Scientific Research

Seismic Performance of Pier Columns Reinforced with High-Performance Materials Based on Finite Elements

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Abstract: This paper focuses on the challenge of insufficient transverse seismic capacity in urban elevated twin-column pier bridges. By conducting finite element simulations, it studies how externally reinforcing pier columns with Fiber-Reinforced Polymer (FRP), Engineered Cementitious Composite (ECC), and Ultra-High Performance Concrete (UHPC) affects their bearing capacity, stiffness, ductility, and energy dissipation. The results indicate that UHPC significantly enhances the bearing capacity of concrete columns, while both ECC and UHPC effectively improve ductility and energy dissipation. In contrast, FRP reinforcement shows no significant effect on bearing capacity, stiffness, or ultimate deformation. These findings provide reference data for strengthening similar projects.

Keywords: high-performance materials; externally bonded reinforcement; concrete columns; load bearing capacity; energy dissipation capacity

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1 Introduction

The twin-column pier is a common pier form found in urban elevated bridges. The transverse stiffness of the twin-column pier bridge is large, but the seismic response is significant, and its cross-sectional size and material strength are difficult to meet the requirements of the current seismic code [1]. Externally bonded reinforcement is a common method to reinforce existing concrete structures due to its ease of construction and the ability to effectively improve the durability and seismic performance of the structure [2]. High-performance materials, such as Fiber-Reinforced Polymer (FRP), Engineered Cementitious Composite (ECC), and Ultra-High Performance Concrete (UHPC), have been gradually applied in the field of structural reinforcement because of their performance advantages over other materials.

FRP is a commonly used reinforcement material for concrete structures because of its light weight, high strength, and corrosion resistance [3]. Externally bonded FRP reinforcement can effectively improve the seismic performance of concrete columns. Cao et al. [4] compared the effects of two reinforcement methods—circumferential CFRP wrapping and L-shaped CFRP with transverse integration—on the ductility of seismically damaged high-strength concrete columns. The results revealed that L-shaped CFRP with transverse integration was a more effective reinforcement method, and the ductility of the reinforced samples was significantly improved.

ECC exhibits excellent tensile ductility and crack control. By bridging mechanism of the short-cut fibers, the ECC achieves a tensile strain performance of more than 3%, which is more than 300 times greater than that of ordinary concrete, through strain hardening with step-by-step multi-cracks [5]. Moreover, even under

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load-bearing conditions, the crack width of an ECC can still be kept below 100 μm, which effectively blocks the intrusion of harmful external ions, thus ensuring the durability of the material [6]. This step-by-step fine crack extension characteristic endows ECCs with excellent energy dissipation ability, which has remarkable development prospects in the field of structural seismic reinforcement [7]. Wei et al. [8] used ECC to strengthen concrete columns and conducted a static test study, which revealed that ECC could change the damage mode of concrete columns from bending–shear damage to bending damage, form a fuller hysteresis curve, significantly improve deformation capacity, and slow the degradation of stiffness.

UHPC is a new type of cementitious composite material engineered based on the particle densest packing theory. Characterized by ultra-high strength, superior toughness, and exceptional durability—coupled with its excellent interfacial bond performance with concrete—it has been widely adopted for concrete structure reinforcement [9,10]. Zhang et al. [11] investigated the failure modes, deformability, and energy dissipation capacity of concrete columns strengthened with UHPC jackets under low-cycle reversed loading. The results demonstrated that UHPC reinforcement shifted the failure mode from brittle small-eccentric compression to large-eccentric compression, while significantly enhancing the columns' load-bearing capacity, deformability, and energy dissipation performance.

In summary, high-performance materials such as FRP, ECC, and UHPC have been validated to effectively enhance both the load-bearing capacity and energy dissipation performance of reinforced structural members, thereby improving seismic resilience. This study addresses the deficient transverse seismic resistance of twin-column pier bridges by employing FRP, ECC, and UHPC as externally bonded reinforcement materials. Through finite element numerical simulations, investigate the effects of different material reinforcements on pier components' load-bearing capacity, energy dissipation, stiffness, and ductility, aiming to provide empirical support for similar engineering strengthening projects.

