Lateral impact behavior of Concrete-filled prefabricated UHPC tubular composite pier

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Content

1. Background

Global Infrastructure Challenges

Traditional RC bridge pier facing struggles to meet requirements:
(1) Load-carrying capacity; (2) Durability in harsh environments
(3) Resilience under extreme loading

Heavy load

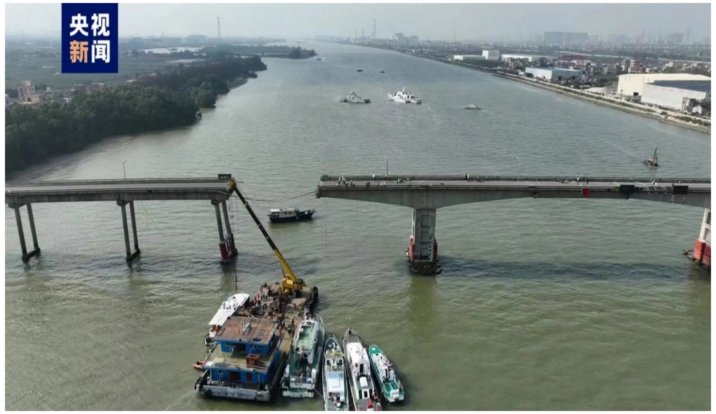
Bridge pier carrying increasing heavy load

Harsh environments

Bridge pier usually serving under harsh environments

Extreme loading

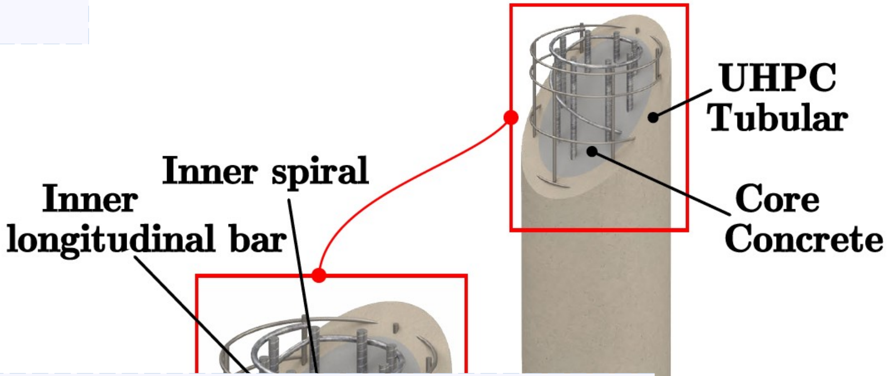
Bridge pier is potentially threatened by extreme loads



1. Background

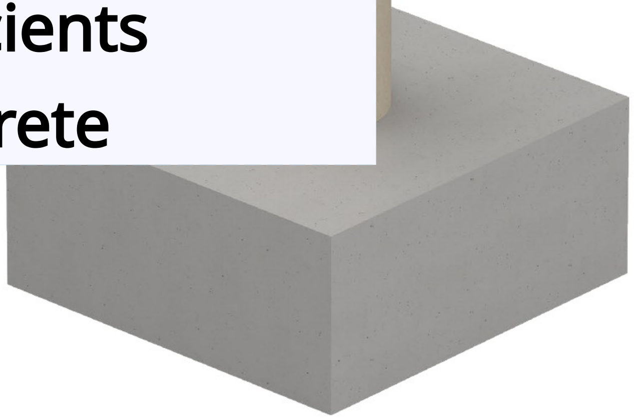
Proposed Solution – CFUT Composite Pier

Concrete Filled UHPC Tube



- **Superior confinement:** enhanced axial/flexural capacity
- **Low permeability:** resistant to chloride-induced corrosion
- **Reduced labor cost:** UHPC tube serves as permanent formwork
- **Material Compatibility:** Similar thermal expansion coefficients
- **Decreasing production costs**: using traditional core concrete

(d) Steam curing (e) Prefabricated UHPC tube (f) Core and base concrete casting



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Specimen Design & Fabrication

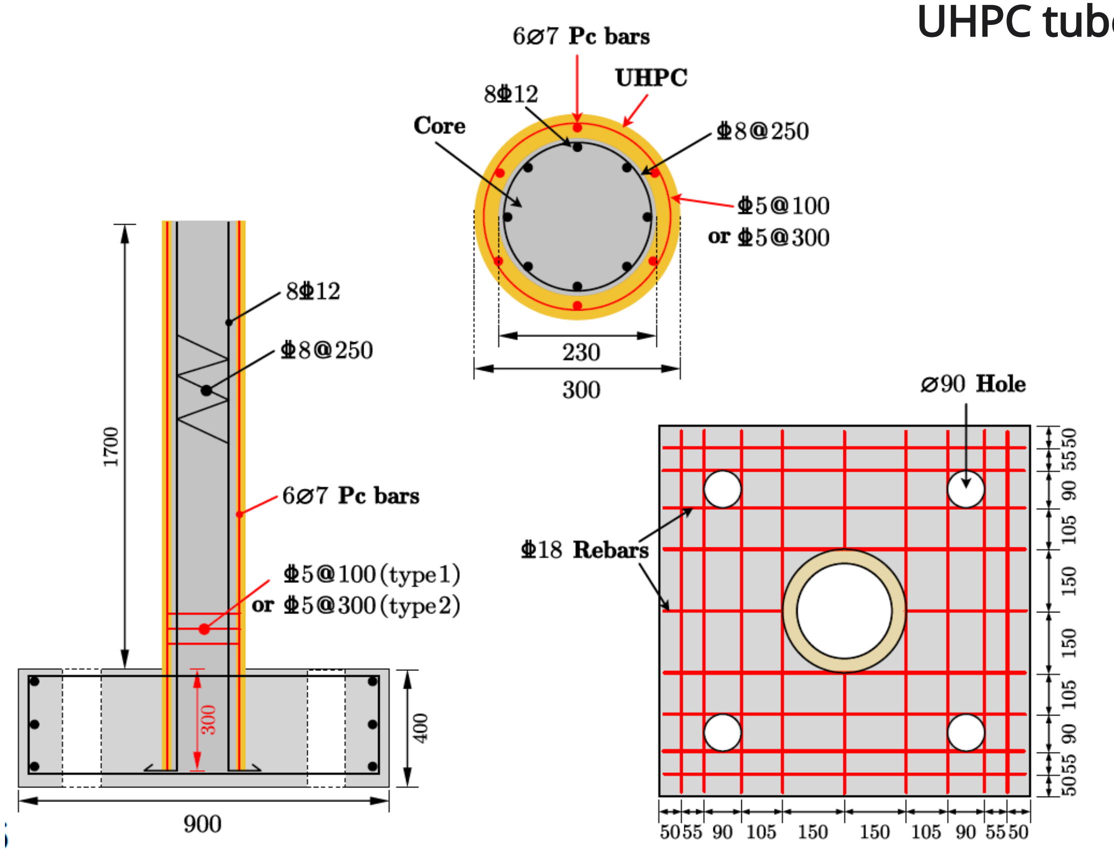
- Prefabricated UHPC outer tube (Ø300 mm × 35 mm thickness) + normal-strength concrete (NC) core + continuous internal steel cage

