

Experimental and numerical investigations on Seismic Performance of Self-Centering Prefabricated Double-Column Piers with BRBs

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1 Introduction

2 Design of self-centering double-column pier models

3 Experimental results

4 Numerical results

5 Conclusions

- The traditional reinforced concrete (RC) double-column piers often suffer damage during earthquakes, which typically necessitates repairs and even complete dismantling. This process leads to significant economic losses and resource consumption.
- As a result, it is essential to develop double-column piers that can minimize seismic damage or maintain their functionality after earthquakes.
- The recoverable functional double-column piers can effectively mitigate seismic damage and even maintain functionality.



Typical earthquake damage of double-column piers

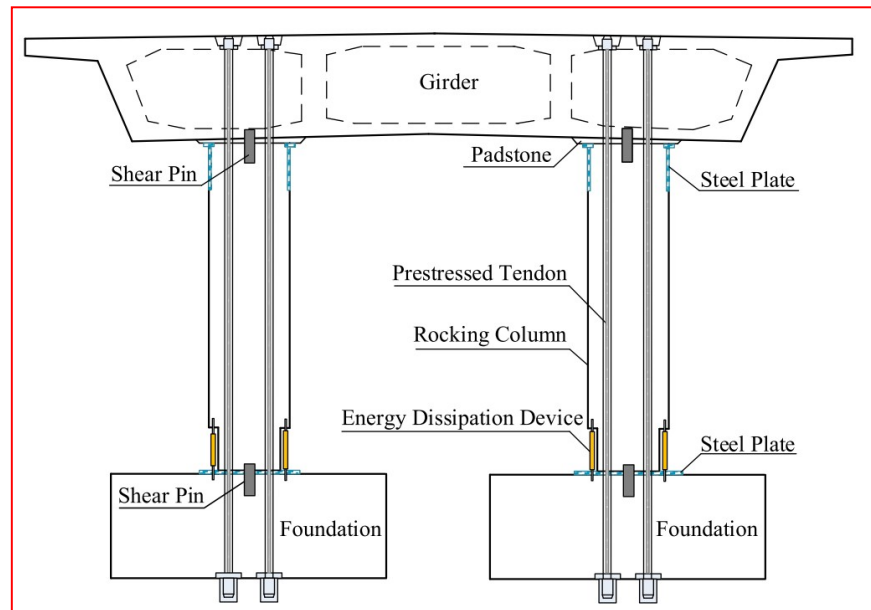
Recoverable functional double-column piers

Self-centering double-column piers

Prestressed tendons are used to connect precast segments.
Restoring forces are provided by prestressing force and gravity

Low residual displacement

Insufficient energy
dissipation capacity



Self-centering double-column piers
(Han, etc.)

Double-column piers with ED components

It includes a cast-in-place double-column piers and replaceable energy dissipation (ED) components

Enough energy
dissipation capacity

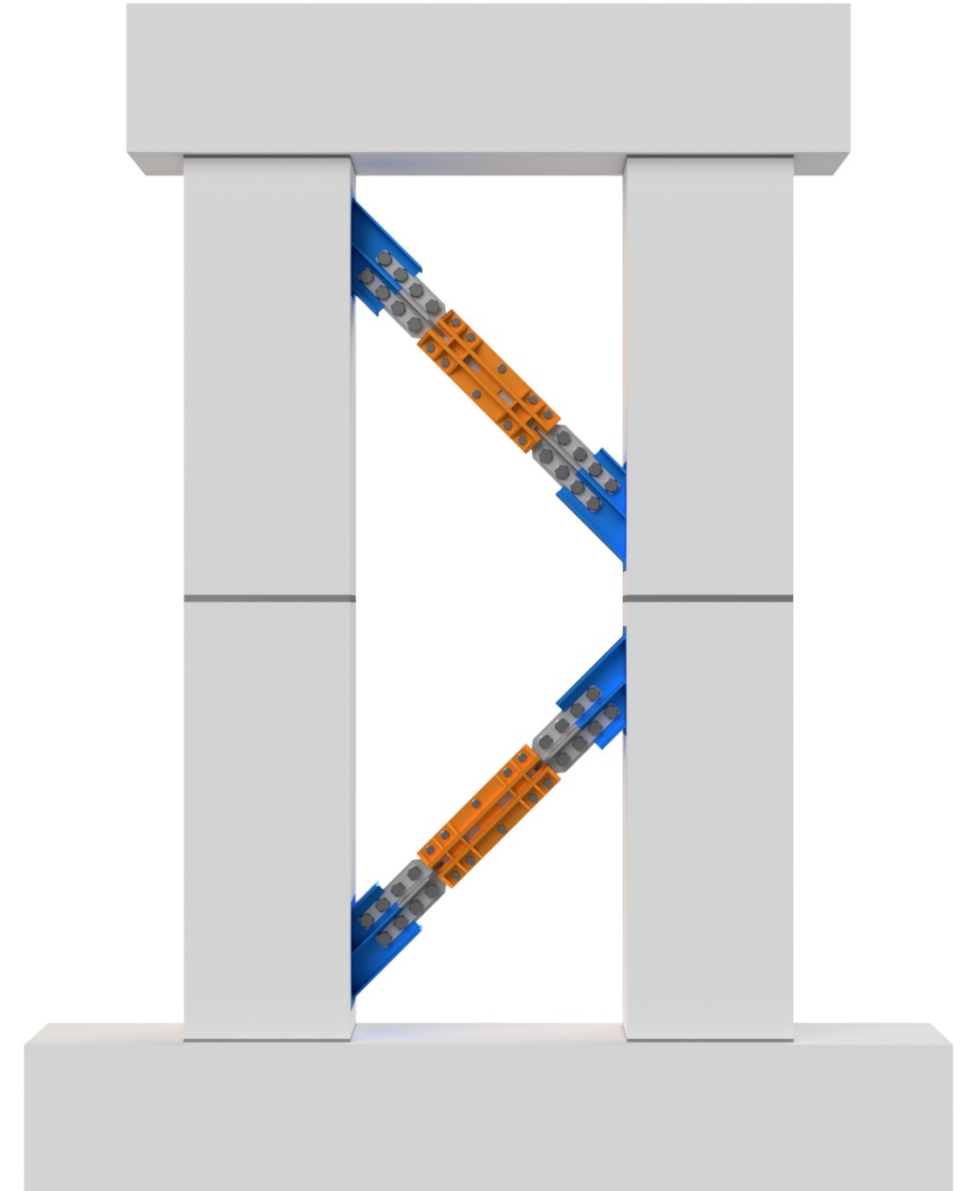
A certain degree of residual
deformation



Double-column piers with ED components (XIE, etc.)

◆ A proposed self-centering double-column pier with BRBs

- A self-centering double-column pier with buckling-restrained braces (BRBs) is proposed and designed to balance the energy dissipation and self-centering capacities.
- The hysteretic behavior of the BRBs is used to overcome the shortcomings of self-centering double-column piers.
- The BRBs are designed to yield before the energy-dissipating bars.
- The BRBs function as structural fuses and external energy-dissipating devices, bolted between the precast segments.
- The self-centering bridge bent with BRBs integrates cooperative mechanisms for load-bearing, stability, energy dissipation, and recoverable capacity.



1 Introduction

2 Design of self-centering double-column pier models

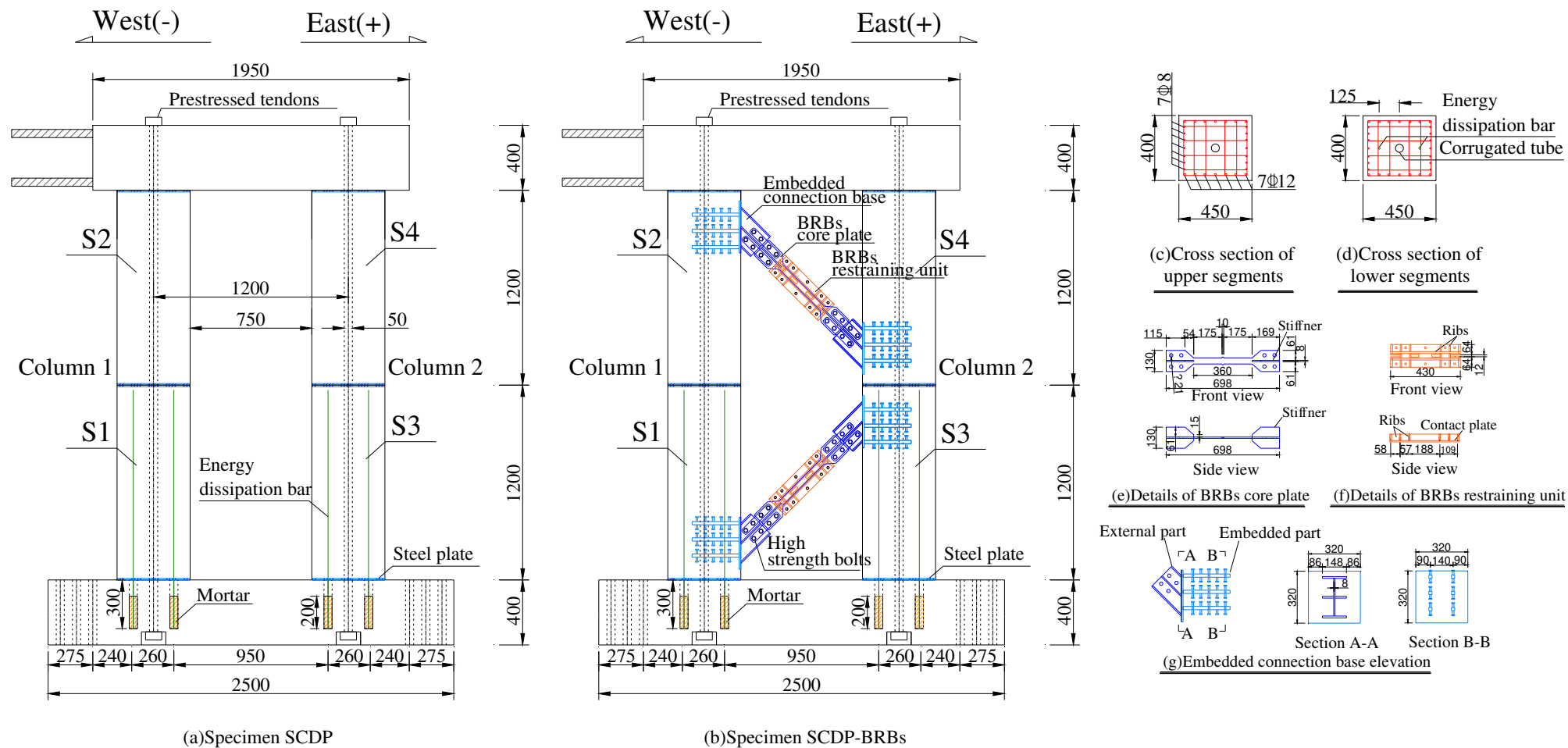
3 Experimental results

4 Numerical results

5 Conclusions

◆ Models design

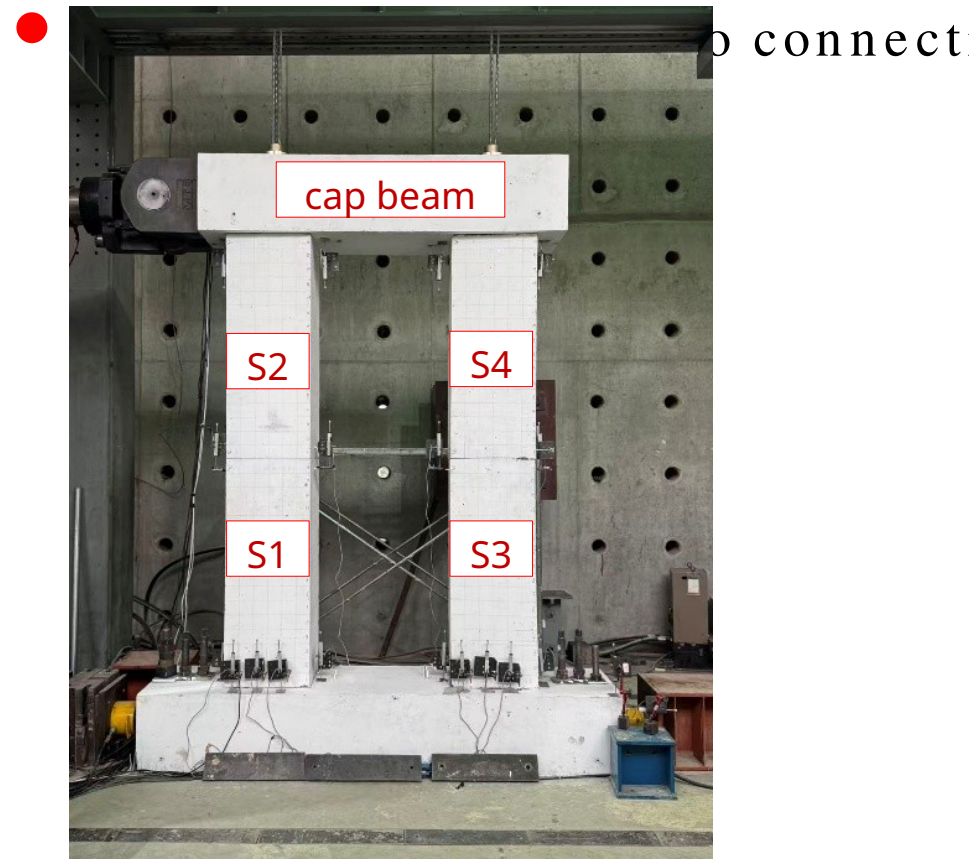
- Specimens self-centering double-column pier (**SCDP**) and self-centering double-column pier with BRBs (**SCDP-BRBs**) are designed at a geometric scale of 1/4. Column clear height: 2400 mm; Each segment height: 1200 m.



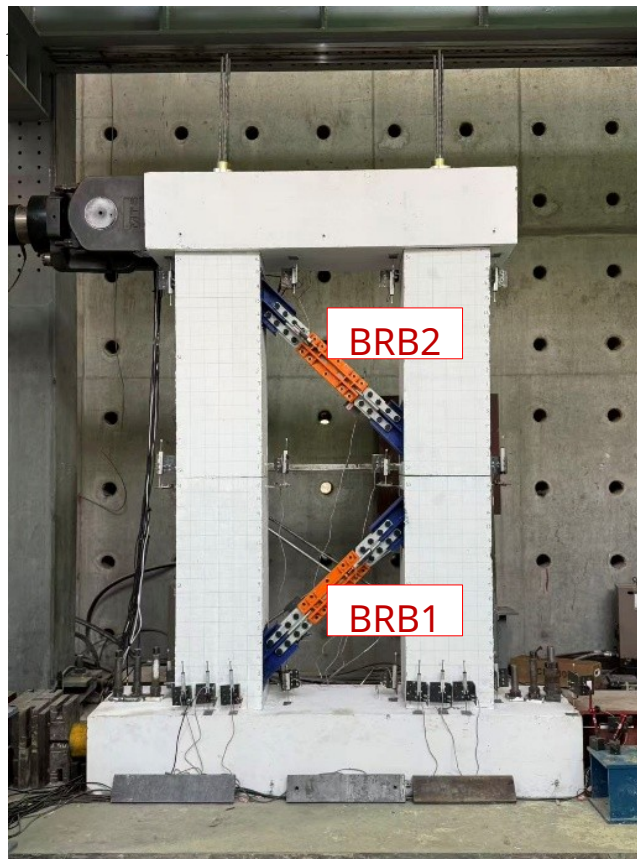
Specimens SCDP and SCDP-BRBs

◆ Models design

- Each column consists of two precast segments connected to the cap beam and footing using unbonded tendons.
- Specimen SCDP-BRBs is identical to Specimen SCDP except for the BRBs.