2 Numerical Modeling

Based on field survey data from Shanghai Inner Ring Road Phase II Elevated Bridge, the model's cross-sectional dimensions and reinforcement layout are shown in Figure1 and Figure 2. Key parameters include:

- Column height: 6,650 mm
- Axial compression ratio: 0.3
- Concrete grade: C30, Elastic modulus: 30 GPa
- Steel reinforcement: HRB335, Yield strength: 270 MPa, Ultimate strain: 0.2, Elastic modulus: 200 GPa

Fixed-end constraints were applied at the model base, and a reference point with kinematic coupling was established at the top surface. Horizontal displacement loading was imposed at the reference points, while out-of-plane displacements and rotational degrees of freedom were constrained.

The mechanical behavior of concrete, ECC, and UHPC was simulated using the Concrete Plasticity Model. The tensile-compressive constitutive relations for concrete were based on "Code for Design of Concrete Structures" (GB50010–2010) [12], while those for ECC and UHPC referenced literature [13,14]. For ECC, the compressive strengths were 30 MPa, 60 MPa, and 95 MPa, with corresponding tensile strengths of 6 MPa, 9.5 MPa, and 13 MPa, respectively. The peak tensile strain for all ECC cases was set to 8%. For UHPC, the compressive strengths were 100 MPa, 130 MPa, and 160 MPa, with corresponding tensile strengths of 9.5 MPa, 12 MPa, and 15 MPa, respectively. The peak tensile strain for all UHPC cases was set to 0.4%.

Concrete, ECC, and UHPC were discretized using 8-node linear hexahedral elements (C3D8R), reinforcing steel was modeled with truss elements (T3D2), and FRP was represented by shell elements (S4R). The mesh division of the model is illustrated in Figure 3, where the mesh size for concrete, ECC, UHPC, FRP, and reinforcing steel was uniformly set to 50 mm.

For specimens with same material parameters, the skeleton curves under cyclic loading are nearly identical to the load-displacement curves obtained from monotonic pushover analysis. Based on considerations of computational efficiency, this study adopts monotonic displacement loading to analyze the mechanical performance of the model specimens. The selection of the wrapping layer thickness was referenced from the “Technical Specification for Strengthening with High Ductile Concrete” (DBJ04/T 397–2019) [15].