R H 2

R → UHPC tube reinforced by steel fiber

H → High impact velocity

2 → Shear deficit pier



ID	LRT	HRT	Steel fiber	Velocity
UL1	6Ø7	5@100	0	2.58 m/s
UM1	6Ø7	5@100	0	3.52 m/s
UL2	6Ø7	5@300	0	2.56 m/s
RL1	6Ø7	5@100	1%	2.65 m/s
RM1	6Ø7	5@100	1%	3.60 m/s
RH1	6Ø7	5@100	1%	5.03 m/s

2. Method

Material Properties & Mix Design

- **UHPC Variants**:
  - **Plain ("U" series)**: Baseline mix for comparison
  - **Fiber-Reinforced ("R" series)**: 1% vol. steel fibers (30×3 mm, ~1700 MPa tensile strength)

- **Centrifugal Mix Optimization**: Low w/c (0.22), elevated cement/sand ratio, thickener added to prevent segregation & ensure defect-free inner surface
- Core Concrete: C60 grade (w/c = 0.30)

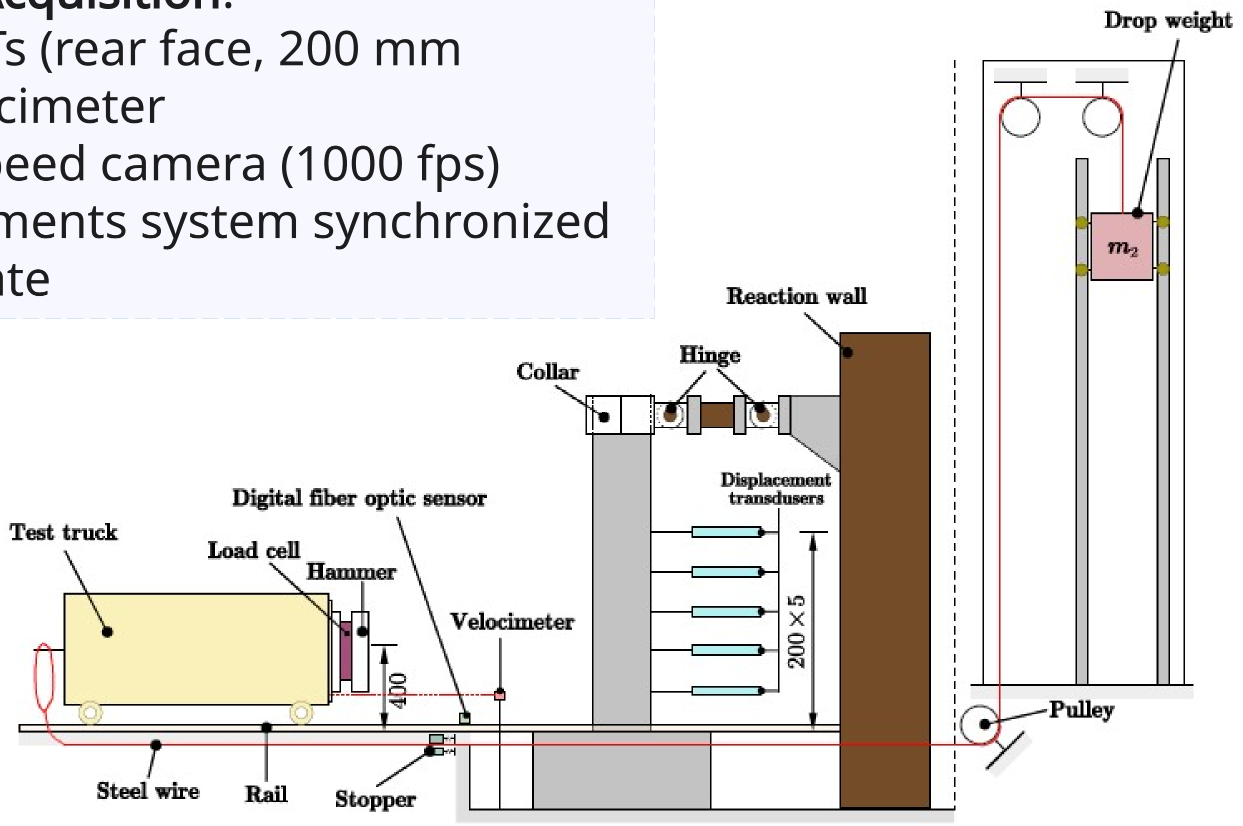
- **Key Mechanical Properties**:
  - UHPC compressive strength: ~115–122 MPa
  - Core concrete strength: ~63 MPa
  - High-strength longitudinal steel: up to 1087 MPa

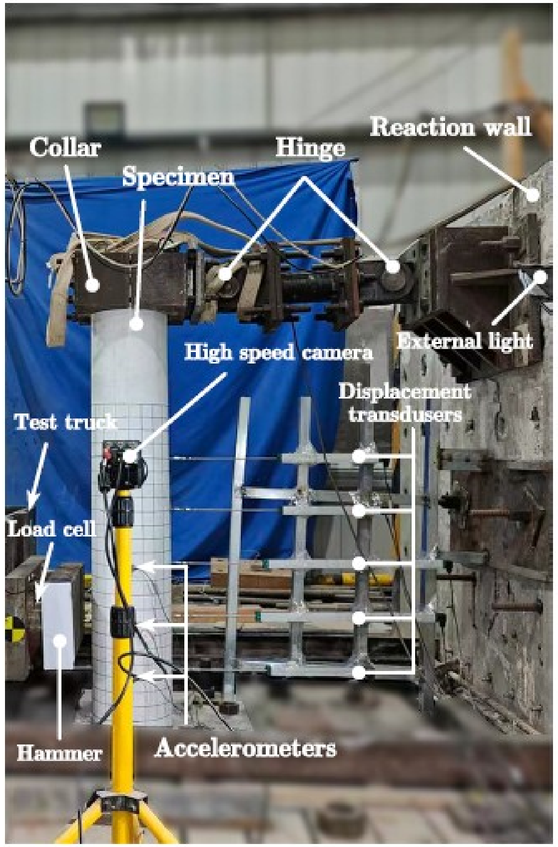
		D_n	Fy	elongation	E_s
Ø 7 Pc bars	UHPC longitudinal reinforcement	7.1 mm	1087 MPa	3.5 %	203 GPa
Ø 5 hoops	UHPC hoops	5.0 mm	552 MPa	8.3 %	198 Gpa
Ø 12 ribbed bars	Core longitudinal reinforcement	12.0 mm	425 MPa	16.6 %	201 Gpa
Ø 8 spiral	Core spiral	8.0 mm	417MPa	16.7 %	200 GPa

2. Method

- **Horizontal Collision Rig**: High-capacity facility simulating vehicular/vessel impact on vertical structural members
- **Impact Truck & Hammer**: 1582 kg base mass + adjustable ballast; 80 mm steel hammer plate (580×300 mm) instrumented with force cell
- **Boundary Conditions:** Propped top support (hinged collar against rigid wall) to replicate pier fixity