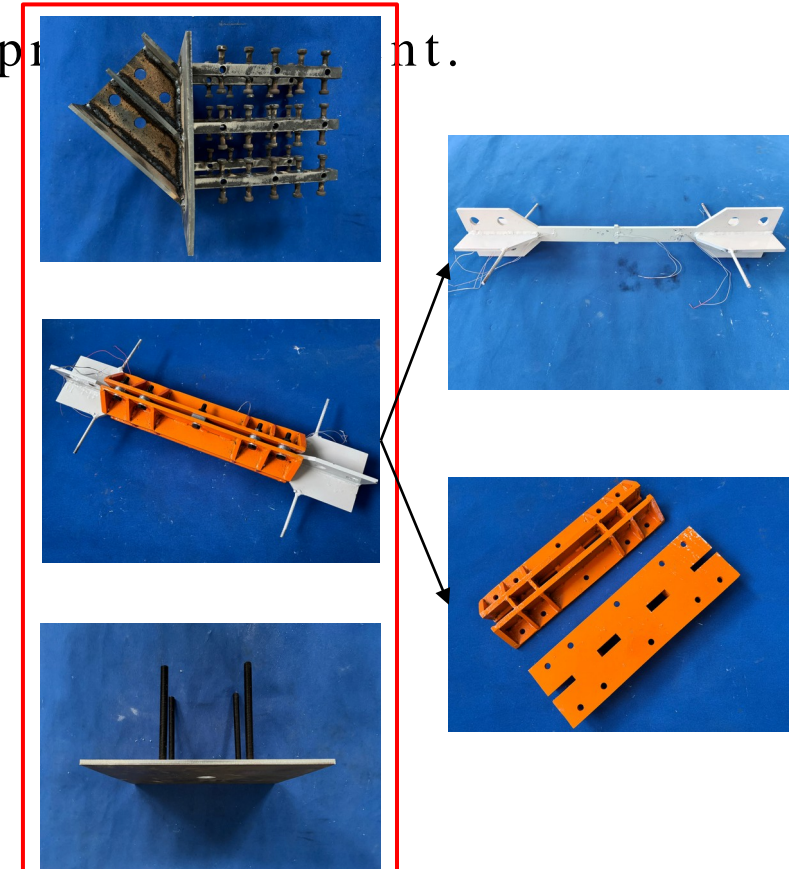


Specimen SCDP



Specimen SCDP-BRBs

in the p... nt.



BRBs and connected members

◆ Specimen installation steps

- Firstly, the footing is elevated and positioned overhead with a distance of approximately 40 cm to provide sufficient space for tensioning the prestressing tendons.
- Next, the precast segments are placed on the footing like building blocks at their designated locations.
- The prestressing tendons are inserted into the PVC ducts embedded in the precast segments.
- Installing the cap beam, followed by the sequential installation of load cells and anchorage devices.
- Tensioning the prestressing tendons



Assembling process of specimen SCDP



Assembling process of specimen SCDP-BRBs

◆ Sensor layout

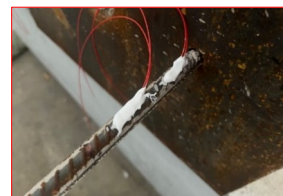
- **Load cells, LVDTs, and strain gauges** are used to monitor the prestressing force, the opening at the joints, and the energy-dissipating bar strain, respectively.
- **LVDTs** are used to record the axial deformation of BRBs and the compression zone height in the bottom column.



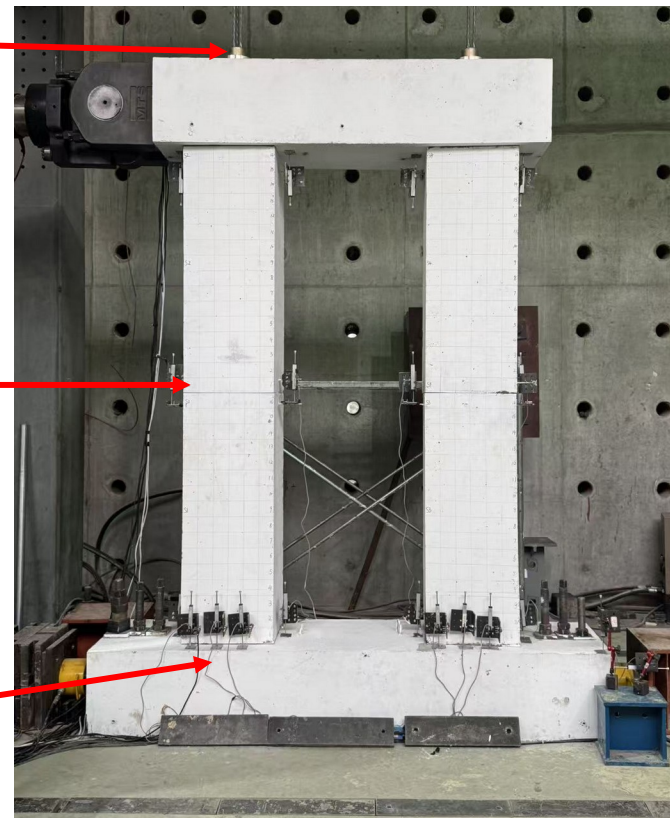
Tension force



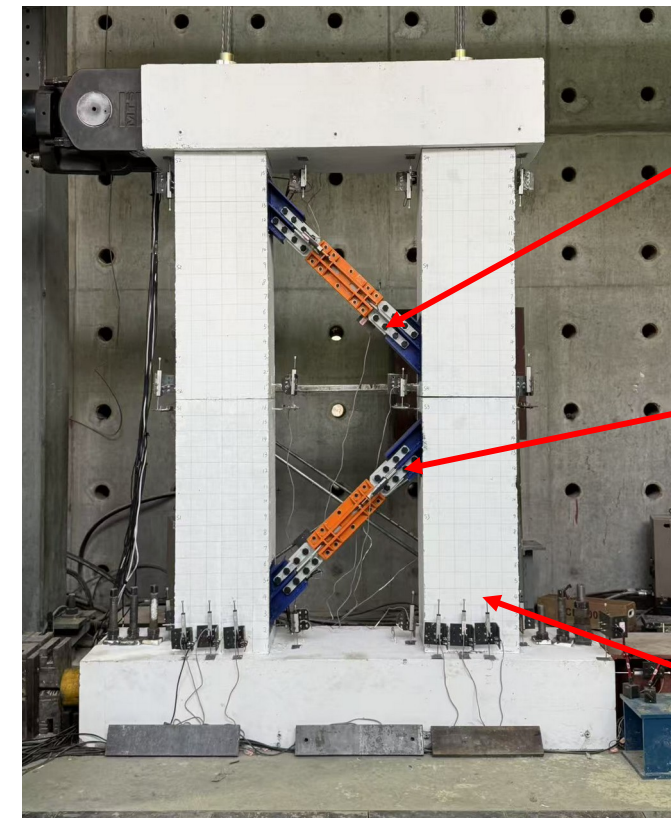
Joint opening



ED bars strain



Specimen SCDP



Specimen SCDP-BRBs



BRBs slip



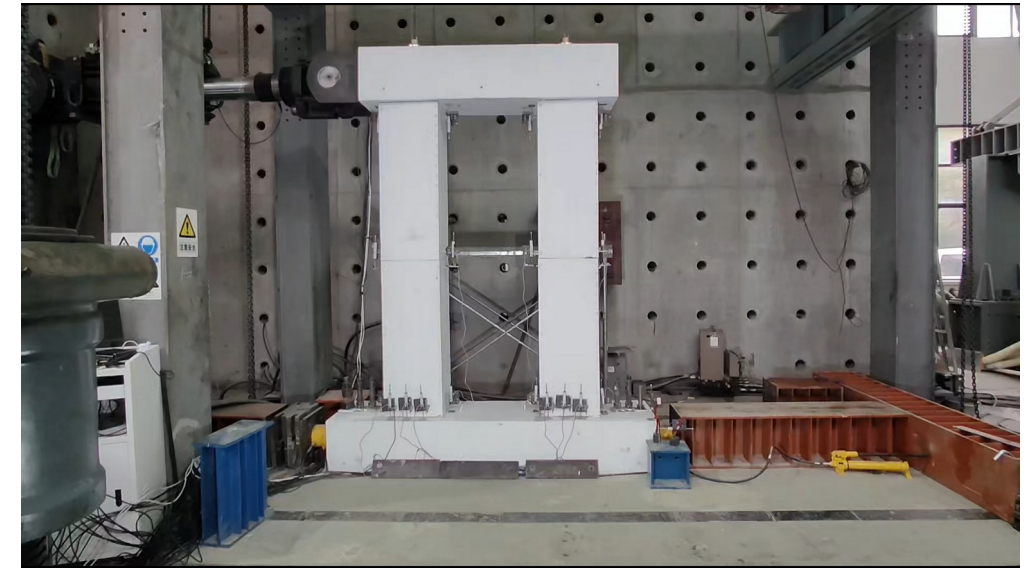
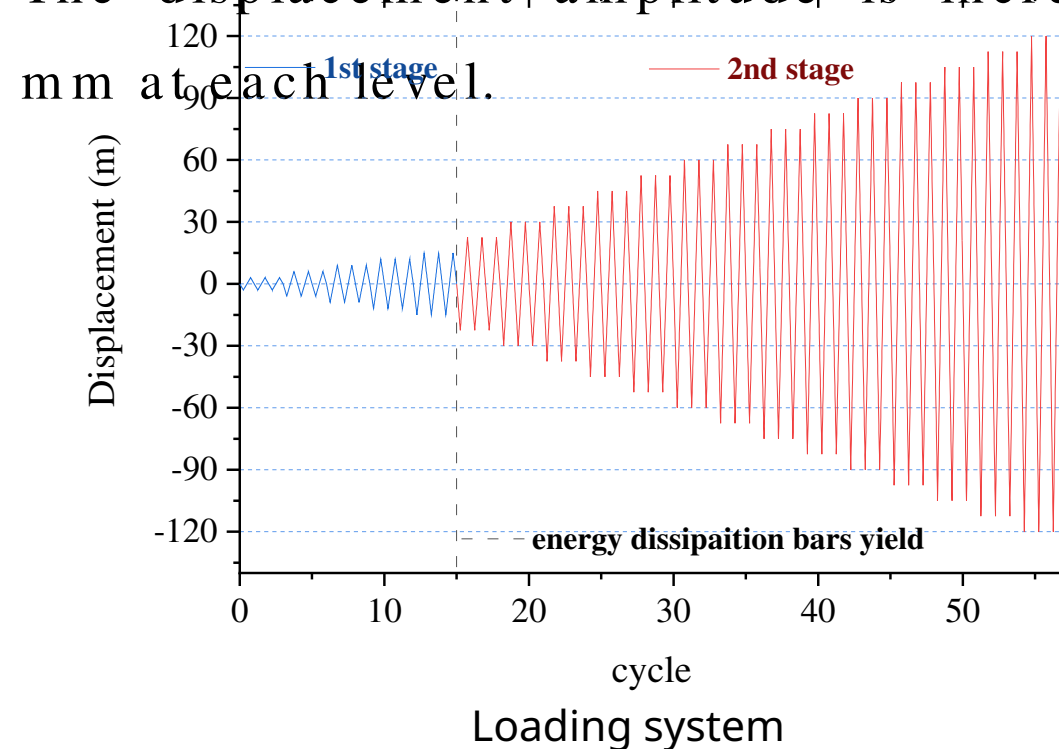
BRBs axial deformation



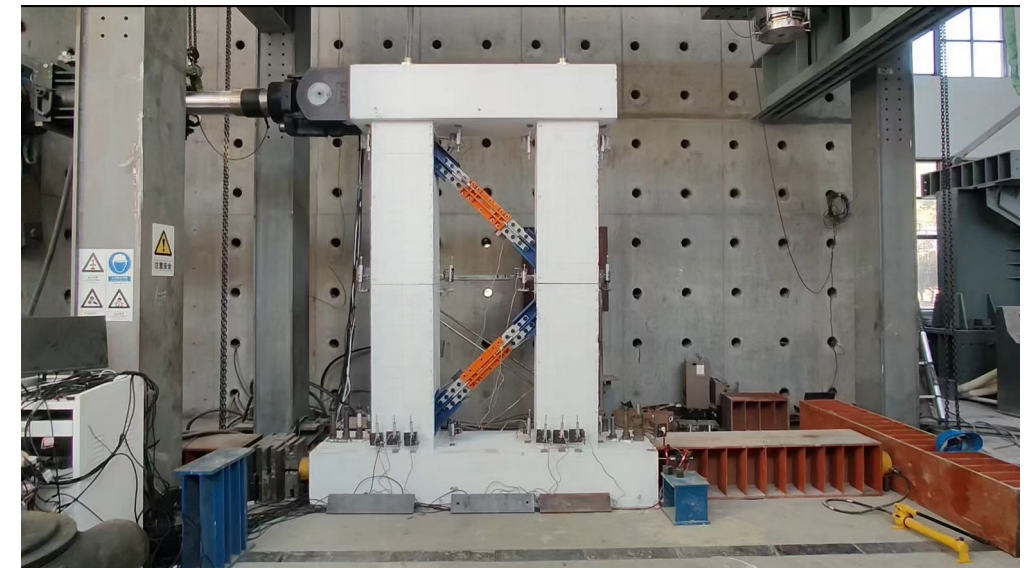
Compression zone depth

◆ Test loading protocol

- A mixed displacement control system is employed for the tests.
- The initial displacement amplitude is 3 mm, and is increased by 3 mm at each level, up to 15 mm.
- The displacement amplitude is increased by 7.5 mm at each level.



Specimen SCDP under cycle load



Specimen SCDP-BRBs under cycle load

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◆ Experimental phenomena

- Experimental phenomena and failure mode of the self-centering double-column pier (**Specimen SCDP**).

