with CFRP profile is increased by 3.65%, 5.65% and 7.32%, respectively compared with the model without CFRP profile. It can be found that the lateral deflection of the CFST columns with the inner I-shaped CFRP is about 1.3 times that of the CFST columns. It shows that the CFRP profile improves the deformability of the model.

6 LIMIT SLENDERNESS RATIO

Figure 13 shows the load-longitudinal strain curve of different slenderness ratio (23.08-92.27). It can be seen from Figure 13 that the longitudinal deformation of the ultimate bearing capacity decreases with the increasing of slenderness ratio. The longitudinal strain of the steel tube is close to $f_y/E_s=0.002669$ when the slenderness ratio is $\lambda=73.82$. When $\lambda < 73.82$, the model reaches the ultimate bearing capacity in the elastoplastic stage. When $\lambda \geq 73.82$, the model reaches the ultimate bearing capacity in the elastic stage. Therefore, the limit slenderness ratio of the elastic instability of the composite column of the cross-section type in this paper is 70.
7 CONCLUSIONS

a) The load-displacement curve of HCFHST long columns with inner I-shaped CFRP profiles under axial load can be divided into elastic stage, elastoplastic stage, plastic strengthening stage and decent stage.

b) The inner I-shaped CFRP profile can improve the bearing capacity and deformation capacity of the CFST members. In addition, the bearing capacity increases as the concrete strength, steel strength, and steel ratio increase.

c) The bearing capacity of HCFHST with inner I-shaped CFRP under axial load decreases with the increase of the slenderness ratio, and the limit slenderness ratio of the elastic instability is 73.82.

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REFERENCES


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