- **Instrumentation & Data Acquisition**:
  - **Displacement**: 5 LVDTs (rear face, 200 mm intervals) + laser velocimeter
  - **Visualization**: High-speed camera (1000 fps)
  - **DAQ**: National Instruments system synchronized at 20 kHz sampling rate





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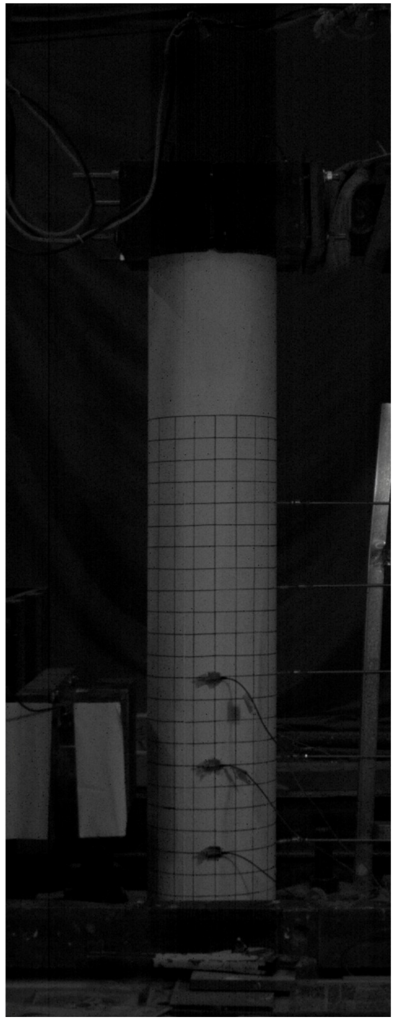
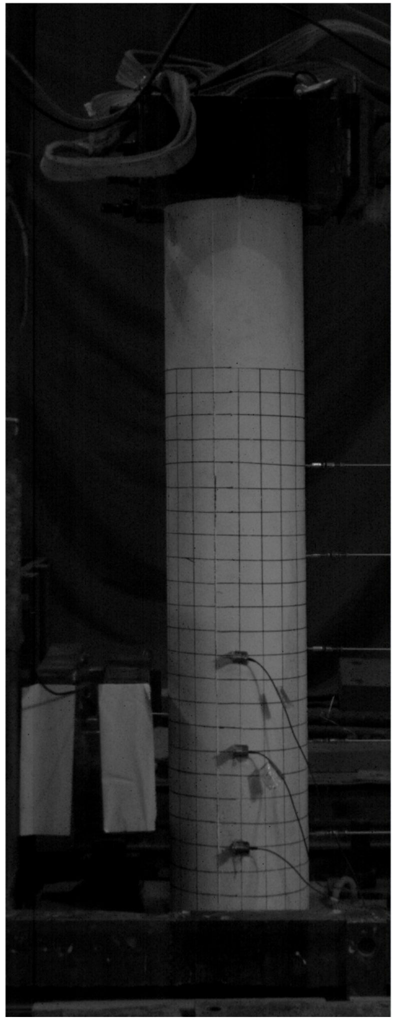
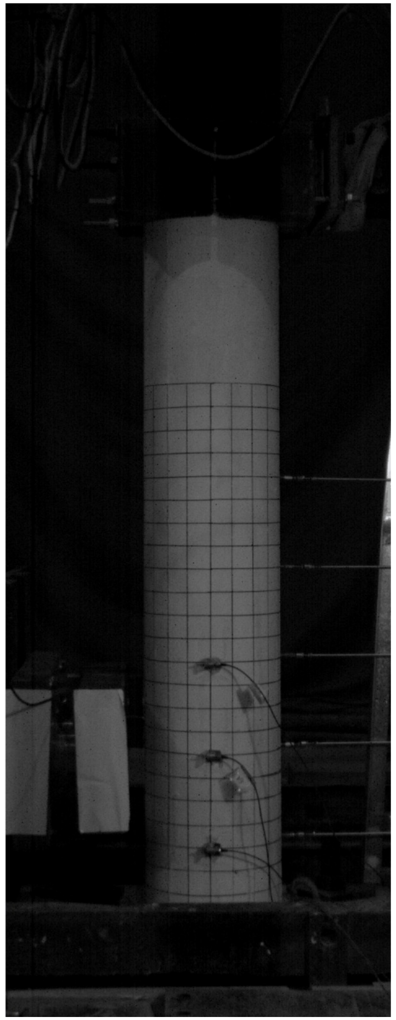
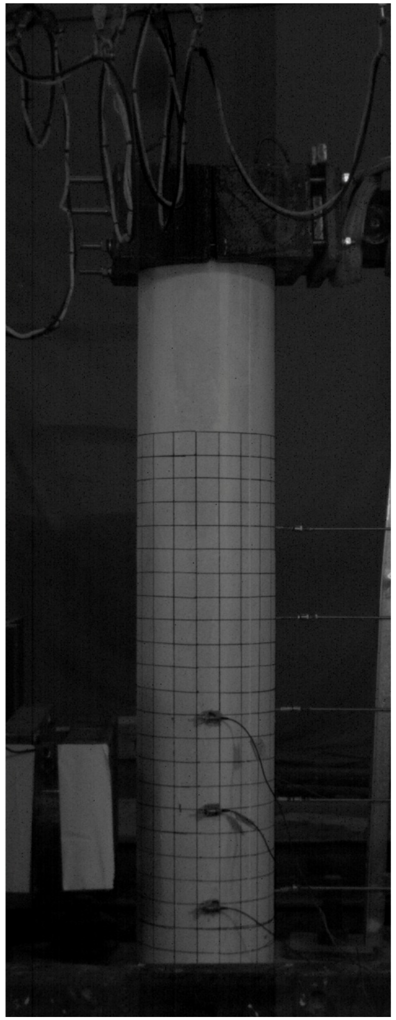
3. Results