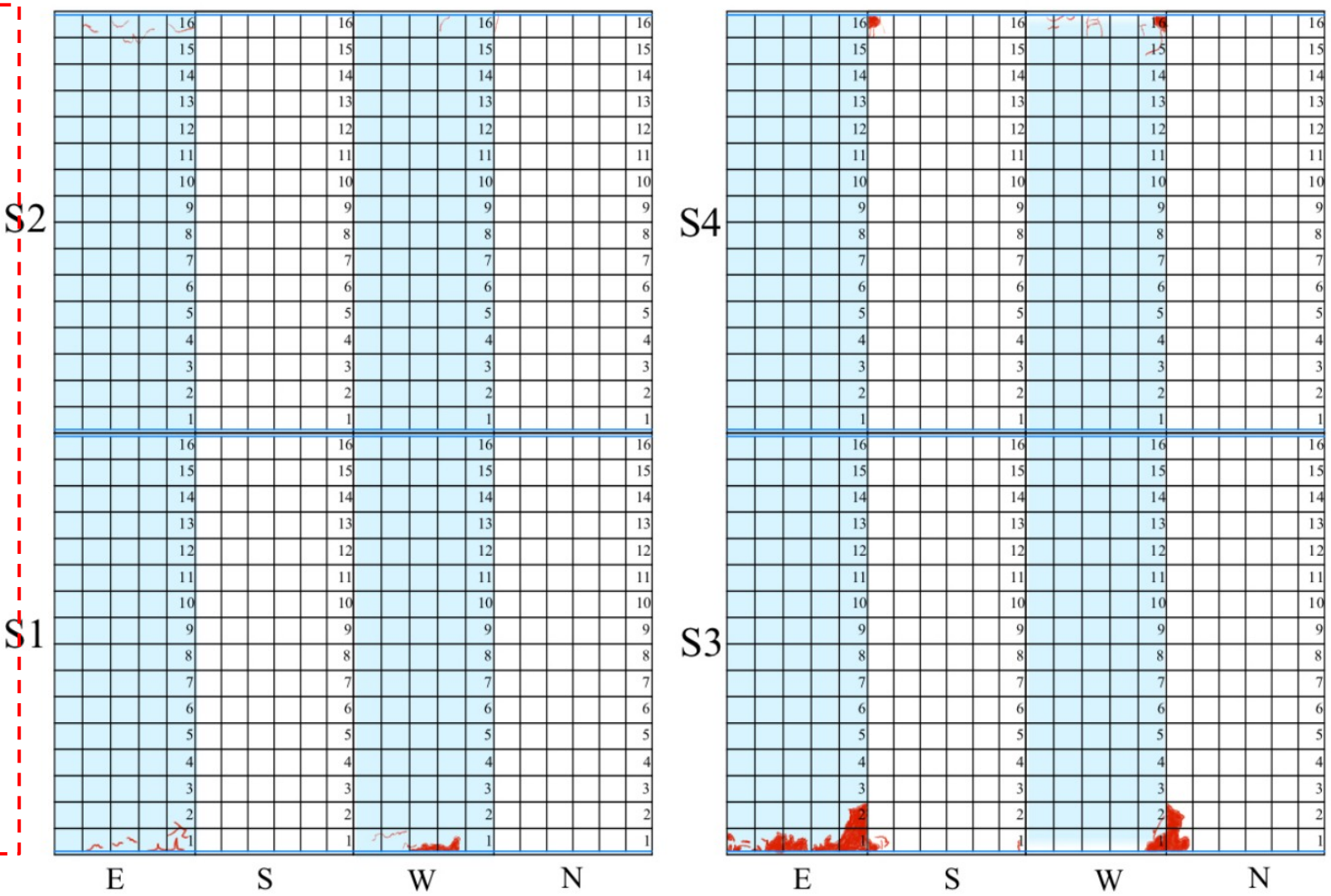


S2
top



S1
base

Concrete is slightly spalled at the **S2 top & S1 base at 120 mm.**





S4
top



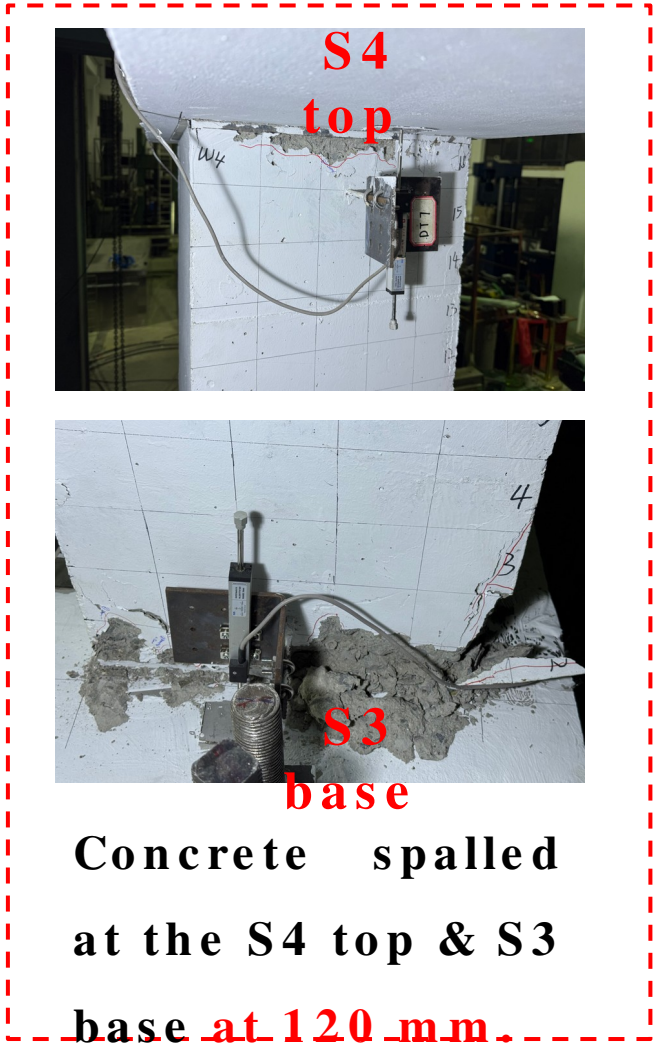
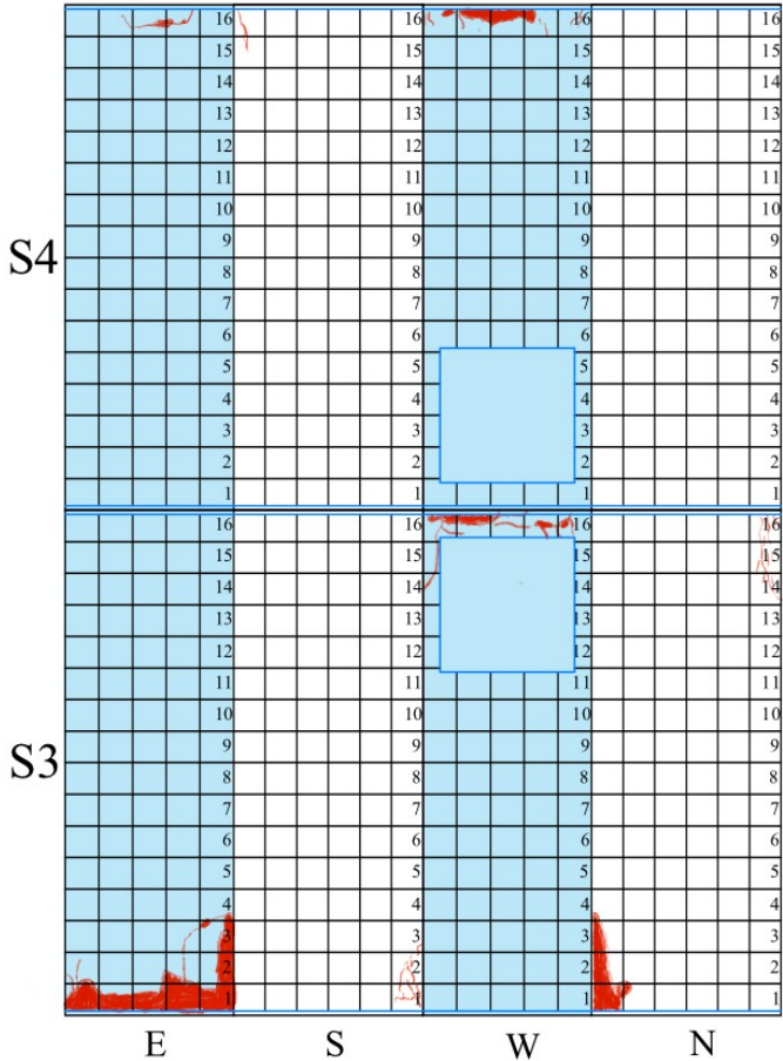
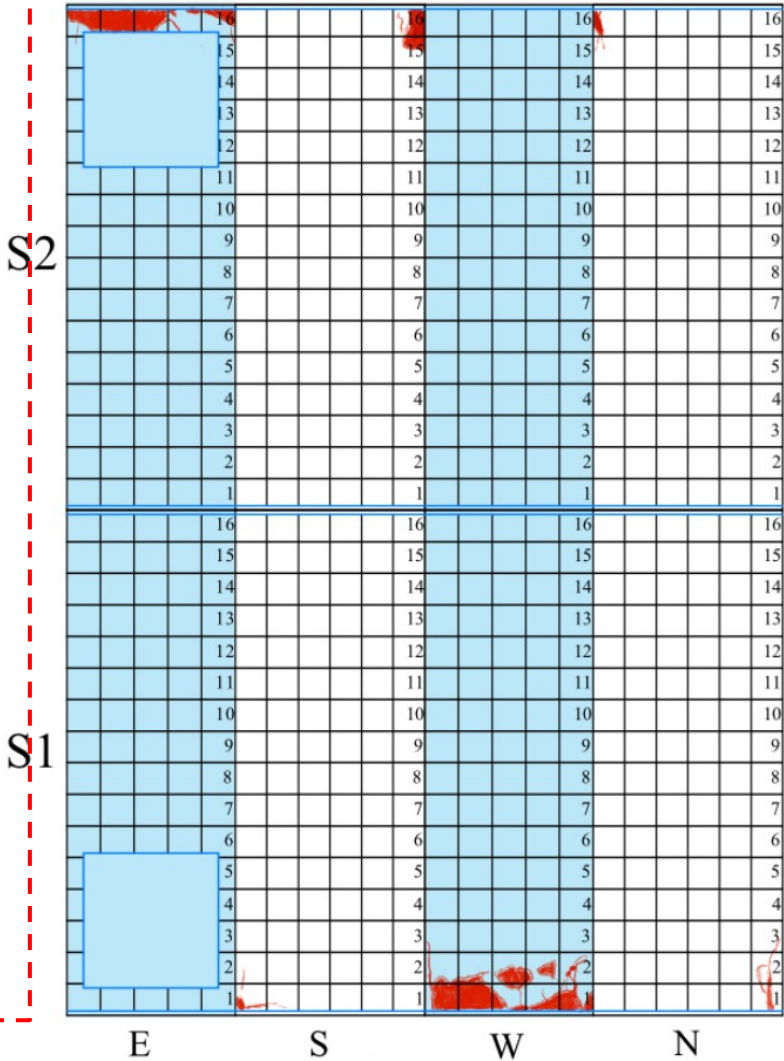
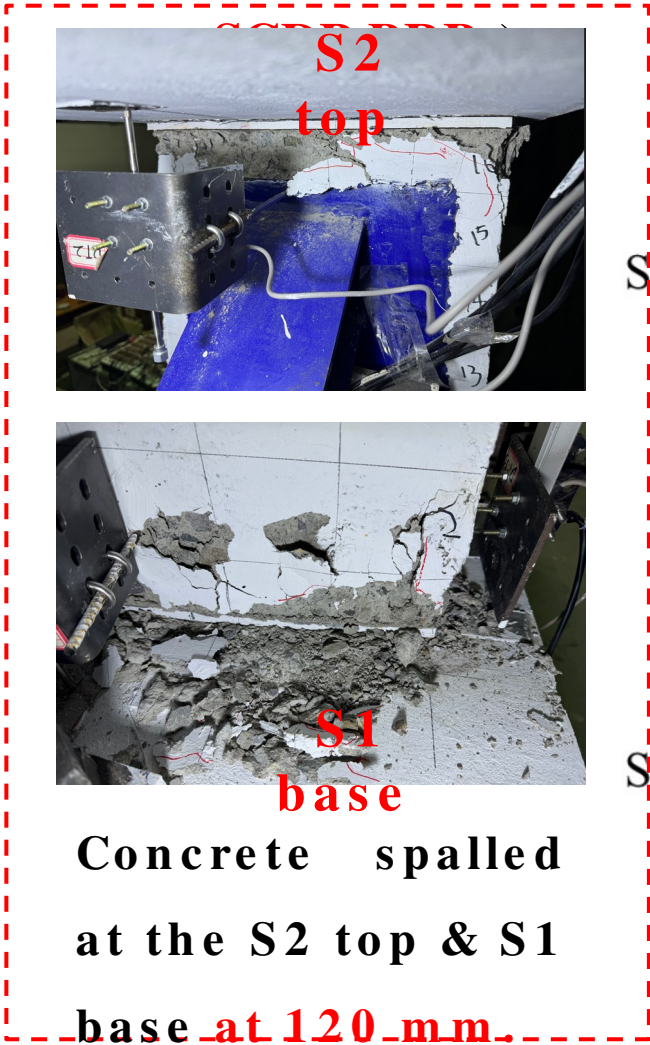
S3
base

Concrete is severely spalled at the **S4 top & S3 base at 120 mm.**

Failure mode and experimental phenomena of specimen SCDP

Experimental phenomena

- Experimental phenomena and failure mode of the self-centering double-column pier with BRBs (Specimen



Failure mode and experimental phenomena of specimen SCDP-BRBs

◆ Experimental phenomena

- Experimental phenomena and failure mode of the self-centering double-column pier with BRBs (**Specimen**



At 120 mm: slippage between the S1 and footing is **31.5 mm**; slippage between the S3 and S4 is **34 mm**.



37.5 mm: BRB1 fractured;
45.0 mm: BRB2 fractured.



90 mm: the BRB1 and BRB2 fractured again

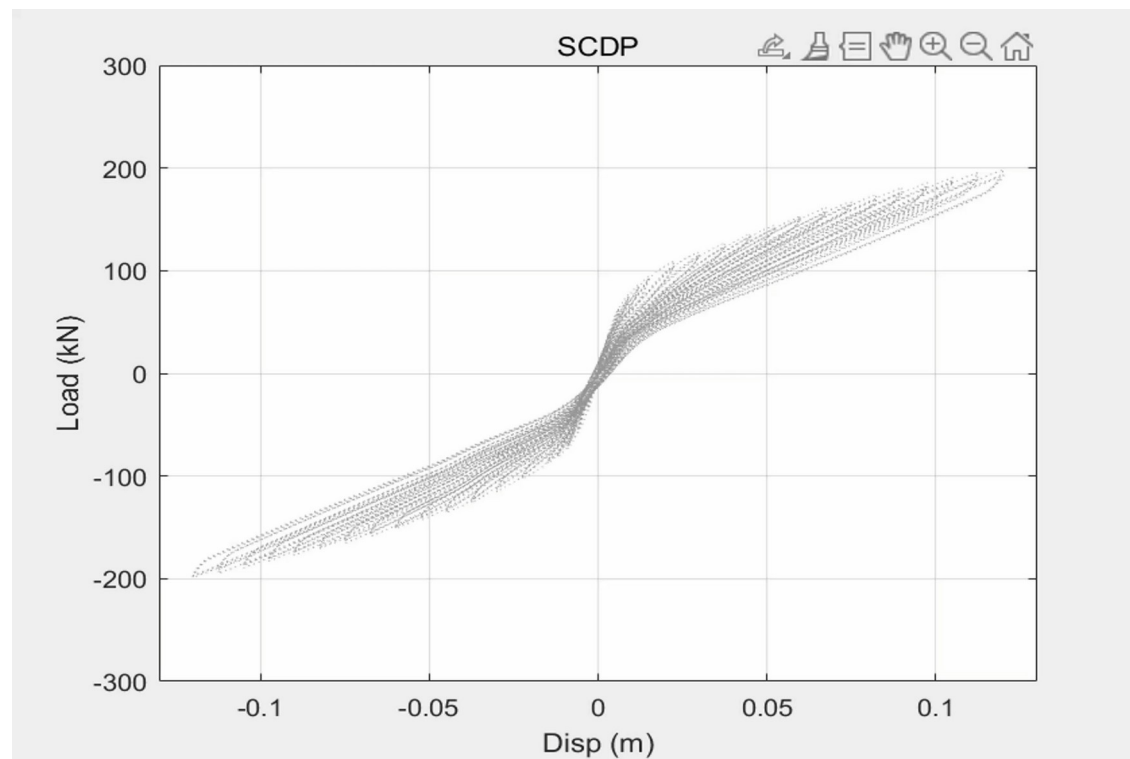


The test phenomena of the BRB core

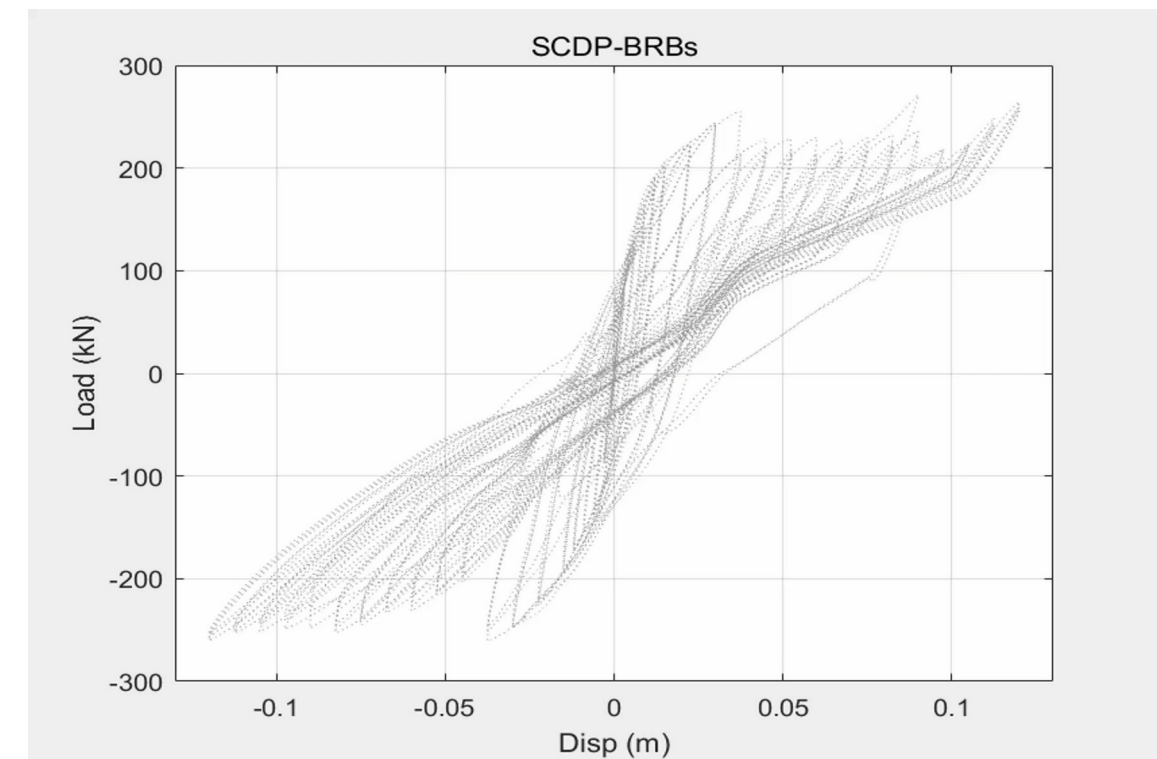
Failure mode and experimental phenomena of specimen SCDP-BRBs

◆ Hysteresis curve

- The hysteretic curves of the specimen SCDP-BRBs are fuller than those of the specimen SCDP.
- The hysteretic curves of the specimen SCDP are flag-shaped.
- After the BRBs in the SCDP-BRBs specimen fracture, the remaining hysteresis curves resemble a flag shape. However, asymmetric behavior is observed in the specimen SCDP-BRBs after the