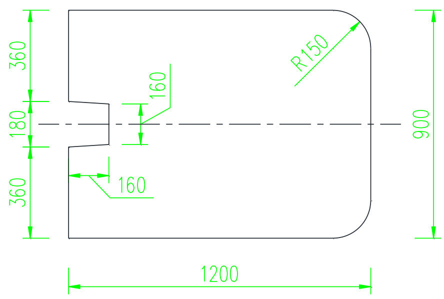


Figure 1 Section size of pier

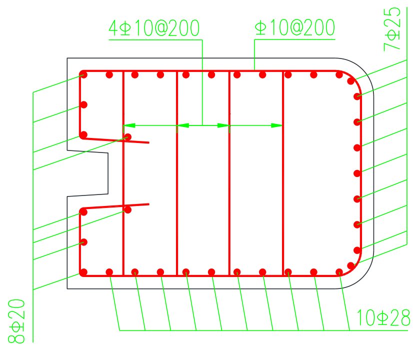


Figure 2 Rebar configuration of section

Figure 3 Concrete/ECC/UHPC/FRP mesh diagram

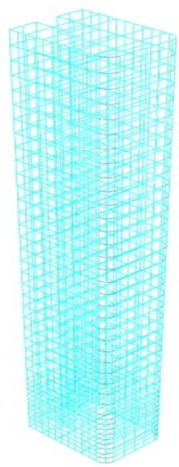
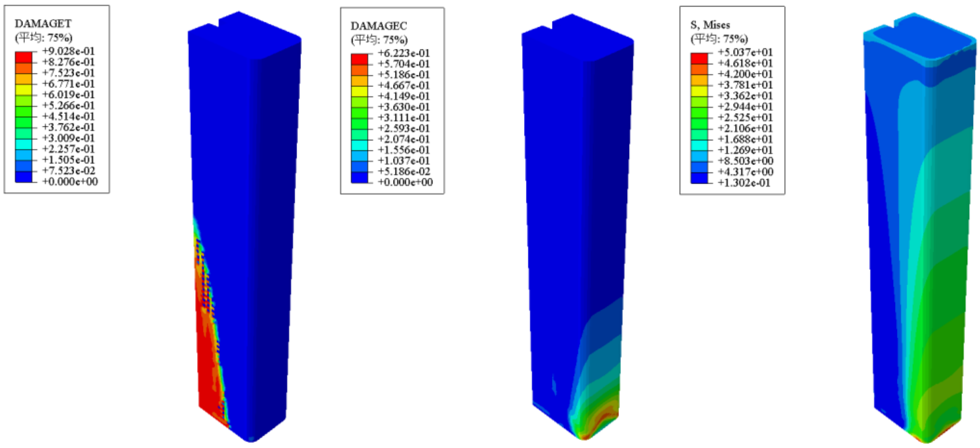


Figure 4 Rebar mesh diagram

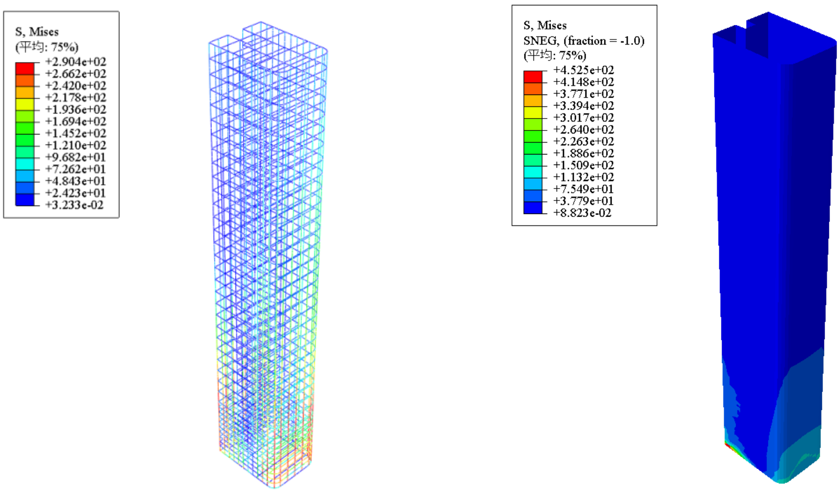
3 Results and Discussion

3.1 Externally Bonded FRP Layer

Concrete columns externally bonded with FRP layers having tensile strengths of 700-MPa, 1,400-MPa, and 2,100-MPa were subjected to monotonic pushover loading. The damage states and stress contours of FRP-reinforced concrete columns at peak load are presented in Figure 5 (Note: since the damage patterns of columns reinforced with three strength grades of FRP were essentially identical, only simulation results for the 700-MPa FRP-reinforced column are displayed). It is observed that the damage in both the FRP and concrete was primarily concentrated at the column base. As the tensile strength of FRP increased, the concrete damage evolution and steel reinforcement stress remained largely unchanged. These phenomena indicate that the tensile capacity of the FRP was not fully utilized.



a) Tensile damage b) Compressive damage c) Concrete Mises stress



d) Rebar Mises stress e) FRP Mises stresses

Figure 5 Damage and stress contours of 700-MPa FRP-reinforced columns at peak loading

The load–displacement curves of the FRP-reinforced columns with different strength classes are shown in Figure 6. The externally bonded FRP enhances the load-bearing capacity and stiffness of the columns. Still, this effect is not obvious due to the high tensile strength of the FRP and the low tensile strength of the concrete and steel rebars. The incongruity of the two results indicates the tensile strength of the FRP is not being fully utilized. The peak load–displacement and residual strength of the FRP-reinforced columns are greater than those of the original concrete columns, which indicates that the FRP has a certain restraining effect on the original concrete columns. The area surrounded by the load–displacement curves and axis of the FRP-reinforced columns is larger than that of the ordinary concrete columns (original RC-column), which indicates that the externally bonded FRP enhances the energy dissipation capacity of the concrete columns. However, the different FRP strength grades have essentially the same effect on the energy dissipation enhancement of the samples.