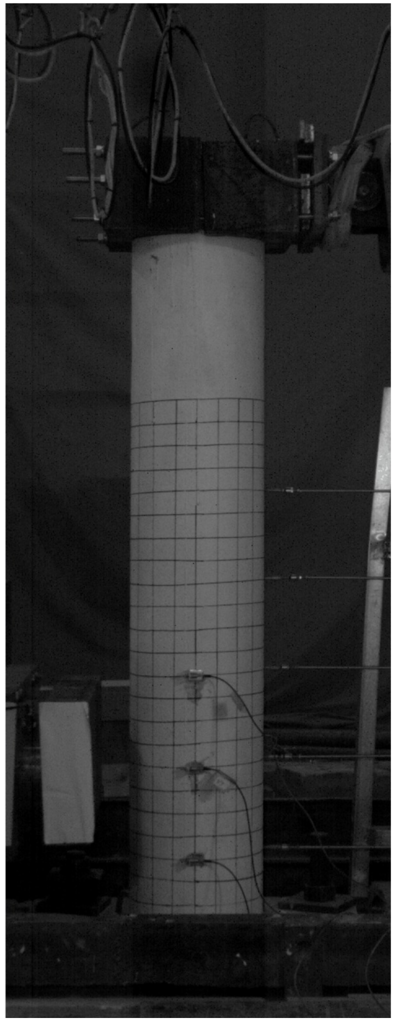
Impact progress

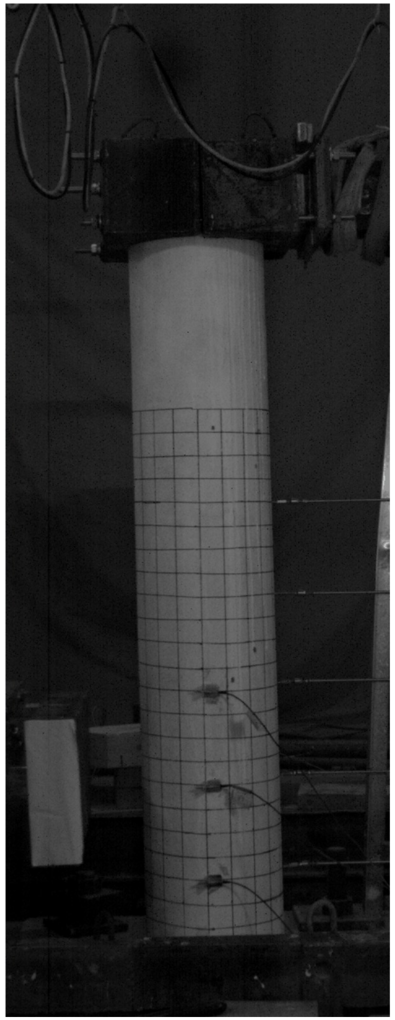

UL1


UM1

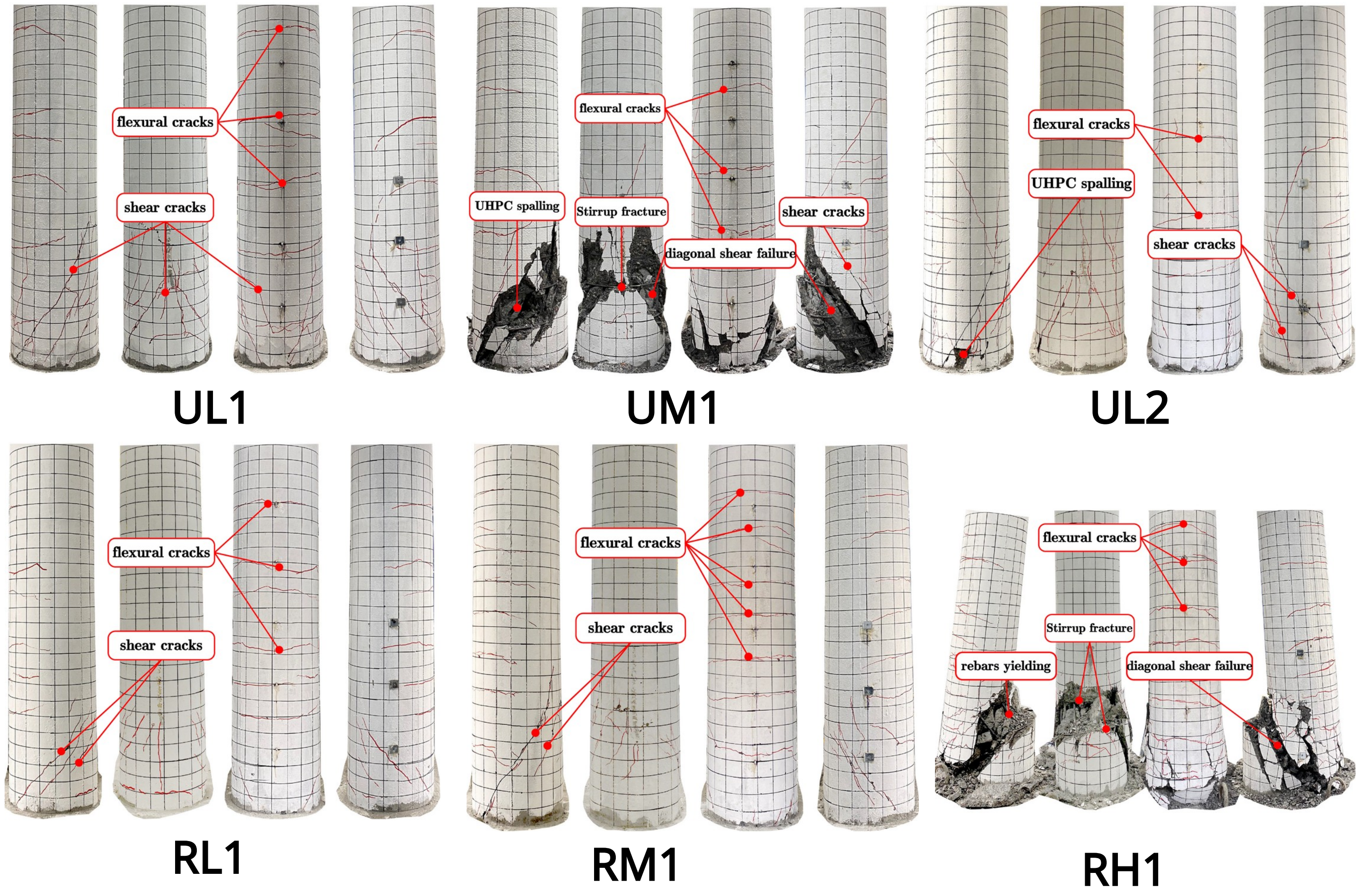

UL2


RL1


RM1


RH1

3. Results



Low-Velocity Impact ($v_i \approx 2.5$ m/s):

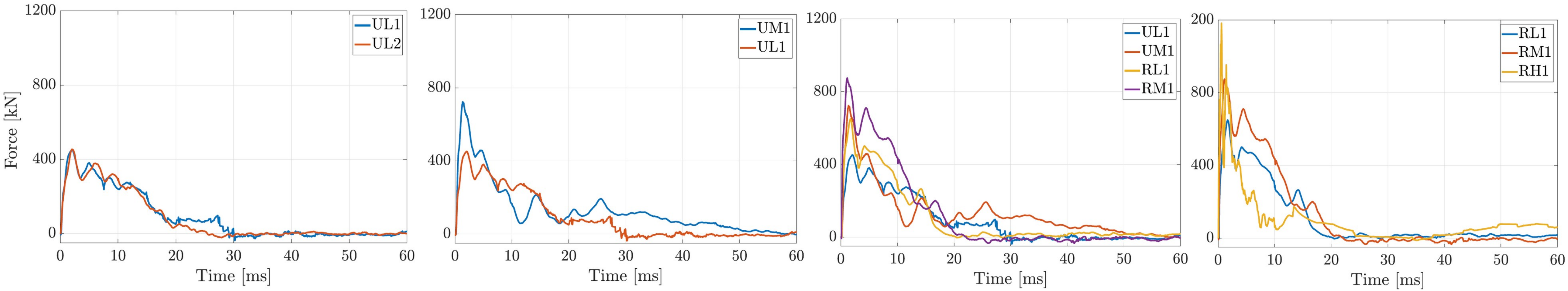
- **L-series (UL1, RL1): Combined flexural-shear failure**
  - ➢ Diagonal shear cracks + vertical flexural cracks on rear face
  - ➢ RL1: Higher micro-crack density → fibers constrain crack propagation via bridging effect
- **Shear-Deficient (UL2): More pronounced shear damage**
  - ➢ Wider diagonal cracks + localized spalling near base
  - ➢ Lower transverse reinforcement → reduced dynamic shear capacity