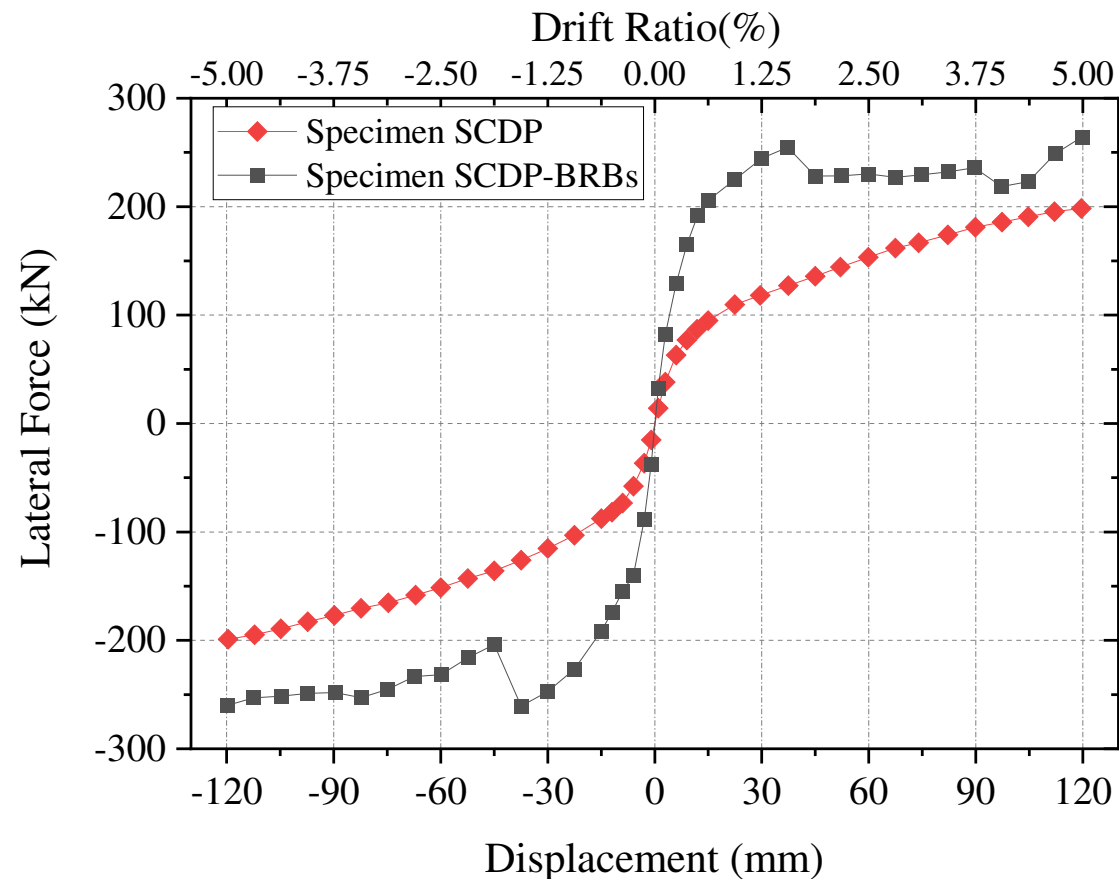
Hysteretic curves of Specimen SCDP



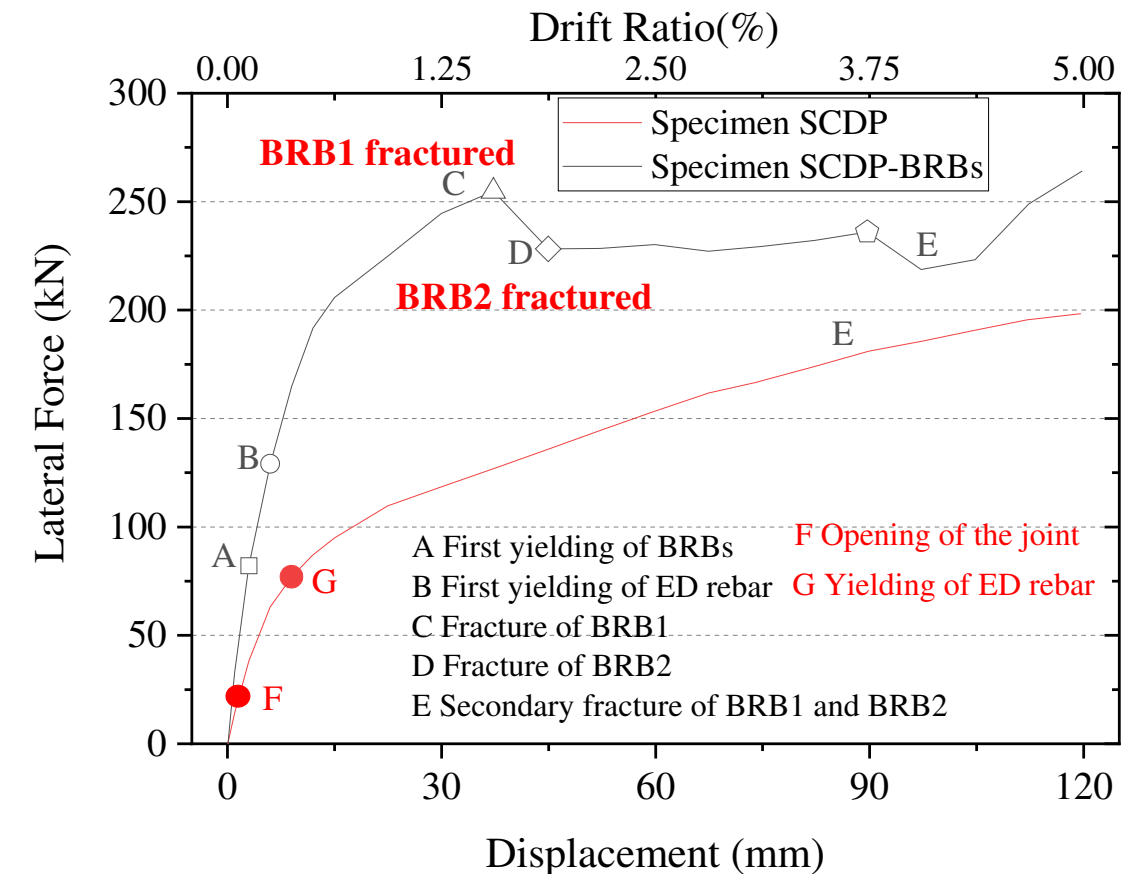
Hysteretic curves of Specimen SCDP-BRBs

◆ Skeleton curves

- The strength of SCDP-BRBs increased by **100.4%** at 37.5 mm and by **33.4%** at 120 mm compared to SCDP.
- **The BRBs yielded before the energy-dissipating steel bars**, satisfying the structural fuse concept.
- BRB1 fractured at 37.5 mm, while BRB2 fractured at 45 mm, corresponding to **points C and D**.



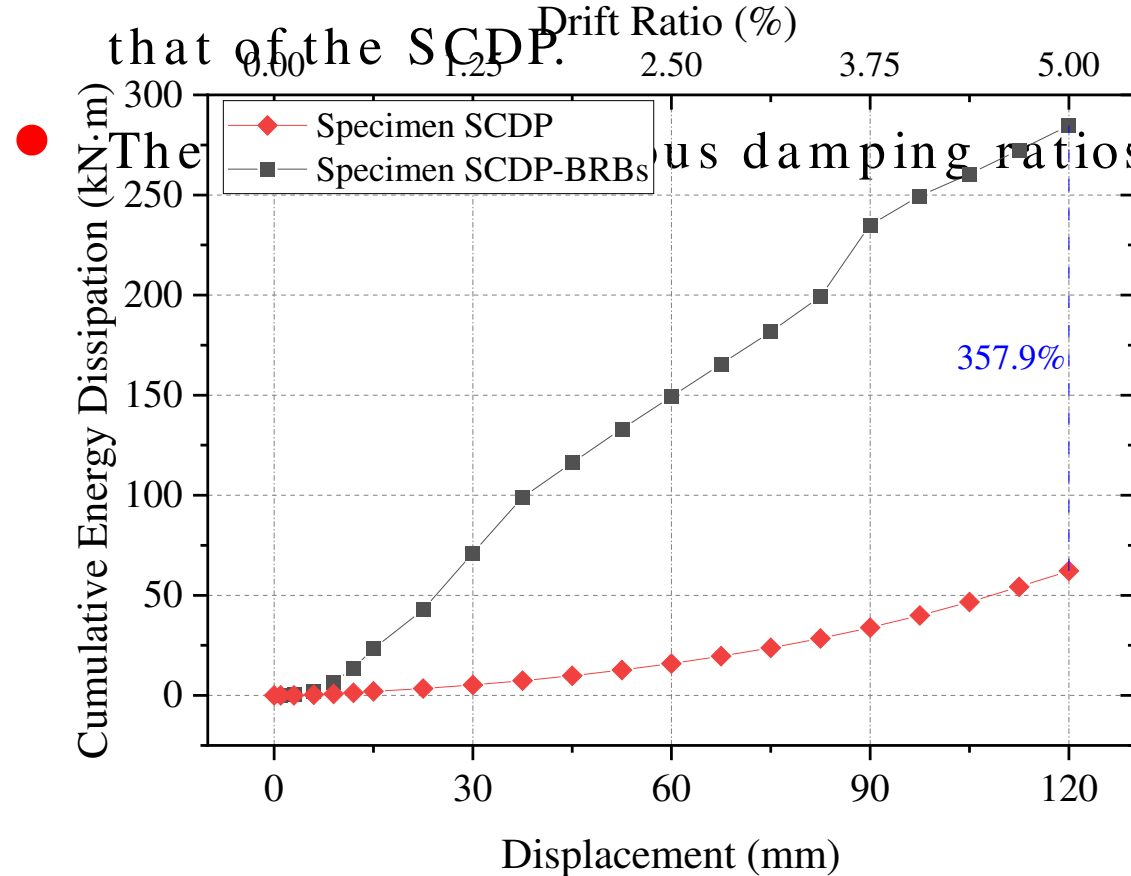
Skeleton curves of both specimens



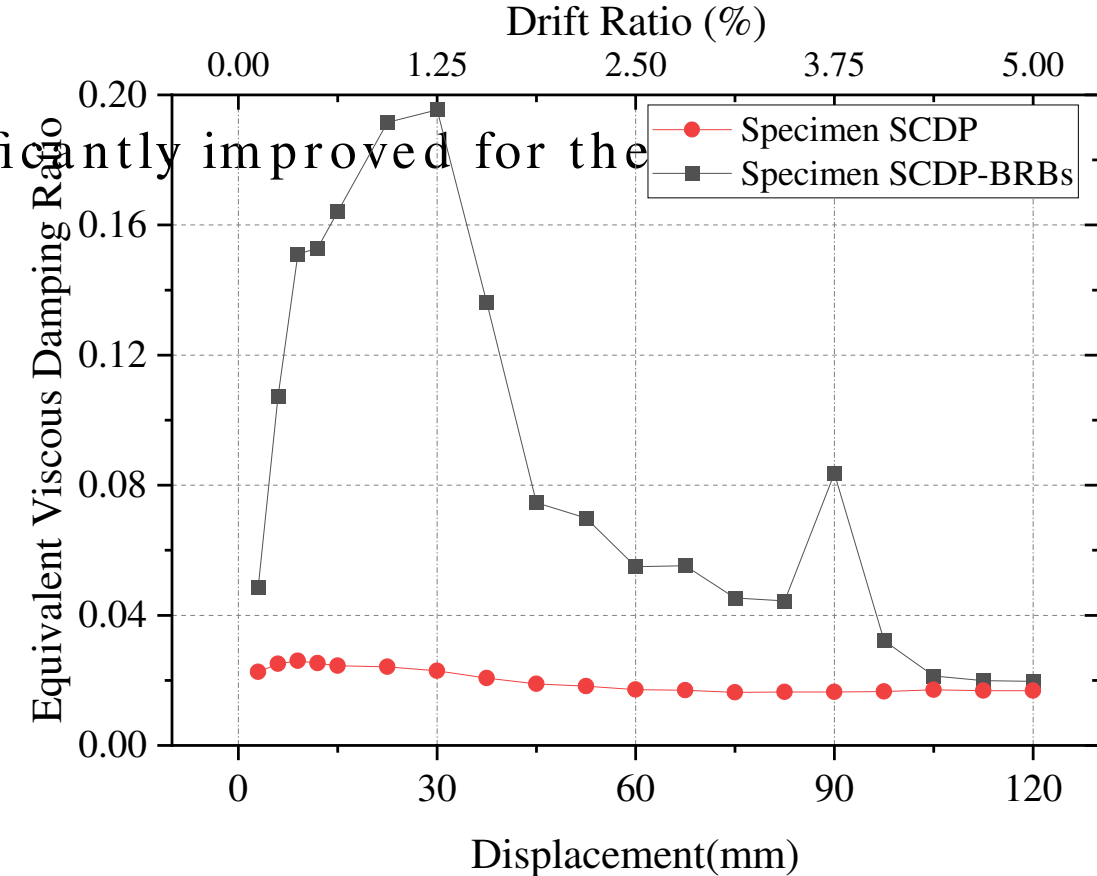
Key seismic performance of both specimens

Test Results

- The cumulative energy dissipation of the SCDP-BRBs is significantly higher than that of the SCDP due to BRBs.
- At 120 mm, the energy dissipation of the SCDP-BRBs is approximately 4.5 times greater than that of the SCDP.



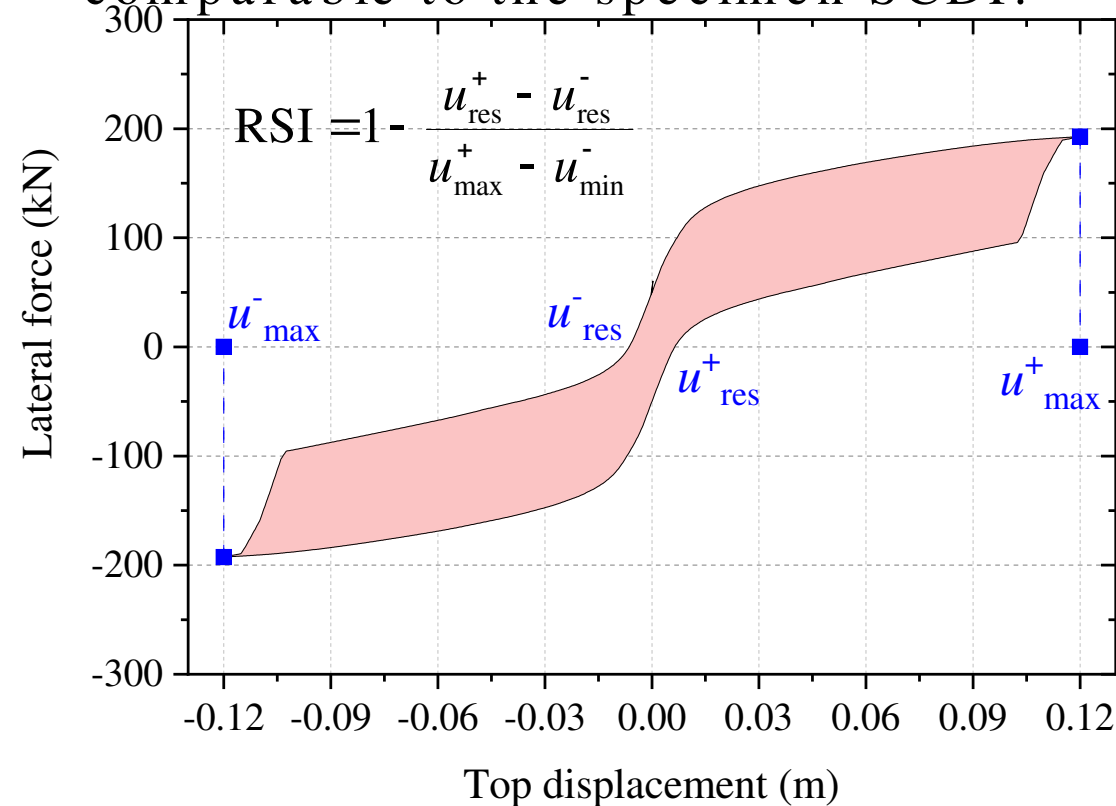
Cumulative energy dissipation



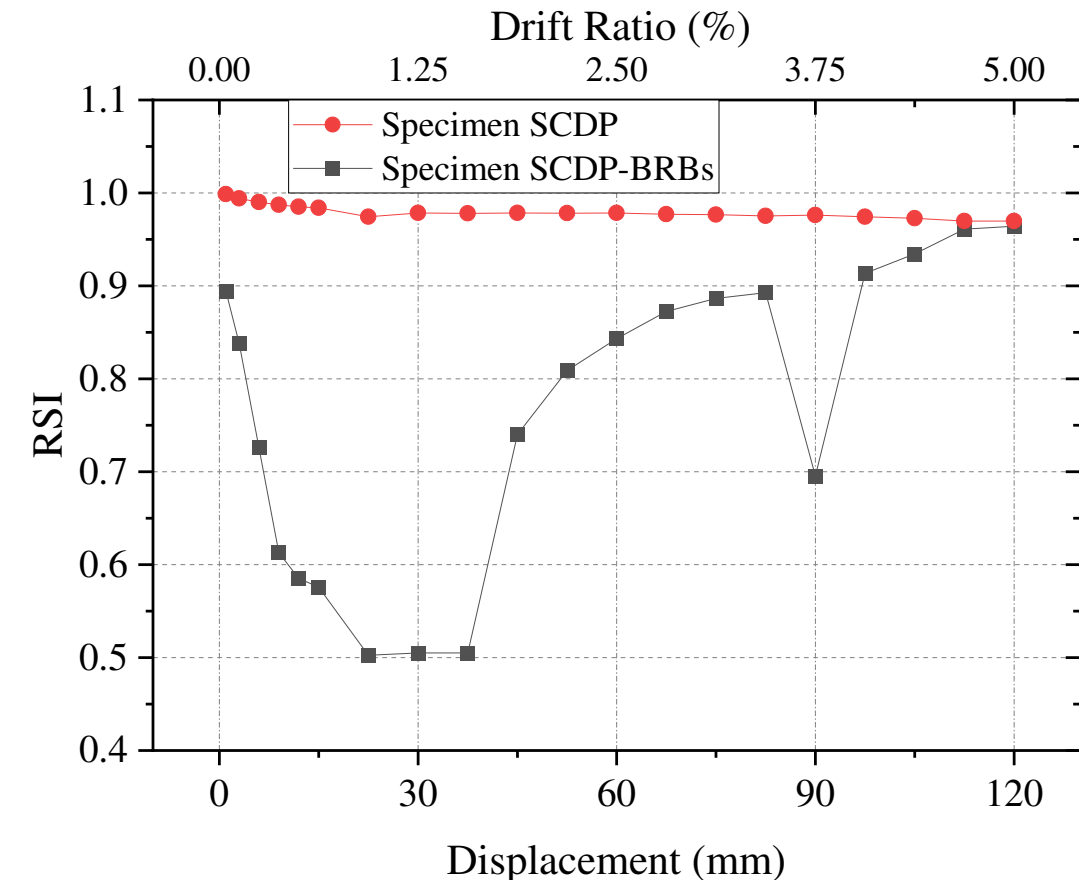
Equivalent viscous damping ratio

◆ Relative self-centering index

- Compared to the specimen SCDP, the residual displacement of the specimen SCDP-BRBs increased.
- However, as the BRBs fractured, the self-centering performance gradually improved, becoming comparable to the specimen SCDP.



