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Zhi-Xiang Yu

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# Table of Contents

Preface XI

## Volume I

### Keynote Lectures

SEISMIC DESIGN AND ANALYSIS OF STEEL PANEL DAMPERS FOR STEEL FRAME BUILDINGS 2
*K.C. Tsai* and C.H. Hsu

THE CONTINUOUS STRENGTH METHOD - REVIEW AND OUTLOOK 15
*L. Gardner*, X. Yun and F. Walport

### Assembled Structure

A NEW TYPE OF ASSEMBLED THERMAL INSULATION DECORATIVE WALL SYSTEM FIRE RESISTANCE STUDY 28
*C.L. Wang*, S.R. Jiang, B.C. Li and S. Li

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 82
*F.W. Wang*, K.M. Zhou and S.T. Ke

### Bridge

SOUND RADIATION OF ORTHOTROPIC STEEL DECKS SUBJECTED TO MOVING VEHICLE LOADS 93
*Y.C. You and X. Zhang*

POWER FLOW ANALYSIS OF BRIDGE U-RIB STIFFENED PLATES BASED ON THE CONCEPT OF STRUCTURAL INTENSITY 102
*D.R. Kong and X. Zhang*
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 CONSIDERIGN 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
SEISMIC COLLAPSE AND DEBRIS DISTRIBUTION OF STEEL FRAME STRUCTURES WITH INFILL WALLS
Z. Xu and F. Lin*

ANALYSIS OF TRANSIENT STRUCTURAL RESPONSES OF STEEL FRAMES WITH NON-SYMMETRIC SECTIONS UNDER EARTHQUAKE MOTION
W.L. Gao, L. Chen and S.W. Liu*

SEISMIC RESILIENCE ASSESSMENT OF A SINGLE-LAYER RETICULATED DOME DURING CONSTRUCTION
T.L. Zhang and J.Y. Zhao*

Stability

LOCAL BUCKLING (WRINKLING) OF PROFILED METAL-FACED INSULATING SANDWICH PANELS - A PARAMETRIC STUDY
M.N. Tahir* and E. Hamed

COMPARATIVE STUDY ON STABILITY OF WELDED AND HOT-ROLLED Q420 L300×30 COLUMNS
A.P. Chou and G. Shi*

ELASTIC BUCKLING OF OUTSTAND STAINLESS-CLAD BIMETALLIC STEEL PLATES SUBJECTED TO UNIAXIAL COMPRESSION
Y.X. Mei* and H.Y. Ban

IMPERFECTION SENSITIVITY OF NON-TRIANGULATED CYLINDRICAL SHELL CONFIGURATIONS
R. Kolakkattol*, K.D. Tsavdaridis, and A.S. Jayachandran

Stainless Steel

MATERIAL PROPERTIES AND LOCAL STABILITY OF WAAM STAINLESS STEEL PLATES WITH DIFFERENT DEPOSITION RATES
S.I. Evans* and J. Wang

A REEXAMINATION ON CALIBRATION OF CYCLIC CONSTITUTIVE MODEL FOR STRUCTURAL STEELS

FINITE ELEMENT MODELING OF CONCRETE-FILLED STAINLESS-CLAD BIMETALLIC STEEL SQUARE TUBES UNDER AXIAL COMPRESSION
Z.J. Chen*, H.Y. Ban, Y.Q. Wang
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.
EXPERIMENTAL STUDY ON BEHAVIOR OF THE GUSSET-PLATE JOINT OF ALUMINUM ALLOY PORTAL FRAME

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Abstract: The aluminum alloy portal frames are increasingly being used for lightweight building construction. This paper investigated the flexural behavior of the bolted gusset-plate joint applied in the beam-beam connection of aluminum alloy portal frames. Bending tests were conducted on 3 aluminum alloy bolted gusset-plate joints. The failure phenomenon indicated that the thin plate joint failed by the buckling of gusset plates, while the thick plate joint failed by the buckling of sleeves. The moment-rotation curves showed that thickening the gusset plate can effectively prevent the buckling of gusset plates and increase the flexural capacity and bending stiffness of joints. In addition, the longitudinal spacing of bolts has a significant influence on the joint stiffness but has no obvious influence on the bearing capacity of the joint. The stress on the two gusset plates of the joint was uneven, which led to the decline of bearing performance of thin plate joints.