Medium-Velocity Impact ($v_i \approx 3.5$ m/s):

- Plain UHPC (UM1): **Brittle shear-dominant failure**
  - ➢ Severe diagonal cracking + extensive concrete spalling
  - ➢ UHPC tube nearly pulverized; reinforcement yielded
- Fiber-Reinforced (RM1): **Maintained structural integrity**
  - ➢ Flexural-shear pattern preserved; no visible spalling
  - ➢ Steel fibers prevent transition to brittle failure via energy dissipation (fiber debonding/pull-out)

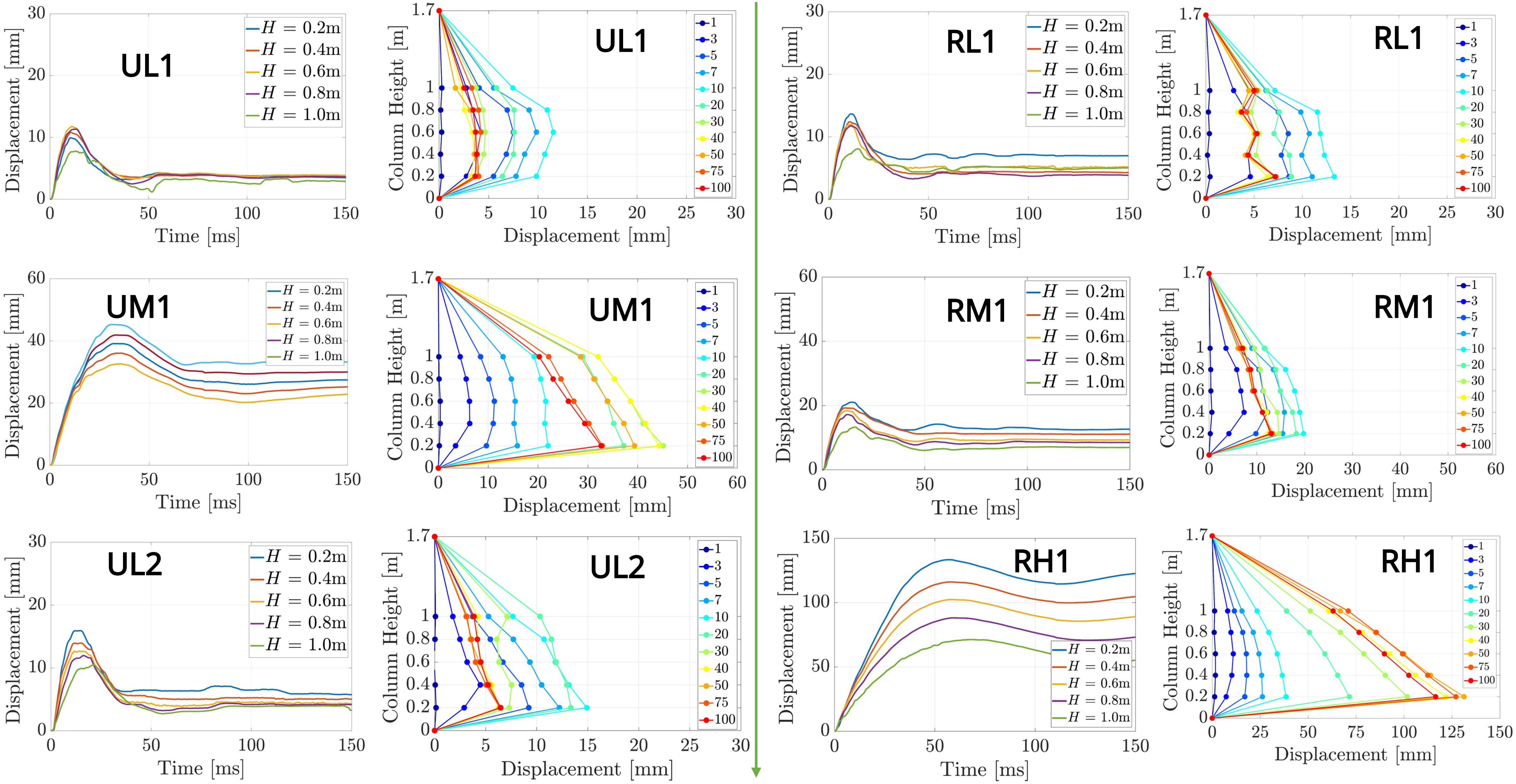
- High-Velocity Impact ($v_i \approx 4.9$ m/s, RH1):
  - ➢ **Total structural collapse**
  - ➢ Severe shear failure + reinforcement rupture + excessive residual displacement
  - ➢ Fiber benefits diminished: matrix crushed before fibers reached full tensile capacity

3. Results   Impact force time history



parameter	Trend	Interpretation
Transverse reinforcement ratio	<5% variation in peak force	Initial peak governed by local contact stiffness & inertial effects, not stirrup spacing
Impact velocity ↑	Peak force ↑ >50%	Higher kinetic energy amplifies dynamic force response
Steel fibers (R-series)	Peak force ↑ ~40% at low velocity	Fibers enhance local matrix stiffness & toughness
Post-peak plateau	R-series maintains higher plateau	Fibers bridge cracks & delay stiffness degradation
Catastrophic failure (RH1)	Abrupt force drop to near-zero	Loss of structural integrity → no rebound capacity