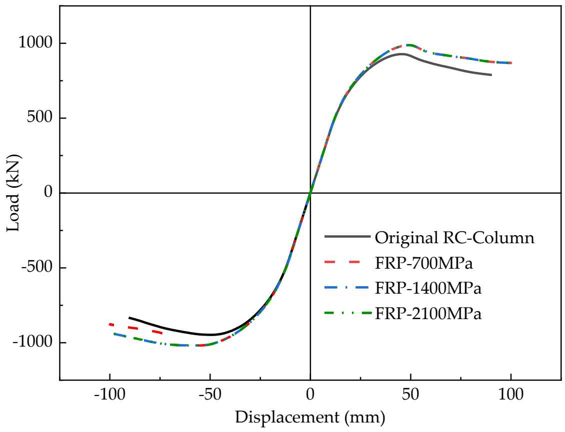
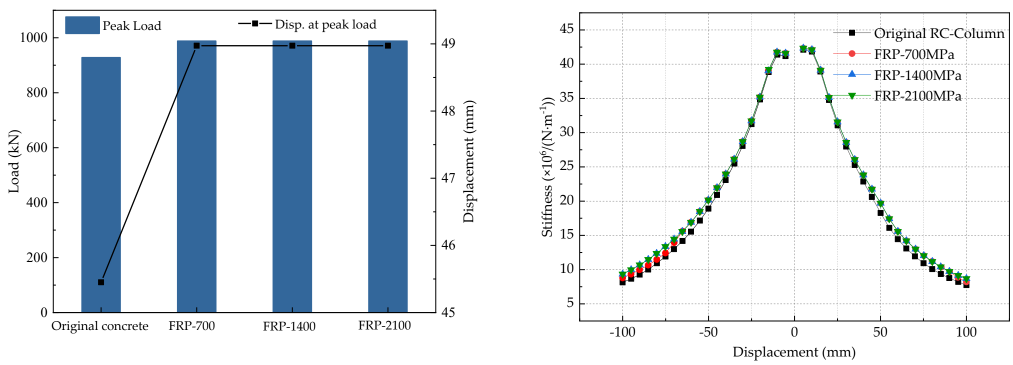


Figure 6 Load–displacement curves of FRP-reinforced columns with different strength classes

The peak loads and displacements versus stiffness of the FRP-reinforced columns with different strength grades are shown in Figure 7. Externally bonded FRP enhances the load bearing capacity and displacement of concrete columns. However, the peak loads and displacements of the reinforced columns essentially remained the same with increasing FRP strength (Figure 7a)), primarily because the tensile strength of the FRP was much greater than that of the concrete, resulting in its strength not being fully utilized. The stiffness degradation of the samples was measured by the secant stiffness, which is defined as the ratio of force and displacement at each point on the load–displacement curve. Figure 7b) shows that the stiffness of the FRP-reinforced concrete columns is slightly greater than that of the original concrete columns and that the rate of stiffness degradation occurs later than that of ordinary concrete columns.