Keywords: Aluminum alloy portal frame; Gusset-plate joint; Flexural behavior; Bearing capacity; Experimental study

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1 INTRODUCTION

The portal frames, made up of cold-formed steel or aluminum alloy components, are increasingly being used for the lightweight building construction due to their advantages, including lightweight, beautiful appearance, and ease of construction [1,2]. It is confirmed that the mechanical behavior of joints will significantly affect the safety of the portal frames by many researchers [3,4]. Hence, many studies on the mechanical behavior of portal frame joints have been conducted.

Masika et al. [5] and Zhang et al. [6] conducted experimental and analytical research on rafter-to-column joints of portal frames built up from cold-formed sections. On the basis of the experimental and numerical results, the analytical method for predicting the strength and stiffness of the connection was proposed. Rinchen et al. [7] carried out a series of full-scale tests on long-span cold-formed steel single C-section portal frames subjected to gravity and lateral load. The test phenomenon showed that the deformations were concentrated at the eaves and the apex.

In portal frames made of aluminum alloy, the rectangular hollow and rectangle-like hollow sections are the most commonly used section type. As a result of the poor welding performance of aluminum alloy, mechanical connections are generally used in aluminum alloy joints. Compared with steel portal frames, aluminum alloy portal frames have better corrosion resistance and lighter weight. However, scarce research results are available in the literature regarding the behavior of aluminum alloy portal frame joints.
In order to resolve the aforementioned research limitations, this paper investigated the flexural behavior of the bolted gusset-plate joint applied in the beam-beam connection of aluminum alloy portal frames. Bending tests were conducted on 3 aluminum alloy bolted gusset-plate joints. The failure phenomenon, ultimate bearing capacity, moment-rotation curves, and moment-strain curves were obtained. On the basis of the test results, it is validated that the aluminum alloy bolted gusset-plate joints are semi-rigid. In addition, the failure pattern and flexural behavior of aluminum alloy bolted gusset-plate joints were summarized.

2 TEST PROGRAM

2.1 Specimen

In this paper, 3 bolted gusset-plate joints were designed and labelled as B1, B2, and B3, respectively. The bolted gusset-plate joints are applied in the beam-beam connection at the ridge of the sloping roof. Therefore, the members are inclined at an angle to simulate the roof slope. The horizontal inclination of members is 18°, which is the common roof angle of portal frames. Each joint specimen consists of two steel gusset plates and two rectangular hollow section members, as plotted in Figure 1. The galvanized bolt M20 bolts, which were tightened in 21 mm drilled holes, are used to connect the gusset plate with the member. All members have the same cross-sectional dimensions, and the height $D$, width $B$, and thickness $t_c$ of the cross-section of the specimen is 200 mm, 120 mm, and 4mm, respectively. The dimensions of gusset plates and members are as shown in Figure 2 and Figure 3, respectively. Two varying parameters, i.e., the plate thickness $t_p$ and bolt longitudinal spacing $d$, were considered, as shown in Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>$t_p$ / mm</th>
<th>$d$ / mm</th>
<th>$D$ / mm</th>
<th>$B$ / mm</th>
<th>$t_c$ / mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>6</td>
<td>300</td>
<td>200</td>
<td>120</td>
<td>4</td>
</tr>
<tr>
<td>B2</td>
<td>6</td>
<td>200</td>
<td>200</td>
<td>120</td>
<td>4</td>
</tr>
<tr>
<td>B3</td>
<td>20</td>
<td>300</td>
<td>200</td>
<td>120</td>
<td>4</td>
</tr>
</tbody>
</table>
2.2 Material properties

Q355B steel [8] and 6082-T6 aluminum alloy [9] were selected for the gusset plate and members, respectively. In order to obtain the actual mechanical properties of these components, tensile tests were performed according to the Chinese mechanical testing standard [10]. The dimensions of all tensile specimens are described in Figure 4. The material properties test results of the steel and aluminum alloy are shown in Figure 5 and Table 2, where $E$ is the elastic modulus, $f_y$ is the yield strength, and $f_u$ is the ultimate strength.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ / GPa</th>
<th>$f_y$ / MPa</th>
<th>$f_u$ / MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>6082-T6</td>
<td>72.6</td>
<td>331.3</td>
<td>364.1</td>
</tr>
<tr>
<td>Q355B</td>
<td>182.2</td>
<td>387.6</td>
<td>551.8</td>
</tr>
</tbody>
</table>
2.3 Strain and displacement measurements