3. Results lateral displacement time history



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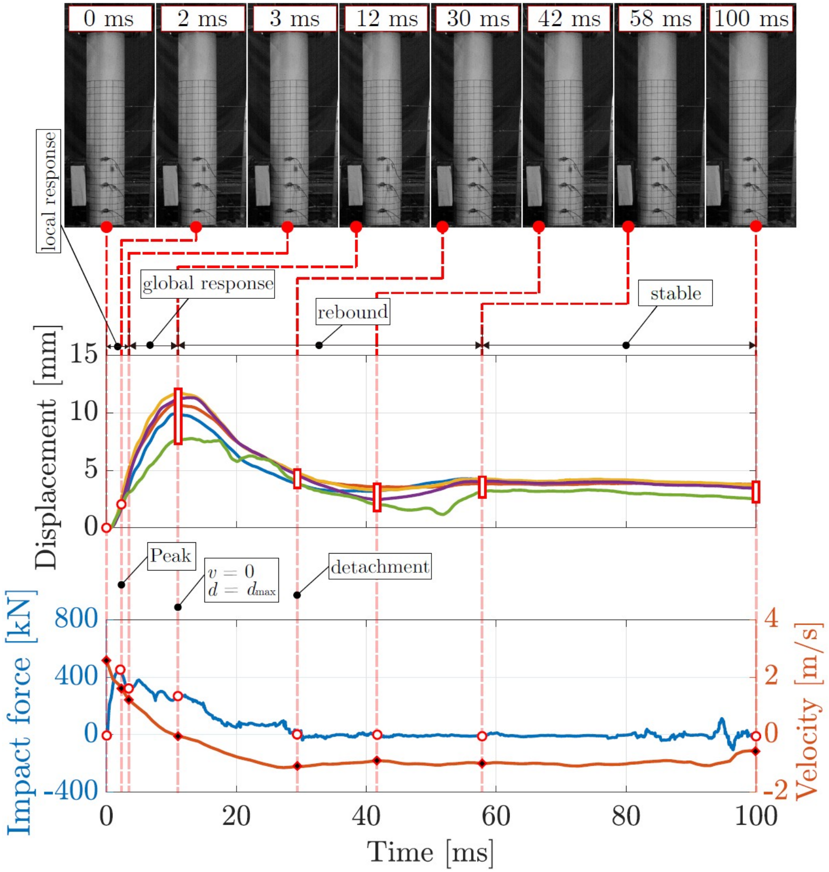
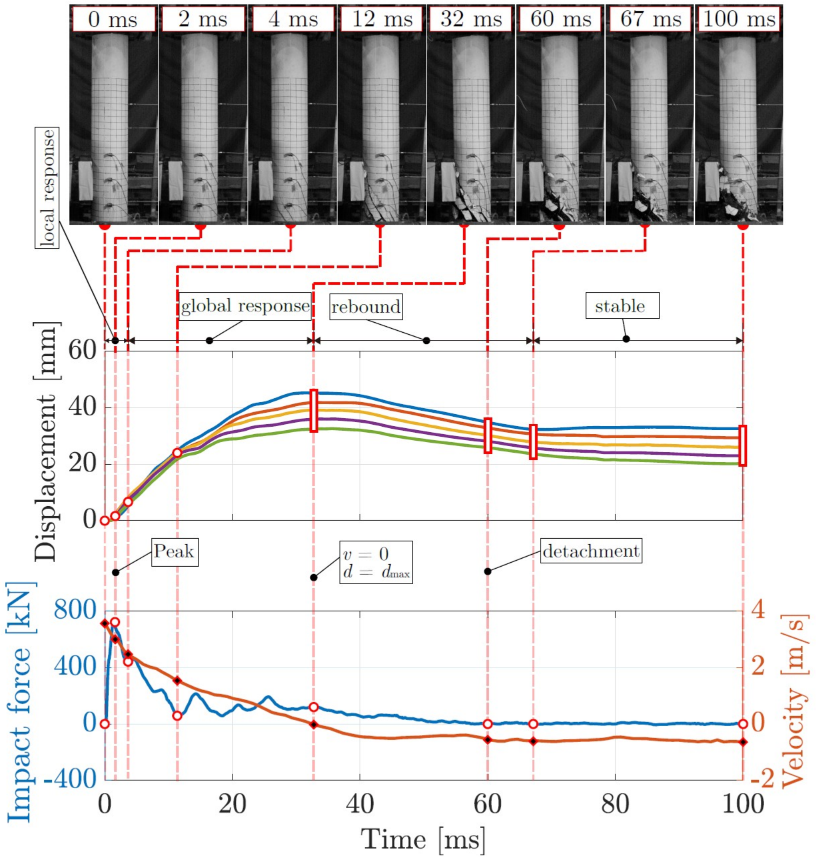
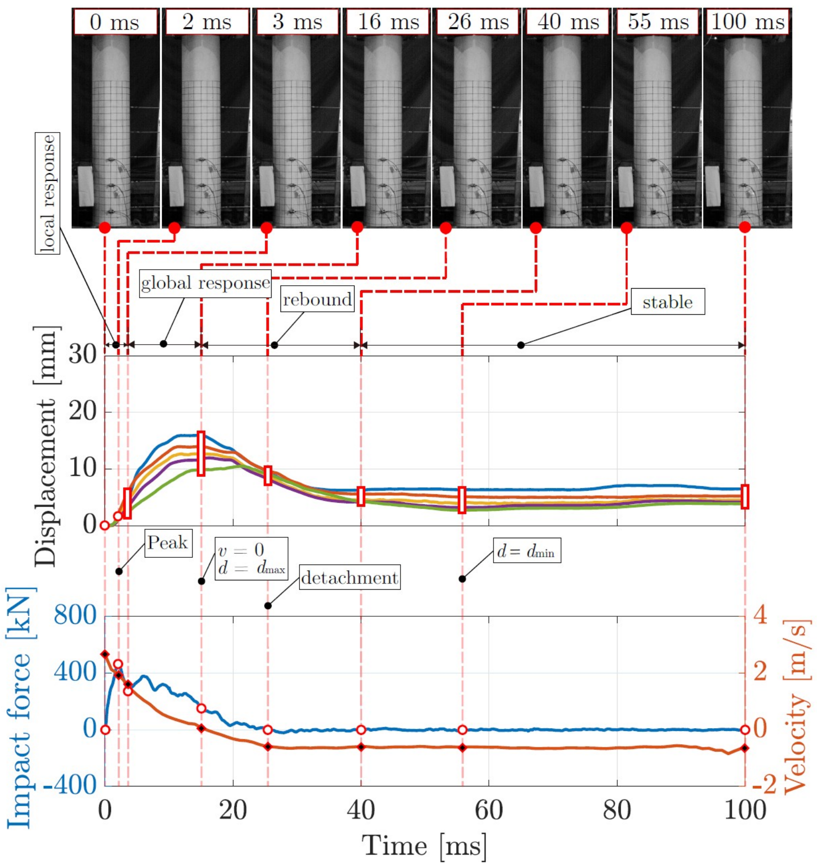
4. Discussion　Four-Stage Damage Evolution Process