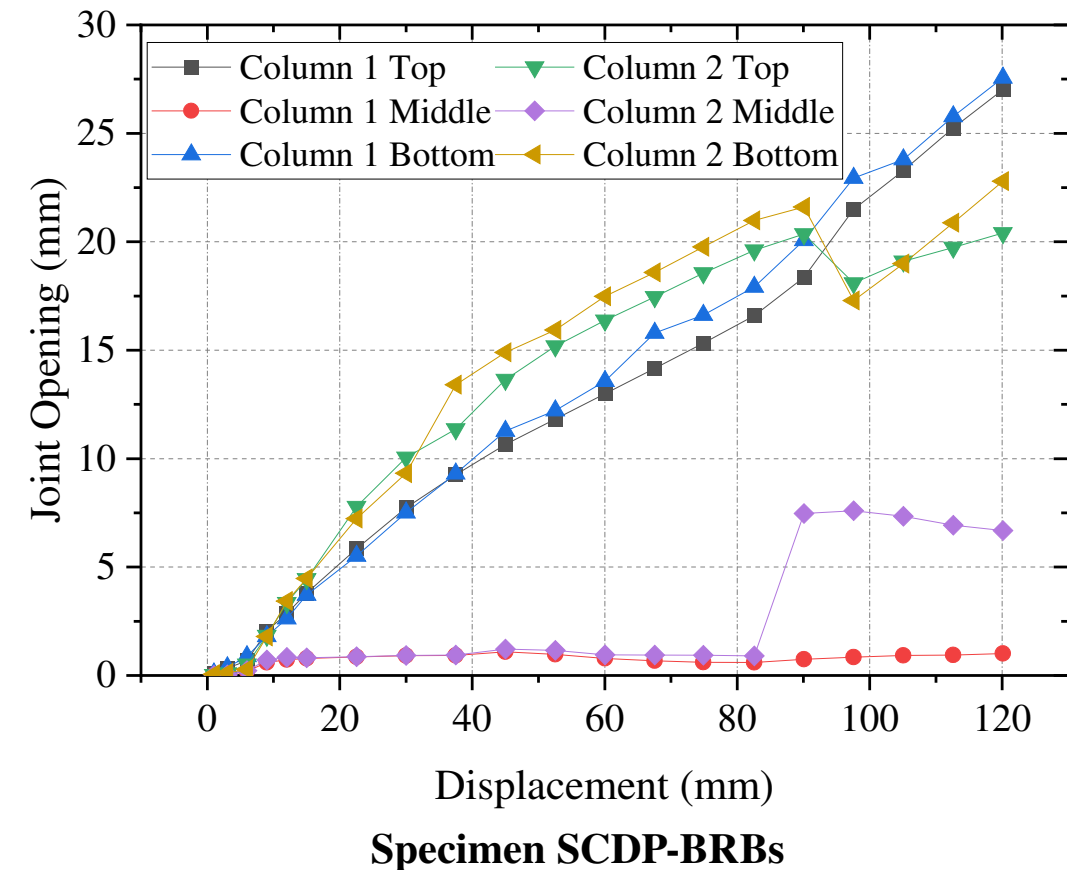
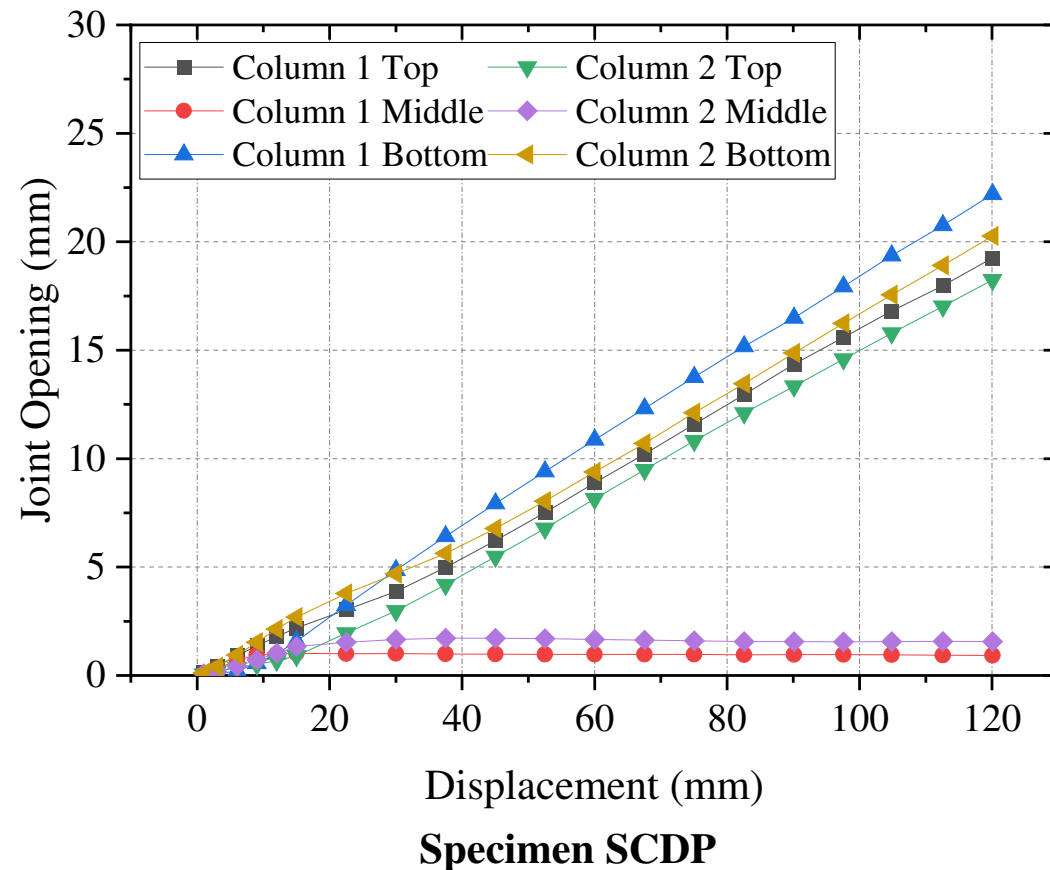
Calculation formula of RSI



Relative Self-Centering Index (RSI)

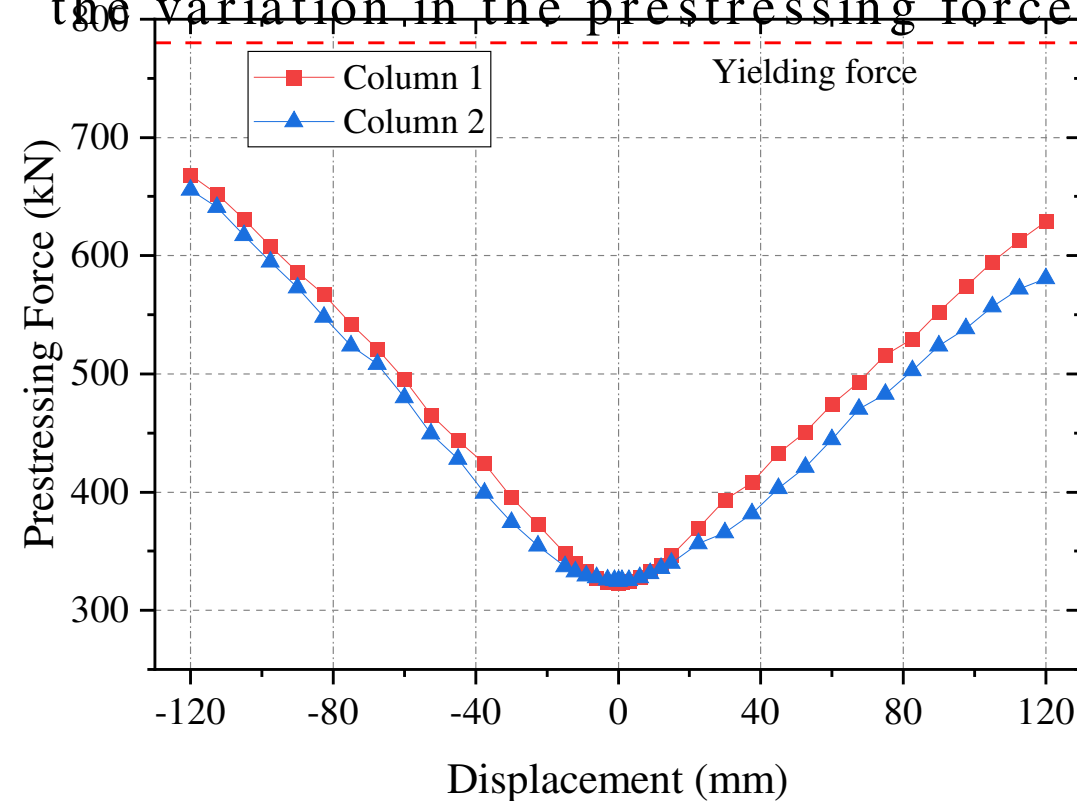
◆ Joint opening

- Significant opening/closing behaviors were observed at the base and top joints of Specimen SCDP; However, only minor deformation was noted at the middle joints.
- BRBs significantly affected the joint opening/closing behaviors of Specimen SCDP-BRBs. The sudden deformation of Column 2 can be attributed to slippage between Segments S3 and S4.

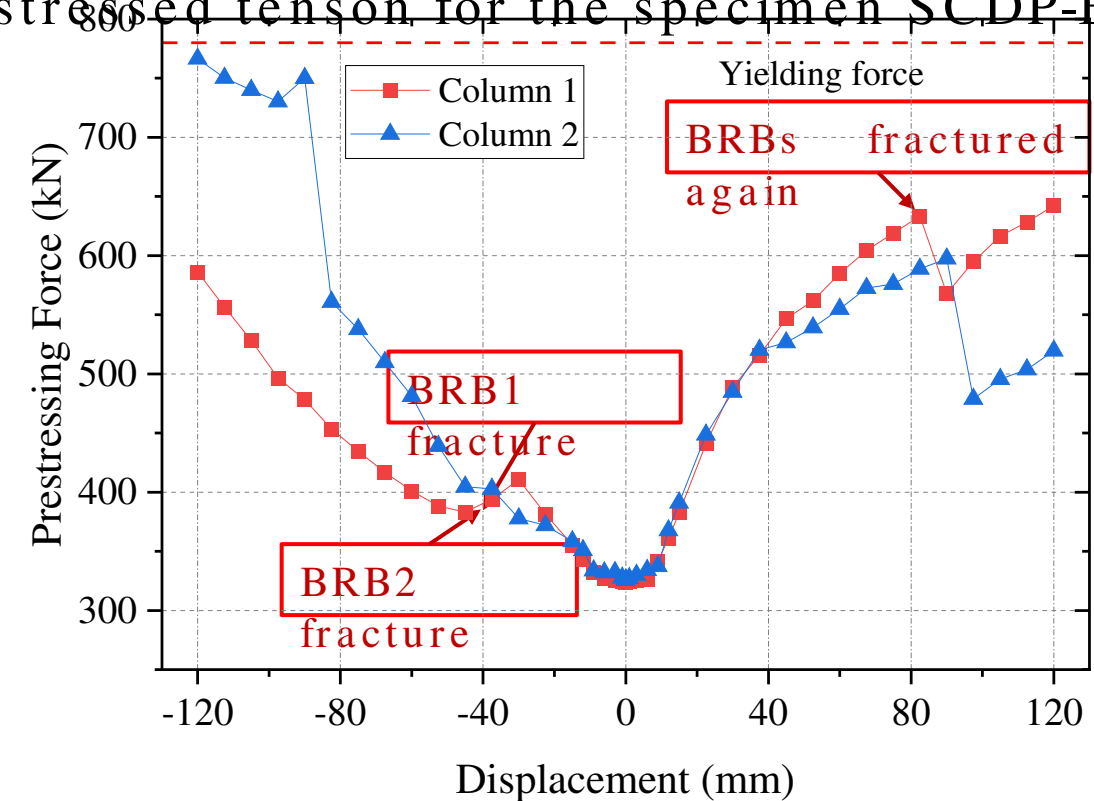


◆ Prestressing force of the prestressed tendon

- Prestressed tendons remained elastic during the test process for specimens SCDP and SCDP-BRBs.
- However, the slippage of precast segments and the fracture of the BRBs significantly affected the variation in the prestressing force of the prestressed tendon for the specimen SCDP-BRBs.