The layout scheme of linear variable differential transducers (LVDTs) and strain gauges (SGs) was described as follows. Four LVDTs (D1~D4) were arranged to record the relative horizontal displacement of the members on both sides, as shown in Figure 6, which can be used to calculate the rotation angle of the joint. Twenty SGs (S1~S20) and eight triaxial strain gauges (T1~T8) were arranged to record the strains of different parts of the specimens during the whole experimental process, as shown in Figure 7 and Figure 8.

![Figure 6: Layout of LVDTs.](image1)

![Figure 7: Strain measurement of members.](image2)

![Figure 8: Strain measurement of gusset plates.](image3)

2.4 Test device

The overview of the test device is shown in Figure 9 and Figure 10. The end of the member was hinged to the clamp support, and the sleeves were designed at the end of the support to provide the load point and connect the support. To apply bending moment to the joint zone and prevent the lateral instability of the beam, the loading distribution beam and lateral restraint device were designed, respectively.
Figure 9: Test device.

Figure 10: Photos of the test device.
2.5 Test procedure

The test procedures are described as follows:

1. Apply a preload, which is 20% of the estimated ultimate load, to ensure that the test instruments work correctly.

2. Apply the load to the specimens until failure occurs. Force control mode was adopted at the beginning of the loading process. When the load-displacement curve presented obvious non-linearity, it was switched to displacement control mode.

3 TEST RESULTS

3.1 Failure modes and ultimate bearing capacity

The B1 and B2 specimen failed by the buckling of gusset plates, as shown in Figure 11. This is because the gusset plates were subjected to compression and bending during the whole experimental process. Since the gusset plates of the B1 and B2 specimens were clamped by the upper flange of the member, torsional deformation also occurred in the gusset plates. The readings of SGs on the member section indicated that the member was still in the elastic stage when the specimen failed. Unlike B1 and B2 specimens, there was no noticeable bulging in the gusset plates of the B3 specimen during the whole experimental process. Eventually, under the combined bending and local compression, the B3 specimen failed by the buckling of sleeves, as shown in Figure 11. There was obvious rotation deformation between the gusset plates and members of the B3 specimen. The failure mode and ultimate bearing capacity $M_u$ are summarized in Table 3.

![Failure photographs](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>$M_u$ / kN·m</th>
<th>Failure modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>20.9</td>
<td>the buckling of gusset plates</td>
</tr>
</tbody>
</table>

Figure 11: The failure phenomenon of specimens.

Table 3: The failure mode and ultimate bearing capacity.
3.2 Moment-rotation curves

The bending moment $M$ of the joint can be calculated according to the jack load. On the basis of the readings of D1~D4, the relative rotation angle of the joint can be calculated as:

$$\delta = \frac{\delta_D - \delta_{D1} + (\delta_{D4} - \delta_{D2})}{2} \quad (1)$$

$$\theta = \arcsin \frac{2h \sin \alpha - \delta}{2h} - \alpha \quad (2)$$

where $\delta$ is the average horizontal displacement difference; $\delta_{D1}$, $\delta_{D2}$, $\delta_{D3}$, and $\delta_{D4}$ are the readings of D1~D4; $\theta$ is the relative rotation angle of the joint; $h$ is the distance between upper and lower measuring points on the same section, and $\alpha$ is the initial horizontal inclination of the member.

Through Eq. (1) and Eq. (2), the moment-rotation ($M$-$\theta$) curves were obtained, as shown in Figure 12. It can be seen from Figure 12 that the joints are semi-rigid, with a certain degree of stiffness and rotation capacity. The stiffness of all specimens decreased with the increase of bending moment. The flexural capacity of the B1 and B2 specimens was close, but the stiffness of the B1 specimen was greater than that of the B2 specimen at the initial loading stage. Compared with the B1 specimen, the B3 specimen had a higher flexural capacity, and the stiffness of the B3 specimen did not decrease significantly at the initial stage of loading. On the whole, increasing the bolt spacing can improve the initial bending stiffness of the joint, but it will not affect the ultimate bearing capacity and failure mode. Thickening the gusset plate can effectively prevent the buckling of gusset plates and increase the flexural capacity and bending stiffness of joints.