UL1



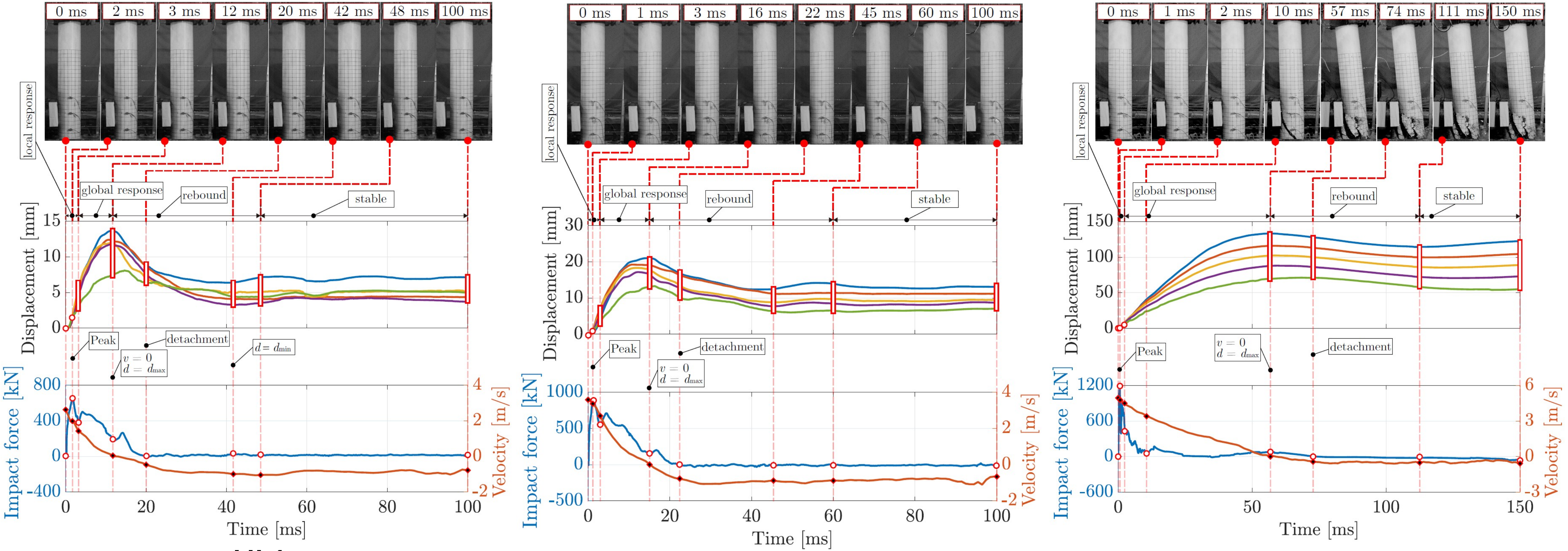
UM1



UL2

I. Local Response	t < 2 ms	• Peak impact force reached • Hammer velocity ↓ ~20%; global displacement <5 mm • Response governed by contact mechanics & inertia
II. Global Response	2–20 ms	• Lateral displacement surges to maximum • Kinetic energy dissipated via flexural-shear deformation & cracking • Peak displacement occurs

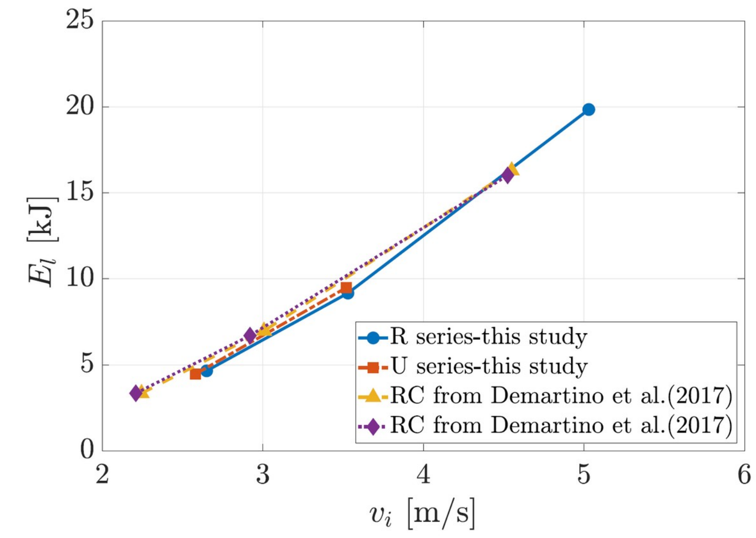
4. Discussion Four-Stage Damage Evolution Process

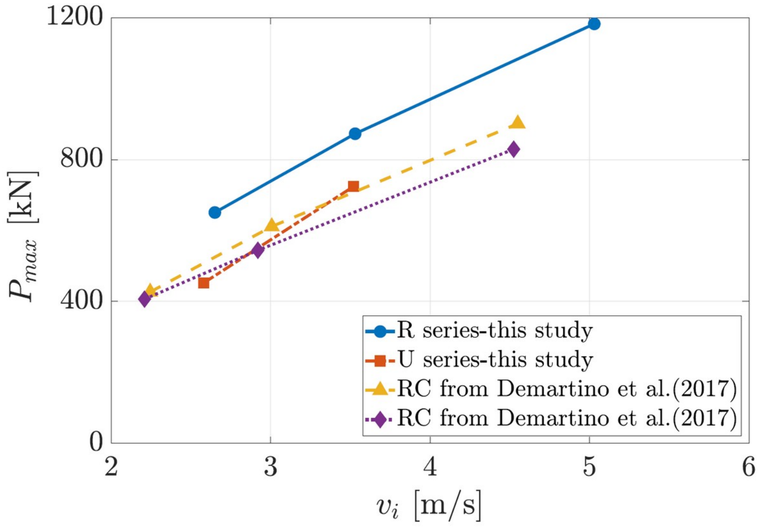


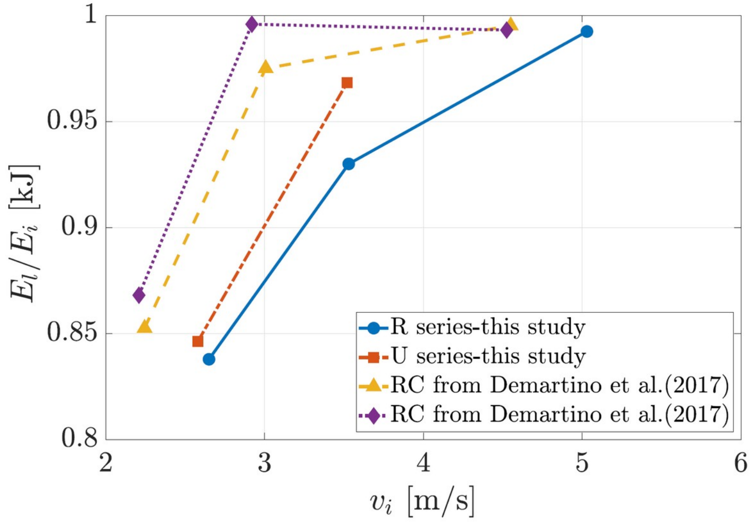
UL1 UM1 UL2

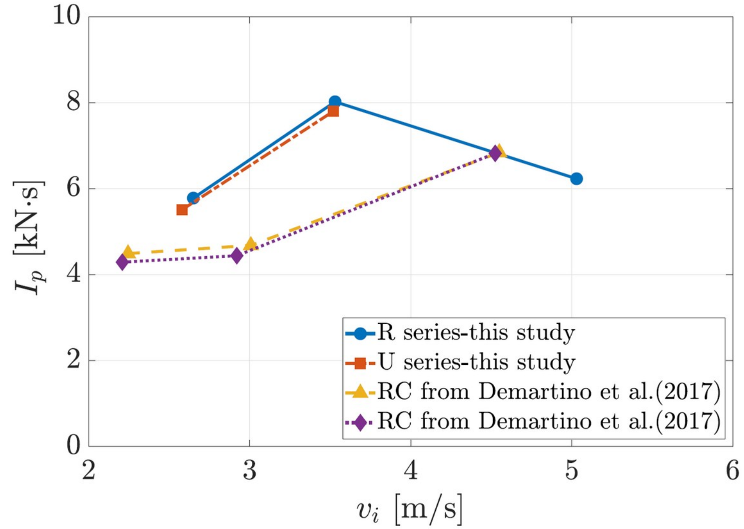
III. Rebound	20–40 ms	• Stored elastic energy drives backward motion • Partial crack closure observed (elastic recovery) • Detachment when contact force → 0
IV. Stable Stage	t > 40 ms	• Residual displacement stabilized • Final damage pattern documented