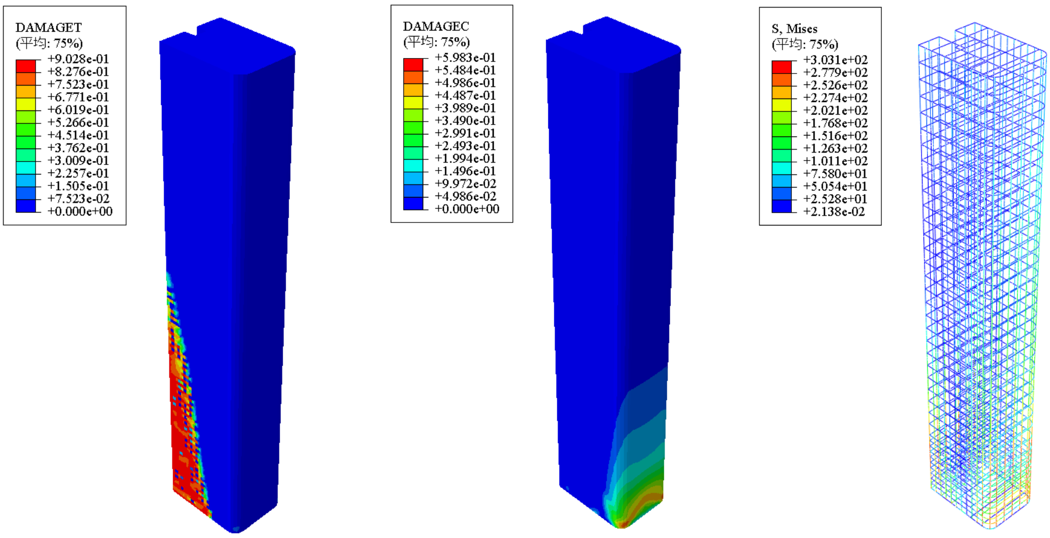


a) Peak loads and displacements b) Stiffness–displacement curves

Figure 7 Mechanical performance parameters of FRP-reinforced columns with different strength classes