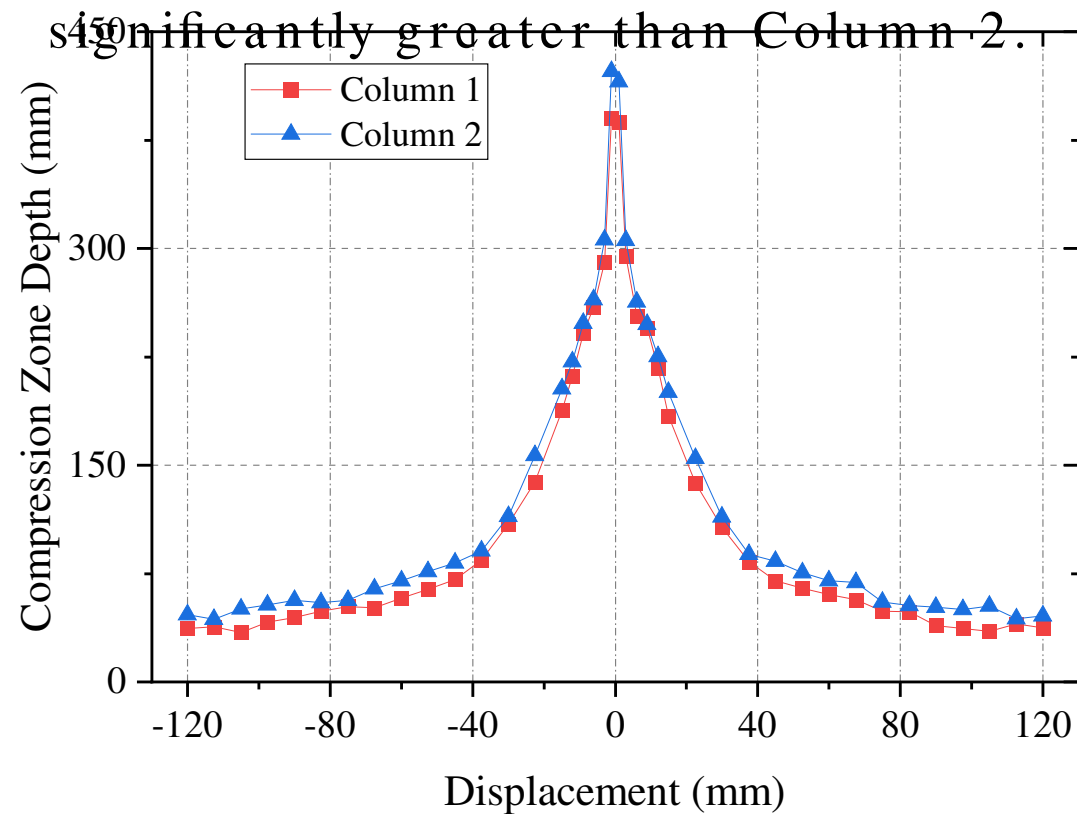
Specimen SCDP



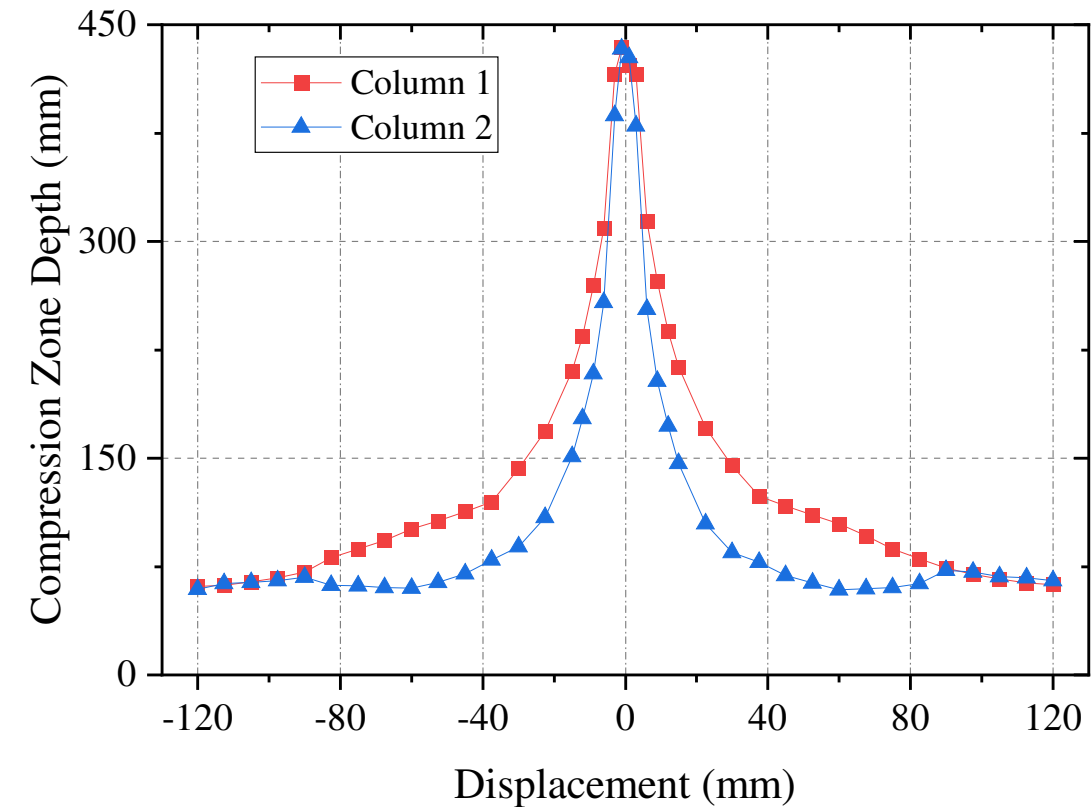
Specimen SCDP-BRBs

◆ Compression zone height

- Specimen SCDP displayed similar, symmetric compression zone heights at the segment base between columns.
- In contrast, Specimen SCDP-BRBs showed an asymmetry at the segment base, with Column 1



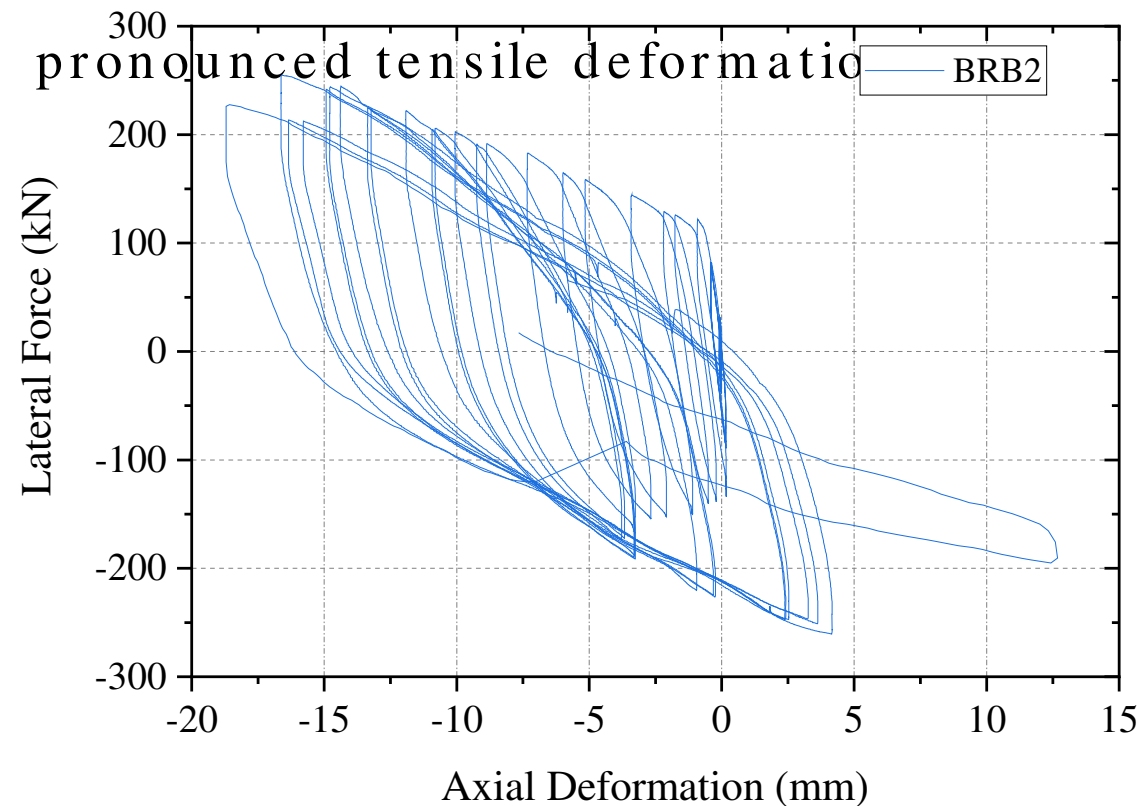
Specimen SCDP



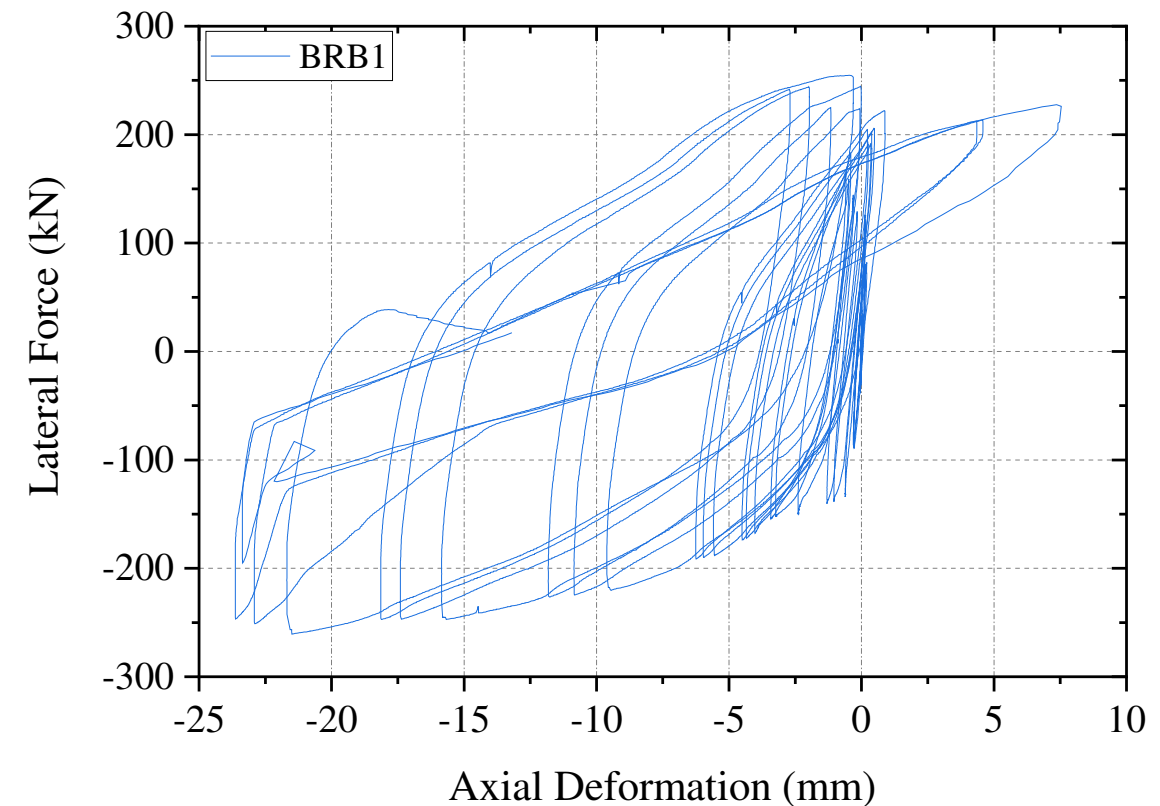
Specimen SCDP-BRBs

◆ Hysteretic curves of BRBs

- Full hysteretic loops of BRBs significantly enhanced the energy dissipation in the specimen SCDP-BRBs.
- However, a noticeable tension-compression asymmetry was observed in BRBs, with more



Specimen SCDP-BRBs



Specimen SCDPSCDP-BRBs

1 Introduction

2 Design of self-centering double-column pier models

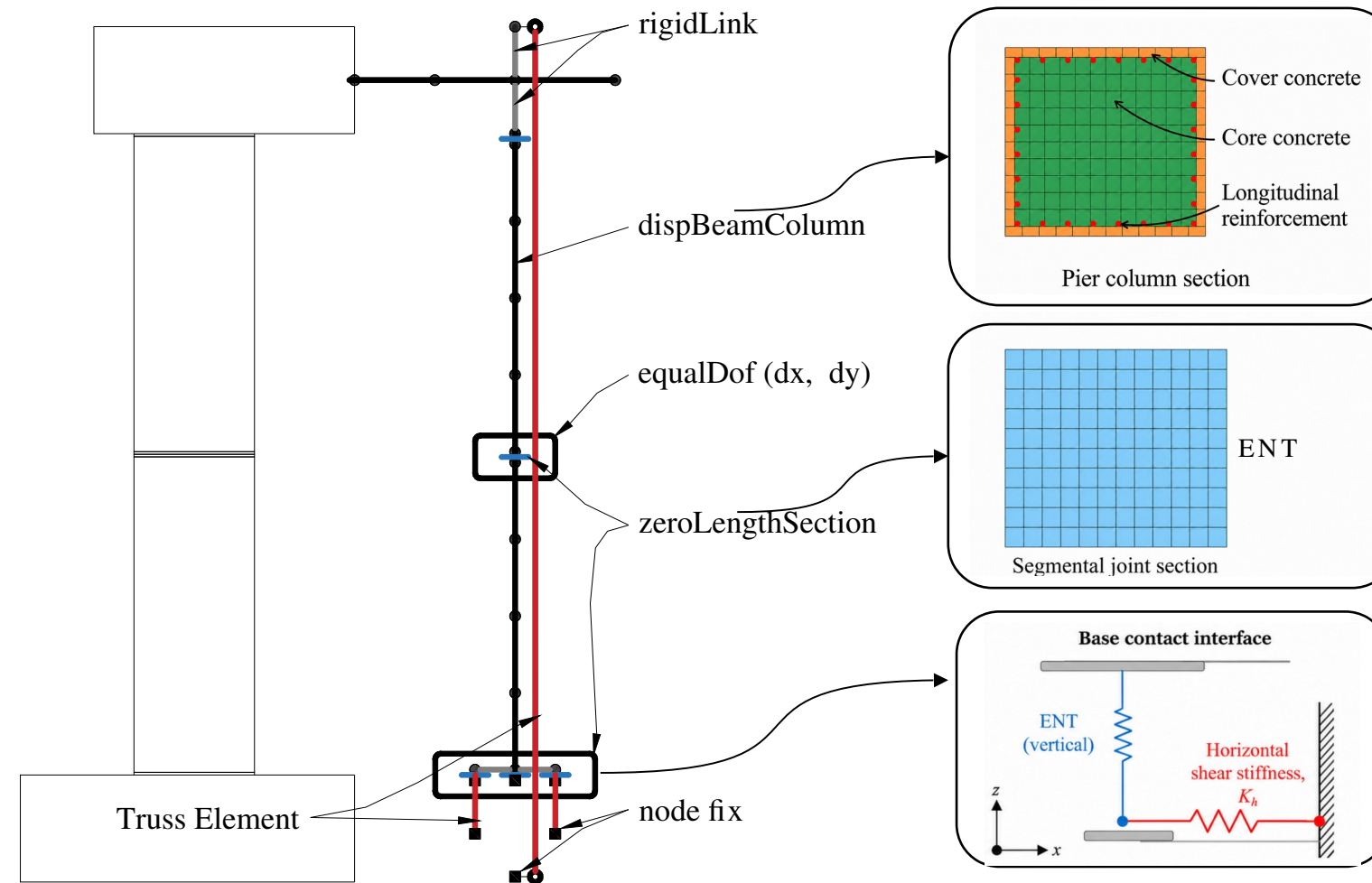
3 Experimental results

4 **Numerical results**

5 Conclusions

◆ Fiber element model of specimen SCDP

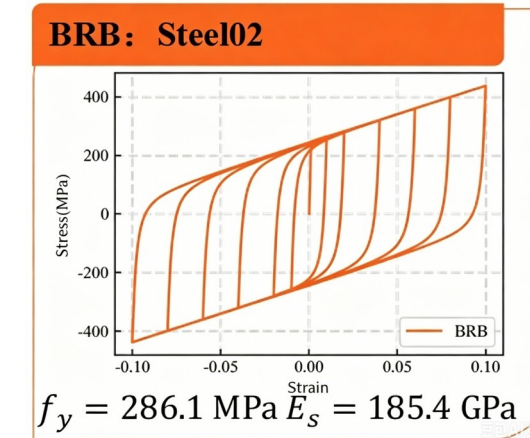
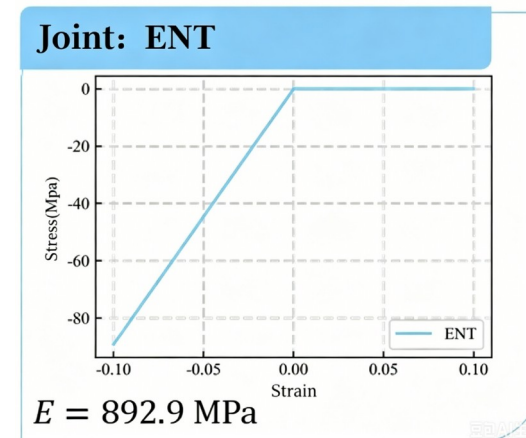
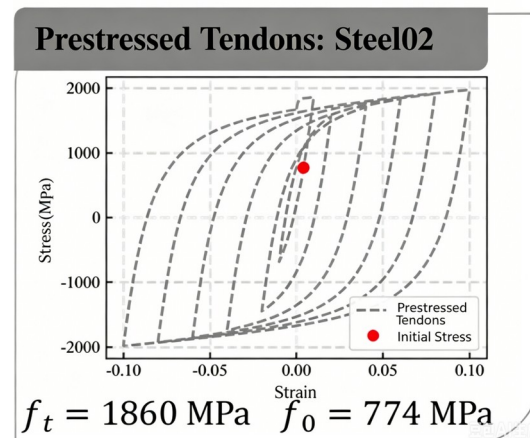
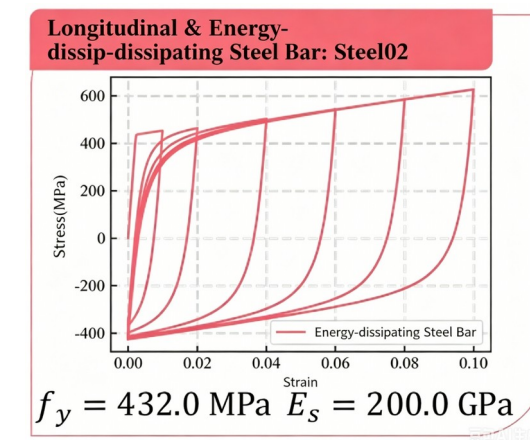
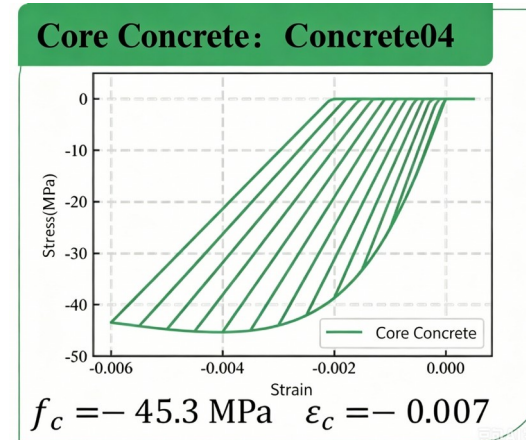
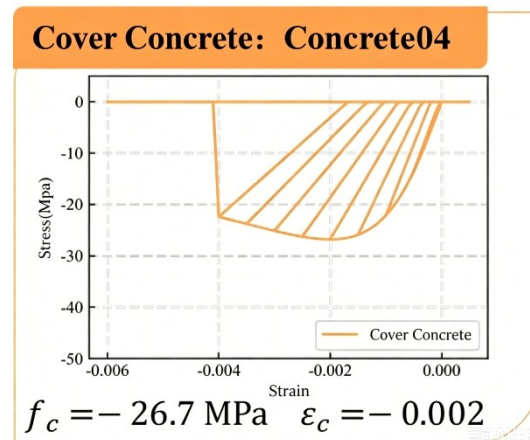
- Cap beam and precast segments: **fiber dispBeamColumn** elements
- Prestressing tendons and energy-dissipating rebars: **truss elements**
- Joints: **zero-length section elements**