4. Discussion CFUT vs. Conventional RC Columns









Loss energy

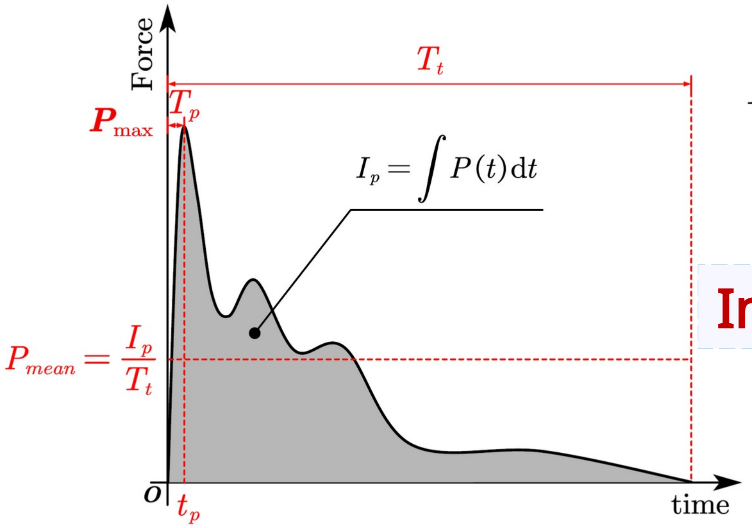
$$E_l = E_i - E_r = 0.5 \times m_1 \times (v_i^2 - v_r^2)$$

Metric	CFUT Columns	Conventional RC	Advantage
Peak impact force	Significantly higher	Lower	Superior local contact stiffness
Energy loss ratio (E_l/E_i)	Lower	Higher	Better elastic recovery & rebound potential
Impulse (low-medium v_i)	Higher	Lower	Sustained reactive force due to higher stiffness
Failure mode transition	Gradual (with fibers)	Brittle	Enhanced damage tolerance
High-velocity impulse	Drops sharply at collapse	Continues increasing	Rapid resistance exhaustion at extreme energies

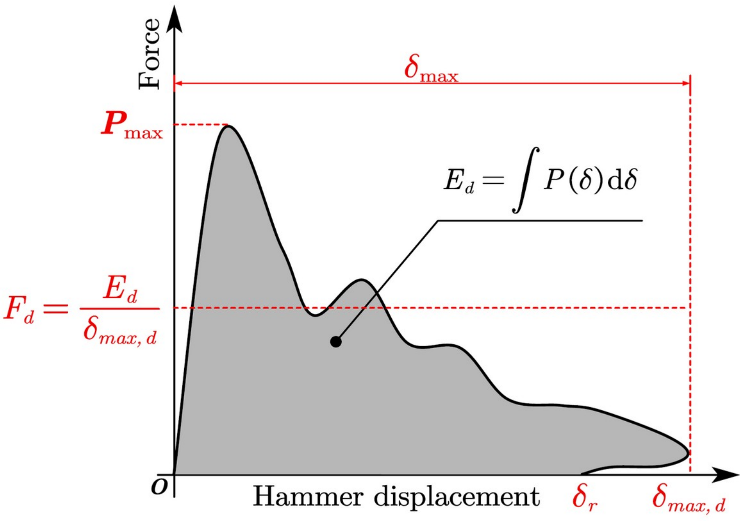
CFUT columns offer superior resilience under service-level impacts; design must account for sudden capacity loss at extreme energies.

4. Discussion

Simplified Dynamic Displacement Prediction Model



Force-time history



Force vs. displacement

$$E_d = \int_0^{\delta_{max,d}} F(\delta)\,d\delta = F_d \delta_{max,d};\ \delta_{max,d} = \frac{E_d}{F_d}$$

We defined two parameters

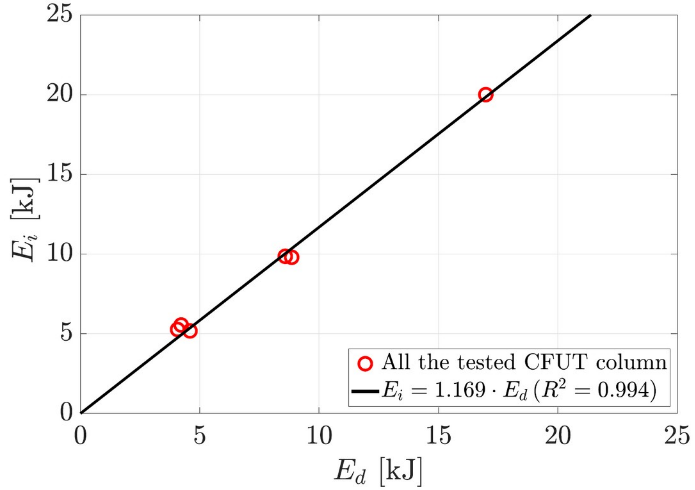
$$\gamma_1 = \frac{E_i}{E_d};\ \gamma_2 = \frac{F_d}{F_c}$$

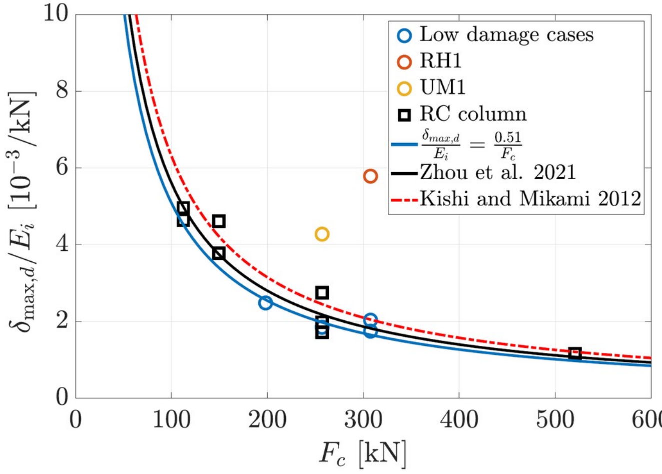
E_i: **Input energy**

F_c: **Static lateral force capacity**

Dynamic lateral displacement capacity

$$\delta_{max,d} = \frac{E_i}{\gamma_1 \gamma_2 F_c} = \gamma \cdot \frac{E_i}{F_c} = 0.51 \cdot \frac{E_i}{F_c}$$





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5. Conclusion

Steel Fibers Enable Ductile Impact Response

- 1 vol% fibers in UHPC tube suppress brittle shear failure → flexural-shear ductility
- ~40% higher peak impact force at medium velocity (3.5 m/s) vs. plain UHPC

CFUT Outperforms Conventional RC

- Superior contact stiffness & energy dissipation → lower energy loss ratio (E_l/E_i)
- Enhanced elastic recovery & reduced permanent deformation

High-Velocity Response Governed by Inertia + UHPC tube

- Initial peak force ($t < 2$ ms) precedes global cracking → UHPC protects core during critical phase

Simplified Design Framework

- Predictive model: **$\delta_{max,8} = 0.51 \cdot (E_i / F_e)$** using static capacity (F_e)
- Dual approach: **ULS** (safe velocity/mass limits) + **PBD** (USACE rotation-based damage levels)
- Enables rapid assessment *without* complex dynamic FEA

Practical Impact

- Supports resilient design of bridge piers, offshore platforms, and coastal viaducts against vehicle/vessel collisions

衷心感谢各位专家！

Thanks for listening!

敬请批评指正！