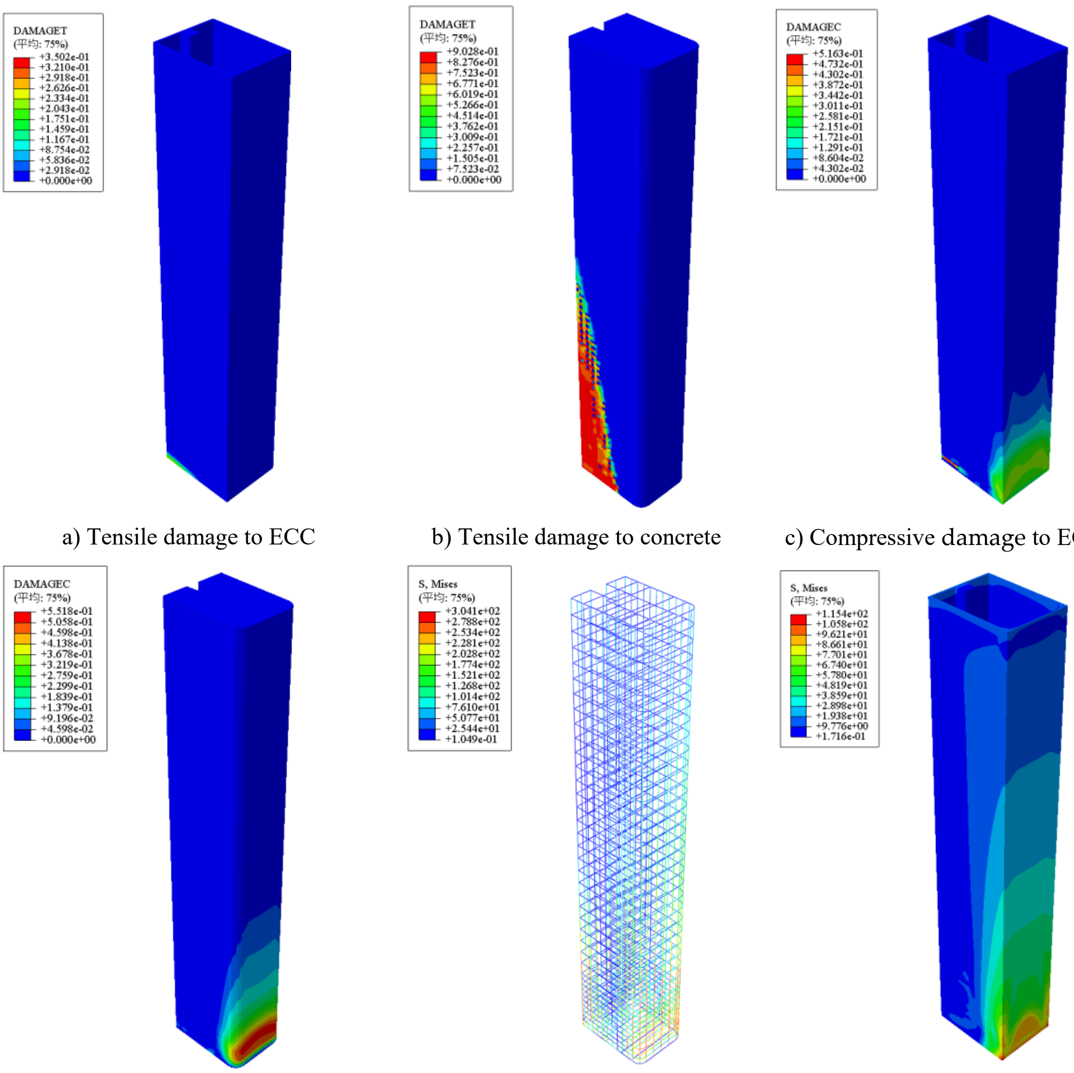
3.2 Externally Bonded ECC Layer

Concrete columns externally bonded with ECC layer of 30 MPa, 60 MPa, and 95 MPa compressive strengths (uniform thickness: 30 mm) and original concrete specimens were subjected to monotonic pushover loading. Damage patterns and stress contours at peak load are shown in Figures 8 – 11, revealing that damage primarily concentrated at the column base in all specimens. Compared to ECC-reinforced columns, the original RC columns exhibited more severe tensile and compressive damage, whereas the ECC layers showed minimal tensile damage due to ECC's superior tensile strain capacity. As the compressive strength of the ECC layers increased, the rebar stress at peak load escalated, demonstrating effective confinement that enhanced the load-bearing capacity.



a) Tensile Damage b) Compressive Damage c) Rebar stresses

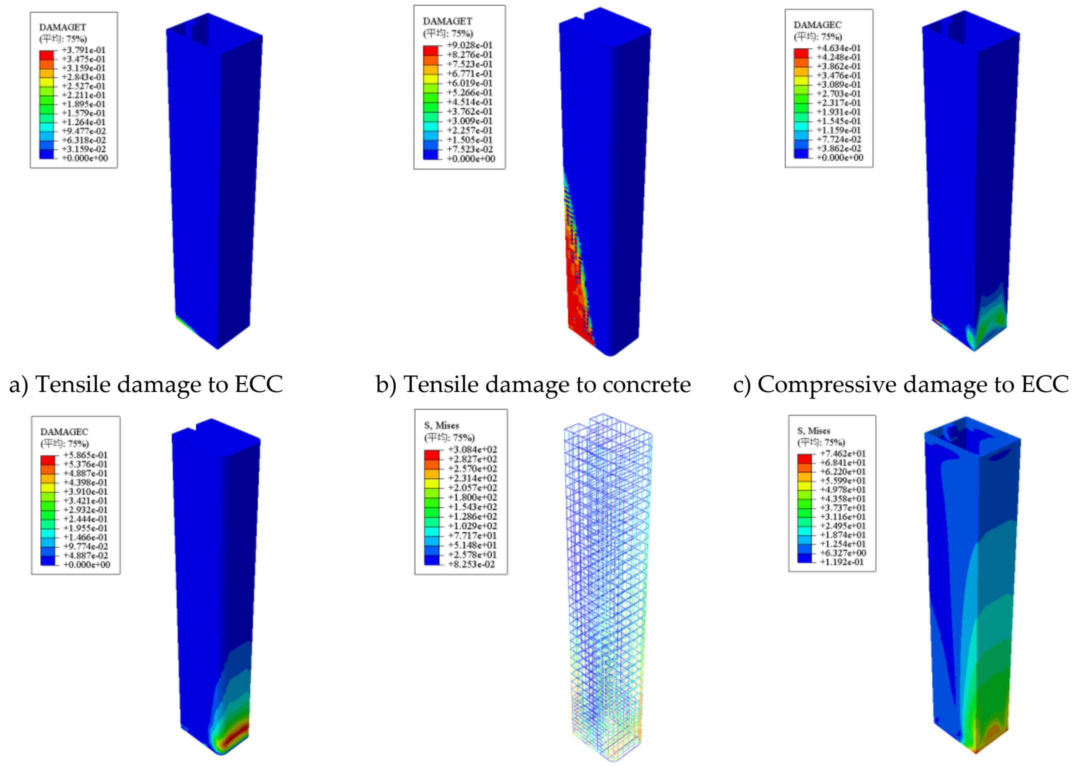
Figure 8 Damage contours and stress contours of concrete (C30) columns at peak loading