Fiber element model of specimen SCDP

◆ Fiber finite element model of specimen SCDP

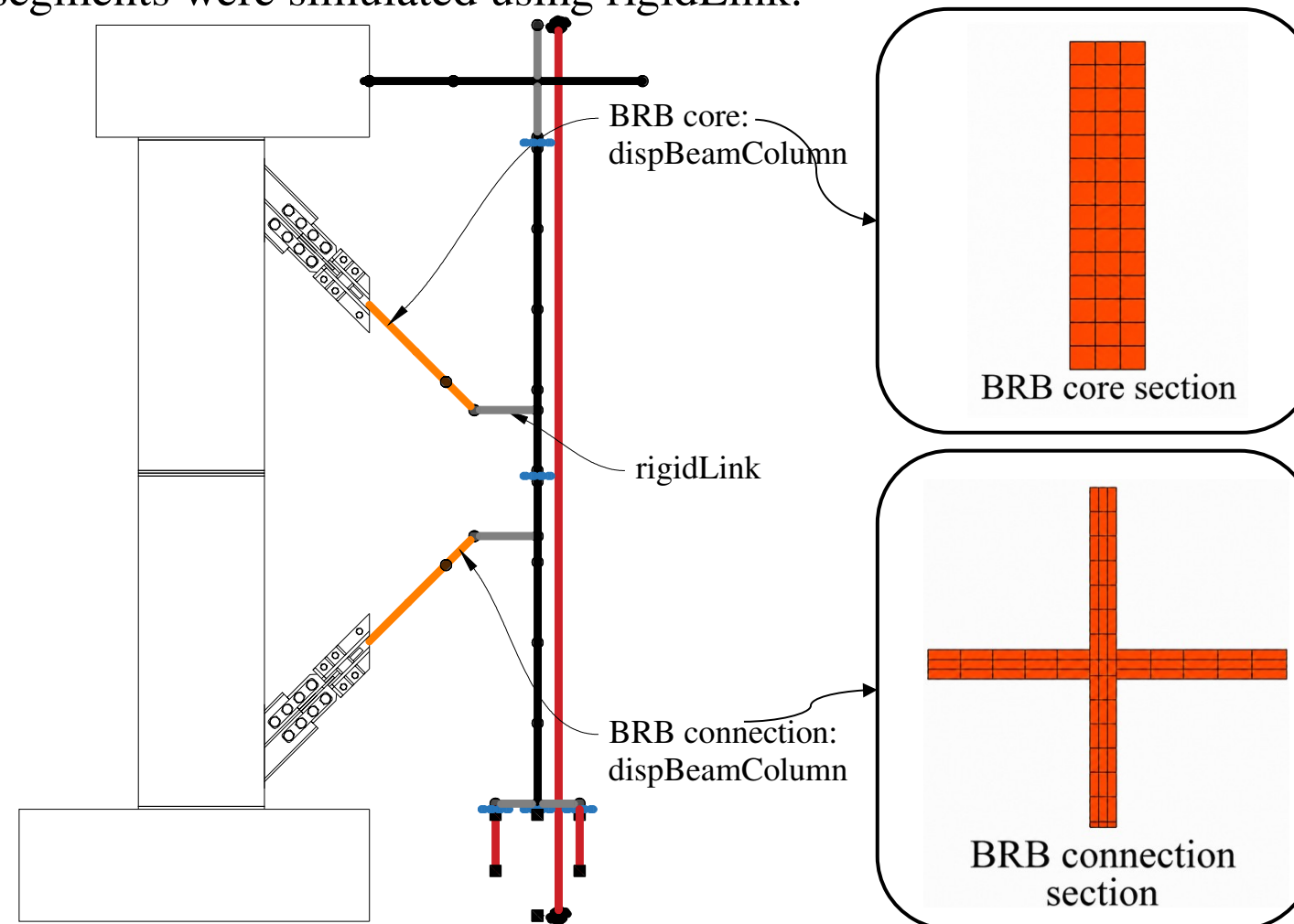
- Concrete: **Concrete04** constitutive model
- Joints: **ENT** constitutive model
- Longitudinal rebars, prestressing tendons, and energy-dissipating rebars: **Steel02** constitutive model



Material Constitutive Models

◆ Fiber finite element model of specimen SCDP-BRBs

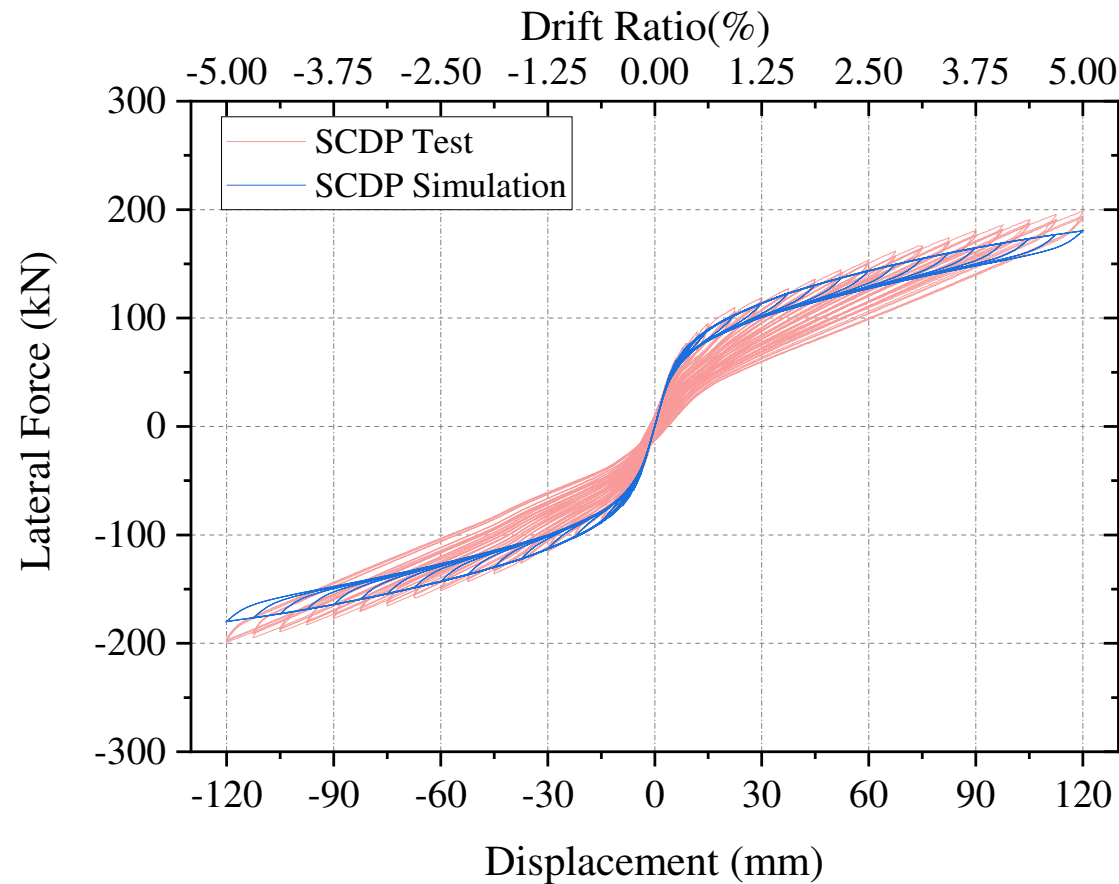
- BRB core and connection segments were modeled using fiber dispBeamColumn elements.
- The BRB embedded segments were simulated using rigidLink.
- BRBs: **Steel02**



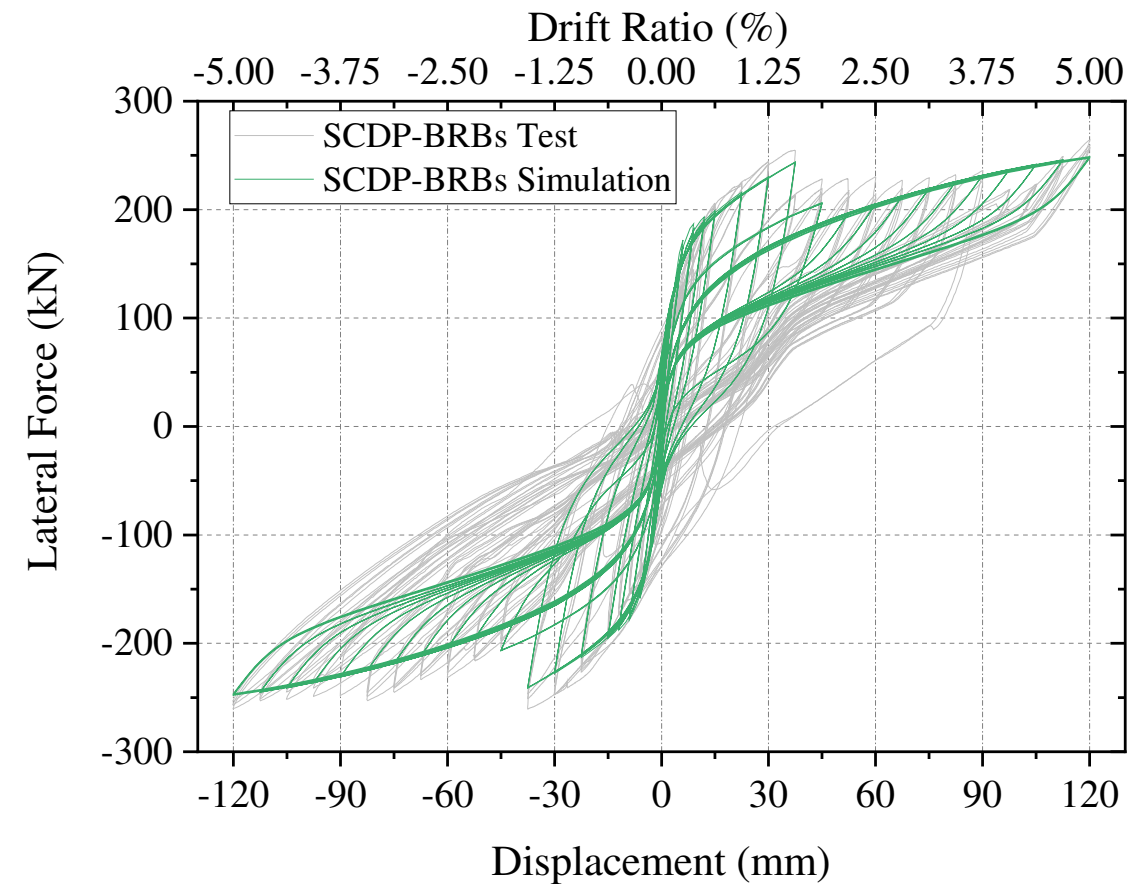
Fiber element model of specimen SCDP-BRBs

◆ Hysteresis curves

- Numerical results for both specimens **generally agree with test results**.
- The fiber finite element models can accurately reproduce hysteretic behavior, lateral force, and stiffness variation.



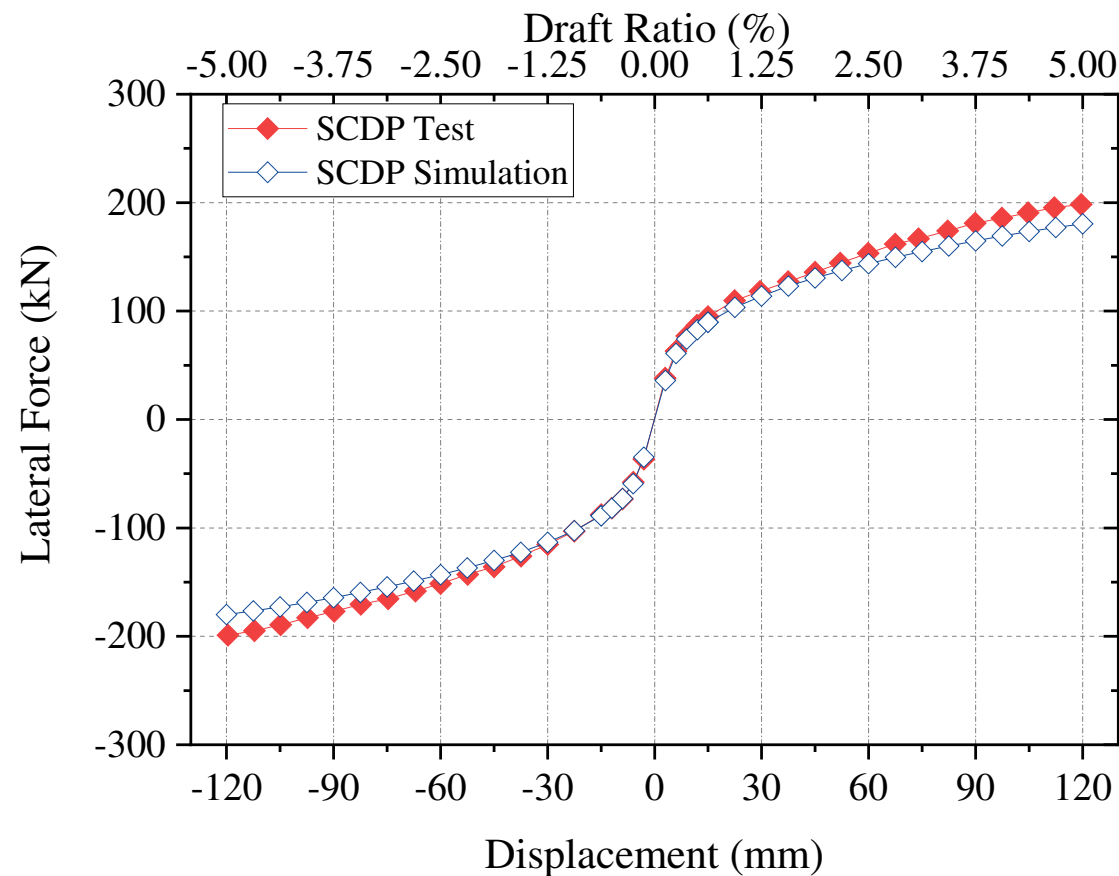
Specimen SCDP



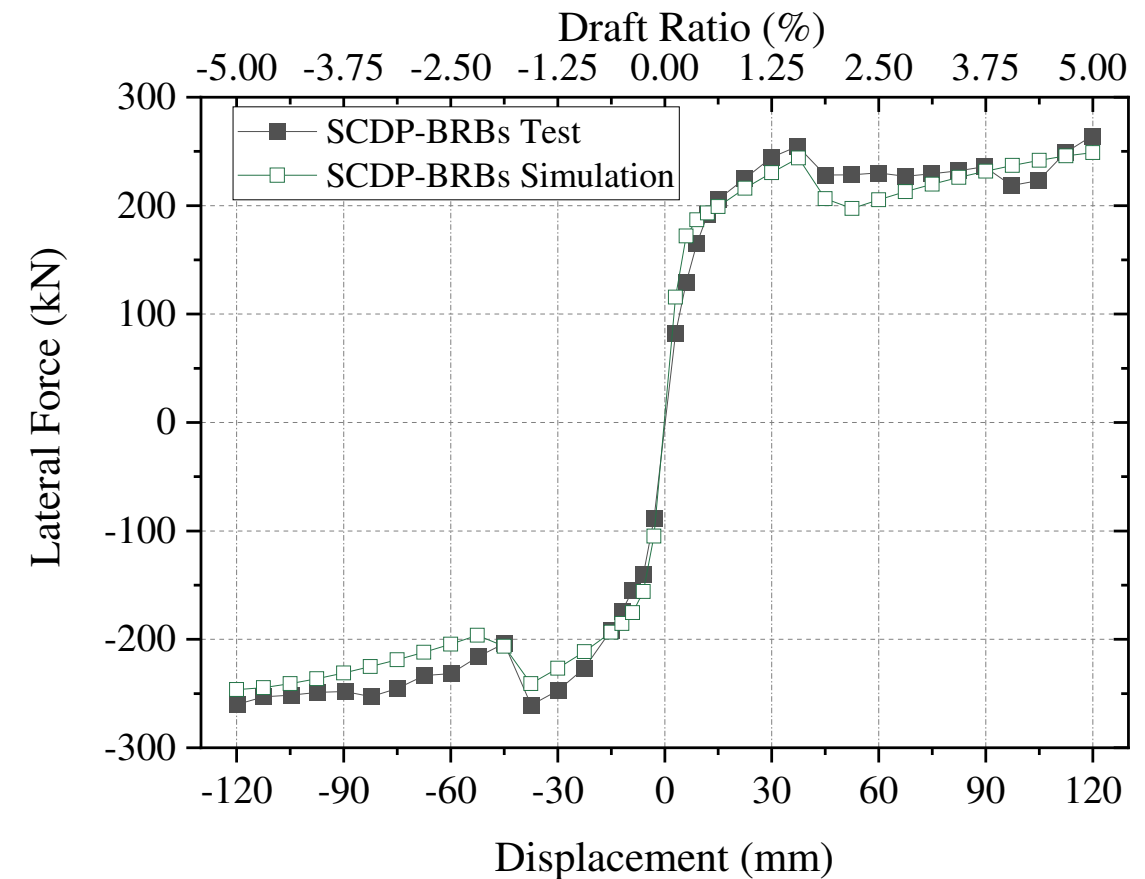
Specimen SCDP-BRBs

◆ Skeleton Curves

- Numerical results agree well with experimental lateral forces for both specimens.
- Average errors: **5.5 %** for Specimen SCDP and **8.6 %** for Specimen SCDP-BRBs.