3.3 Moment-strain curves

The bolted gusset-plate joints can be divided into several zones, i.e., force transfer zone and bending zone, as shown in Figure 13. The moment-strain curves of B1 specimens are shown in Figure 14. It can be concluded that the S1~S8 were still in the elastic stage until the B1 specimen failed. The strain in the force transfer zone of the joint was in the elastic stage, and the tensile and compressive strain in the same section presented good symmetry. However, the strain of the section where measuring points S9~S11 were located was 0.72 times that of the section where measuring points S12~S14 were located, which indicated that the stress on the two gusset
plates of the joint was uneven. The reason for uneven stress was the installation error of gusset plates, and the uneven stress led to the decline of the bearing performance of joints. The strain of T1 and T2 at the hole wall of the member web was in the elastic stage, while the T3 and T4 at the hole wall of the gusset plate were affected by the tensile stress in the bending zone of the gusset plate, so there was an obvious yield phenomenon in the strain of T3 and T4. The triaxial strain gauges T5~T8 in the bending zone were in the middle of the section rather than the edge of the section, so the strain of these measuring points did not yield obviously. According to the trend of the curve in Fig. 14, it can be observed that the strains of T7 and T8 in the tensile zone tended to yield. Therefore, it can be inferred that the section edges of T7 and T8 had yielded.

In addition, when the gusset plates were bulging, the stress in the bulging region would be released, and the cross-sectional stress redistribution would occur.

![Figure 13: Schematic diagram of joint zone division.](image)

![Figure 14: The moment-strain curves of the B1 specimen.](image)

The moment-strain curves of B2 specimens are shown in Figure 15. The strain trend of the B2 specimen was close to that of the B1 specimen. The member section of the B2 specimen was in the elastic stage, and the tensile and compressive strain on the same section presented good symmetry. The section strain in the force transfer zone of the gusset plate was in the elastic stage, and the strain of S9~S11 was about 0.79 times that of S12~S14. The strain at the hole wall of the member web was in the elastic stage, while there was an obvious yield phenomenon at the hole wall of the gusset plate. The tensile strain in the bending zone tended to yield in the later stage, while the compressive strain tended to decrease in the later stage.
The moment-strain curves of B3 specimens are shown in Figure 16. The moment-strain curves of measuring points S1~S8 of B3 specimen showed that the section of B3 specimen obviously yielded at the later stage of loading, which was different from the thin plate specimens (B1 and B2). The strain of S1~S8 also indicated that the joint failed by member buckling. Like the B1 and B2 specimens, the moment-strain curves of measuring points S9~S20 of the B3 specimen show that the force transfer zone of the gusset plate was not yielding, and the strain of S9~S11 was about 0.78 times that of S12~S14. However, the B3 specimen was not failed due to the buckling of the gusset plate, so the uneven stress had no influence on the bearing capacity of the joint. It can be observed that the strain of T1 and T2 was relatively large, which meant that thickening gusset plates made the member failure earlier than the gusset plate.
failure. Unlike the thin plate specimens B1 and B2, the strain of triaxial strain gauges T5~T8 of B3 specimen did not tend to yield, which was consistent with the test results, i.e., there was no obvious damage phenomenon on the gusset plates.

4 CONCLUSION

In this paper, experimental analysis was conducted to investigate the flexural behavior of the bolted gusset-plate joint applied in the beam-beam connection of aluminum alloy portal frames. The main conclusions are drawn as follows:

(1) The bolted gusset-plate joints are semi-rigid, with a certain degree of stiffness and rotation capacity.

(2) The thin plate joint failed by the buckling of gusset plates, while the thick plate joint failed by the buckling of sleeves. Thickening the gusset plate can effectively prevent the buckling of gusset plates and increase the flexural capacity and bending stiffness of joints.

(3) The bolt longitudinal spacing has a significant influence on the joint stiffness but has no obvious influence on the bearing capacity of the joint.

(4) The stress on the two gusset plates of the joint was uneven. The reason for uneven stress is the installation error of gusset plates, and the uneven stress leads to the decline of the bearing performance of thin plate joints.

REFERENCES


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