a) Tensile damage to ECC b) Tensile damage to concrete c) Compressive damage to ECC

d) Compressive damage to concrete e) Rebar stress f) ECC stress

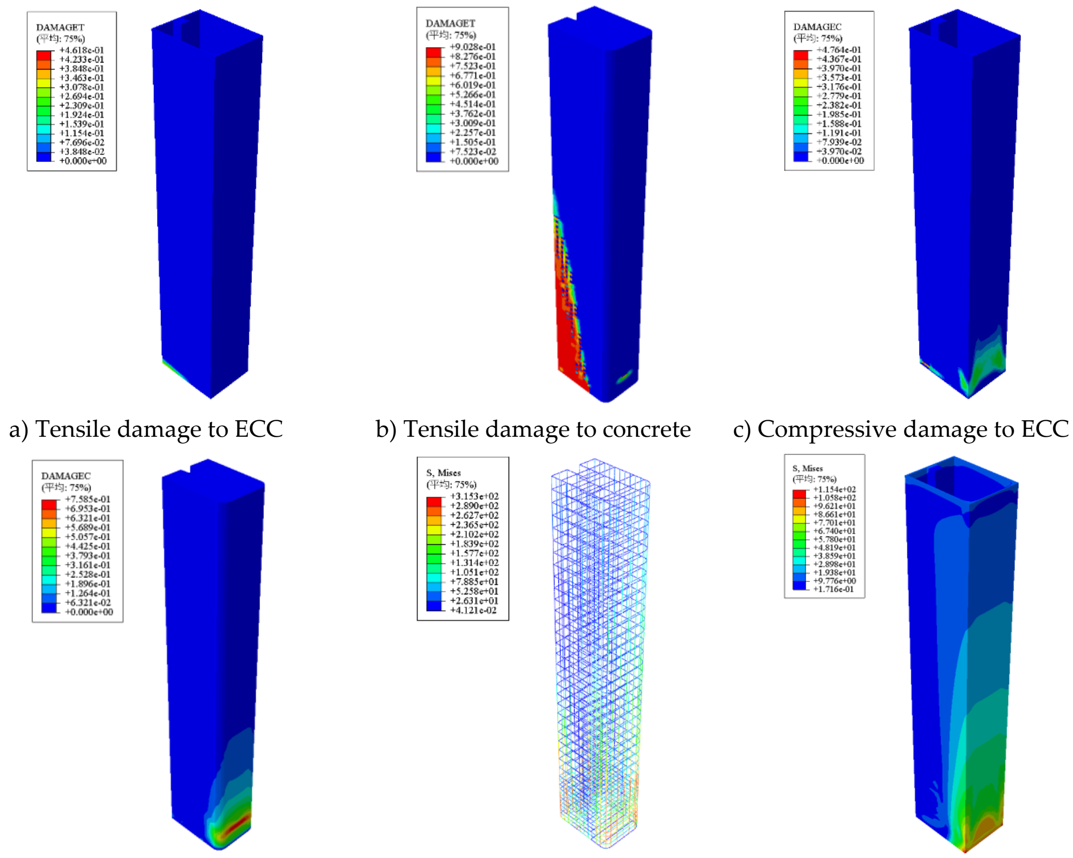
Figure 9 Damage contours and stress contours of columns reinforced with 30 MPa ECC at peak loading



a) Tensile damage to ECC b) Tensile damage to concrete c) Compressive damage to ECC

d) Compressive damage to concrete e) Rebar stress f) ECC stress

Figure 10 Damage contours and stress contours of columns reinforced with 60 MPa ECC at peak loading



a) Tensile damage to ECC b) Tensile damage to concrete c) Compressive damage to ECC

d) Compressive damage to concrete e) Rebar stress f) ECC stress

Figure 11 Damage contours and stress contours of columns reinforced with 95 MPa ECC at peak loading