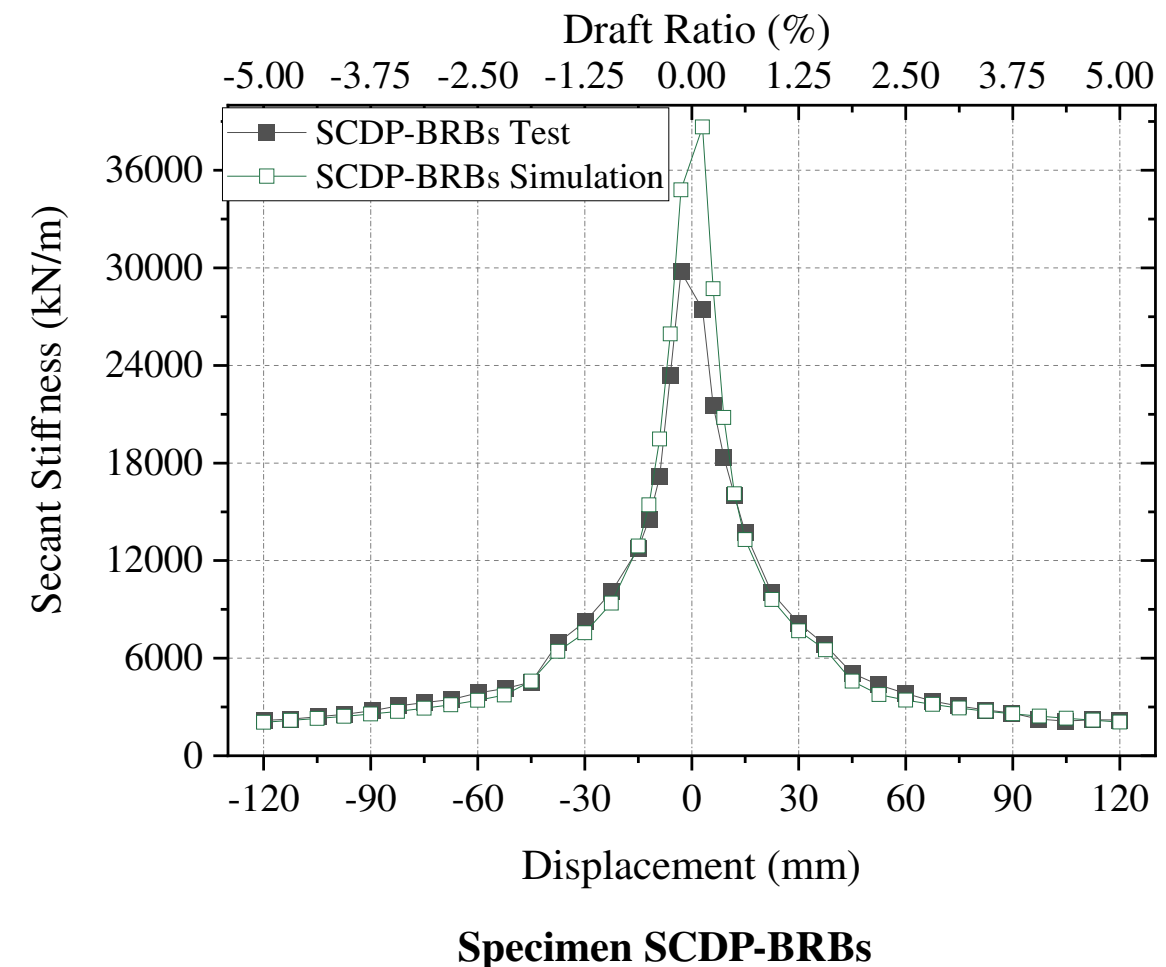
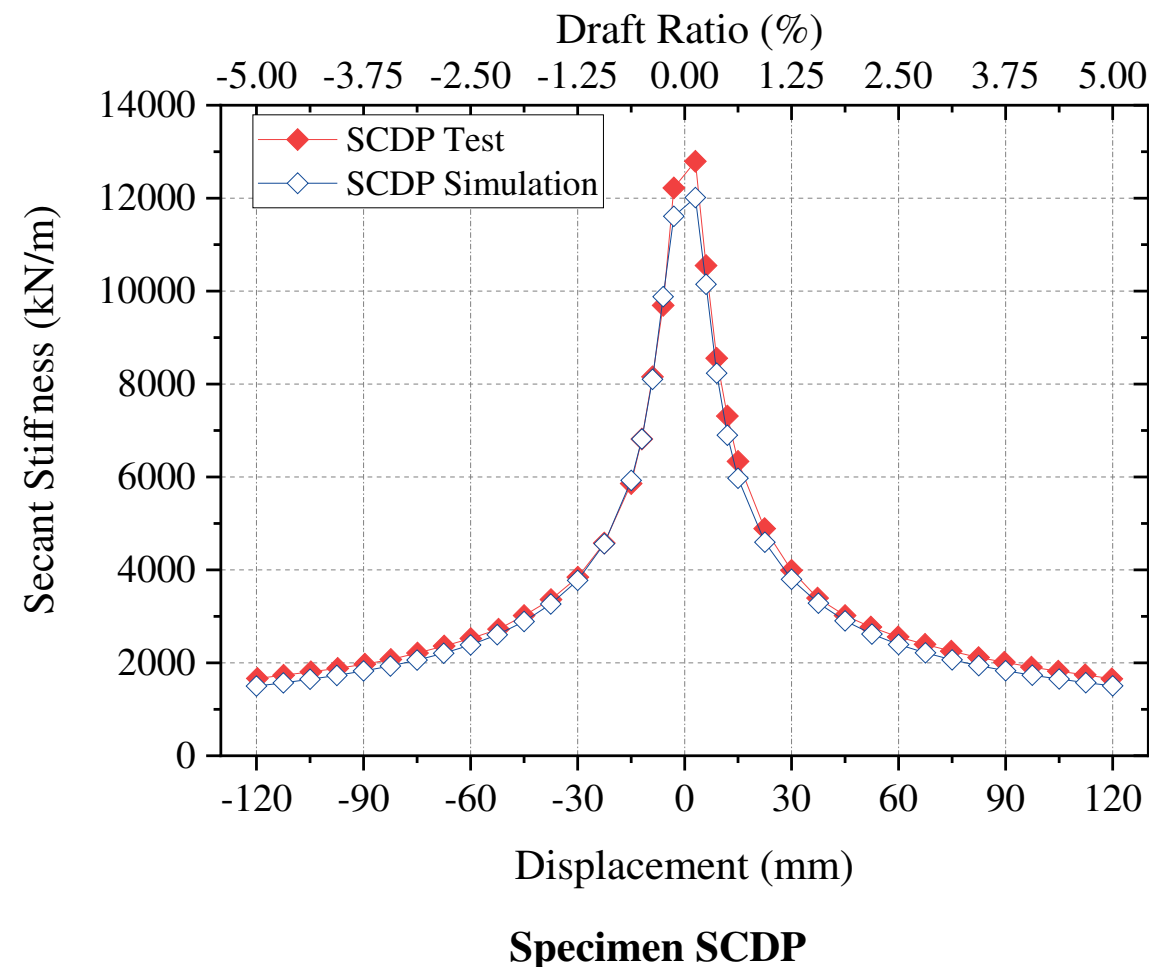
Specimen SCDP



Specimen SCDP-BRBs

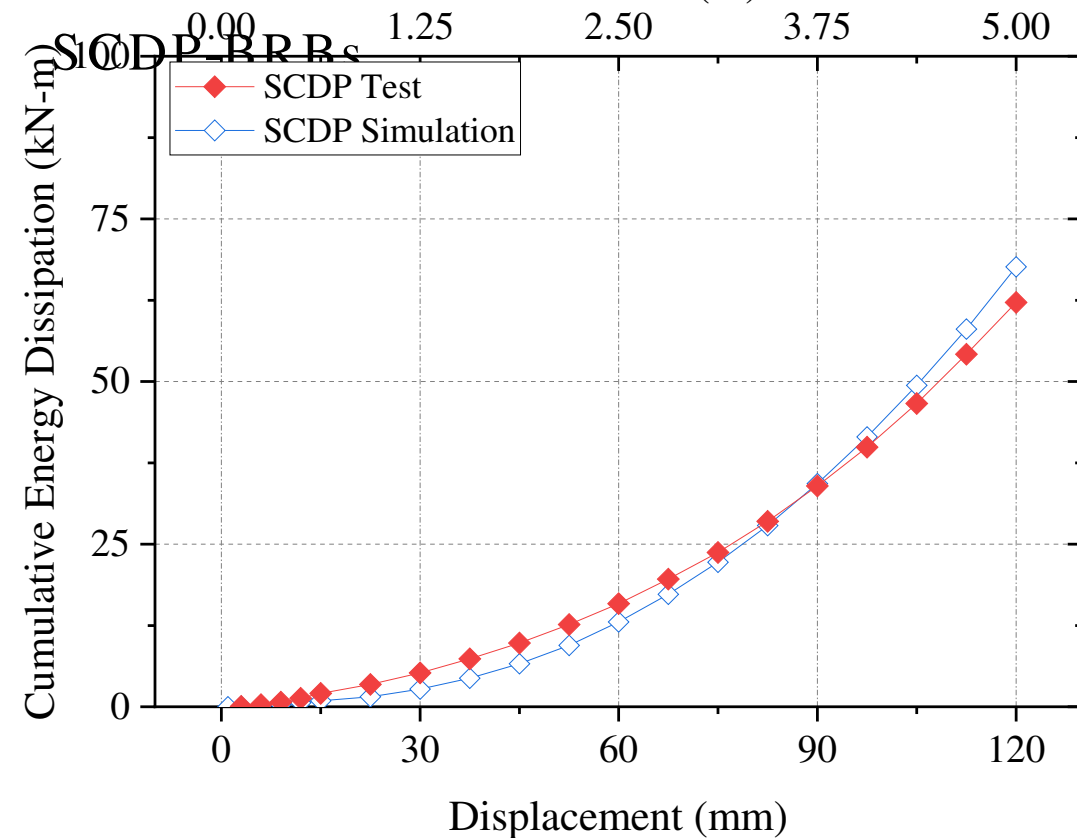
◆ Secant Stiffness

- The fiber finite element models accurately reproduce the stiffness degradation for both specimens.
- Average errors: **5.7 %** for Specimen SCDP and **8.7 %** for Specimen SCDP-BRBs.

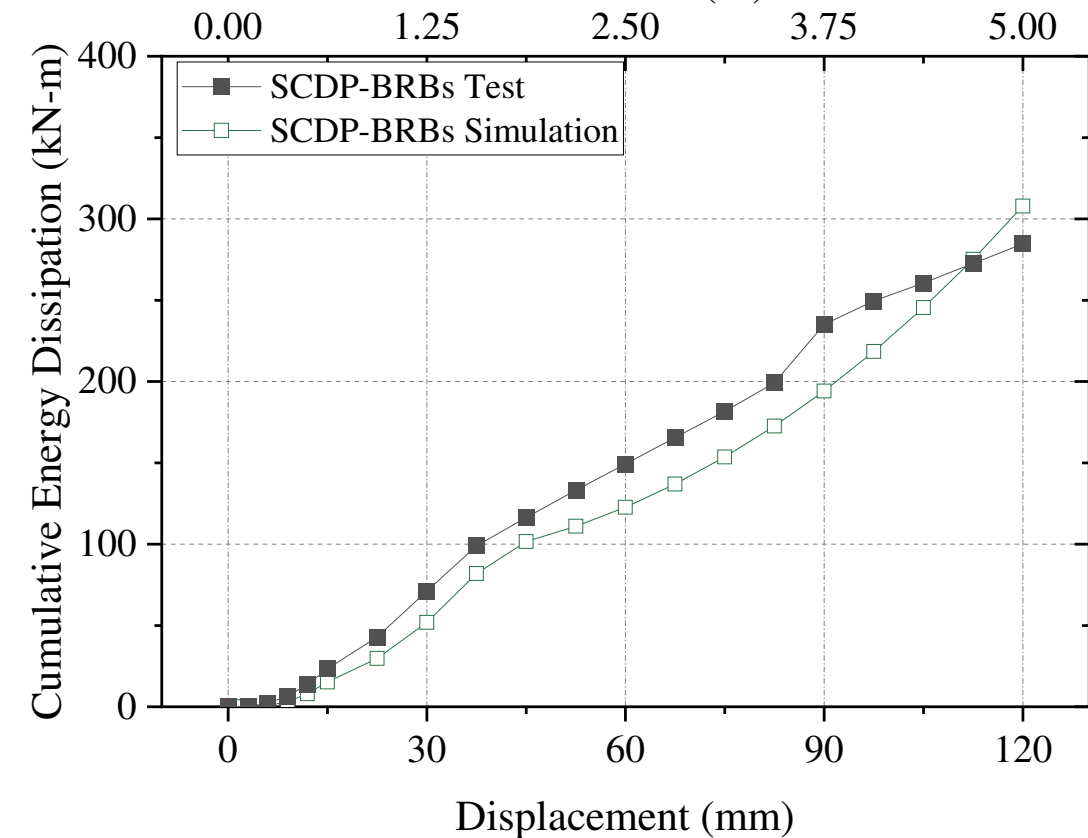


◆ Cumulative Energy Dissipation

- The fiber finite element models effectively capture the cumulative energy dissipation for both specimens.
- The errors at the maximum displacement are **8.8 %** for Specimen SCDP and **7.6 %** for Specimen SCDP-BRBs



Specimen SCDP



Specimen SCDP-BRBs

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◆ Test results

- BRBs significantly improve the seismic performance, including lateral force, cumulative energy dissipation, and equivalent viscous damping ratio of self-centering double-column piers.
- Although the residual displacement of the self-centering double-column pier with BRBs increases compared to that of self-centering double-column piers, it still maintains a good self-centering capability after BRBs fracture.

◆ Numerical simulations

- The numerical simulations effectively reproduce the hysteretic behavior, lateral force, stiffness degradation, and cumulative energy dissipation of both specimens, validating the accuracy and rationality of the fiber finite element models.
- Compared with the experimental results of specimens SCDP and SCDP-BRBs, the average numerical errors for the lateral force are 5.5% and 8.6%, respectively. The average errors for numerical stiffness are 5.7% and 8.7%, respectively. The average errors in the numerical cumulative energy dissipation are 8.8% and 7.6%, respectively.



Thank you for your attention!