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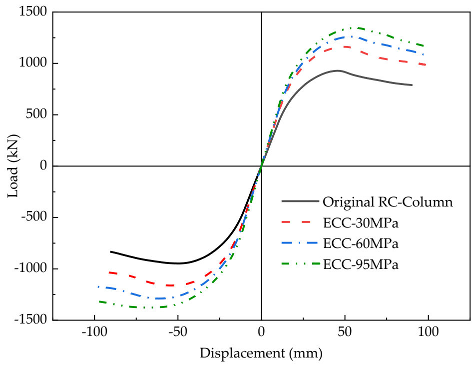
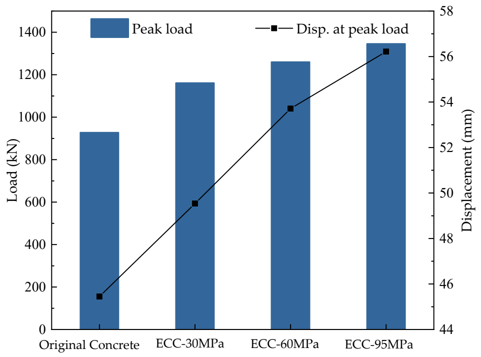
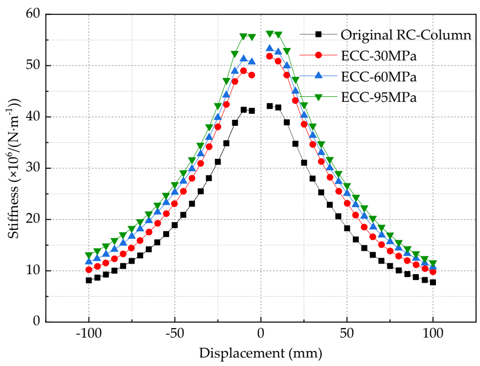
The load-displacement curves, peak loads, displacements, and stiffness degradation under monotonic loading for concrete columns reinforced with varying-strength ECC (compressive strengths: 30, 60, 95 MPa) are presented in Figure 12. As the ECC compressive strength increased, the peak load of specimens rose due to enlarged cross-sectional dimensions provided by the externally bonded ECC layer, which enhanced initial stiffness. Furthermore, both peak and ultimate displacements of ECC-reinforced columns exceeded those of original concrete columns, indicating significantly improved deformation capacity. Owing to bond-induced confinement from the ECC layer, strengthened columns exhibited higher ultimate load-bearing capacity and residual strength, with a slower strength degradation rate compared to reference specimens. The notably larger area enclosed by the load-displacement curves of ECC-strengthened columns demonstrated superior energy dissipation capacity, which increased progressively with higher ECC strength. Additionally, enhanced stiffness was observed in all strengthened specimens relative to original RC-columns, verifying greater resistance to damage progression.



a) Load–displacement curves



b) Peak loads and displacements



c) Stiffness–displacement curves

Figure 12 Mechanical properties of ECC-reinforced columns with different strength classes

Reinforced concrete columns with 60 MPa compressive strength ECC at two thickness values (20 mm and 30 mm) were investigated to study the effect of ECC layer thickness on mechanical performance. The load–displacement curves are shown in Figure 13. With increasing thickness of the bonded ECC layer, the load-bearing capacity of reinforced concrete columns gradually increases, and the initial stiffness, the peak displacement, and the energy dissipation capacity also increases.

3.3 *Externally Bonded UHPC Layer*

Concrete columns externally bonded with UHPC layers of 100 MPa, 130 MPa, and 160 MPa compressive strengths (uniform thickness: 30 mm) were subjected to monotonic pushover loading. Damage patterns and stress contours at peak load are shown in Figure 14 to Figure 16. It can be observed that the failure modes of UHPC-reinforced columns were fundamentally similar to those of ECC-reinforced columns, with damage concentrated at the column base. However, distinct tensile damage occurred in the UHPC layers – a contrast to ECC-reinforced columns – though less severe than in the original concrete. This phenomenon primarily stems from UHPC's inferior deformation capacity compared to ECC, yet its steel fiber bridging mechanism still grants superior deformability relative to conventional concrete. Increasing UHPC compressive strength raised reinforcement stresses at peak load, confirming enhanced load-bearing capacity through UHPC-induced constraint provision.

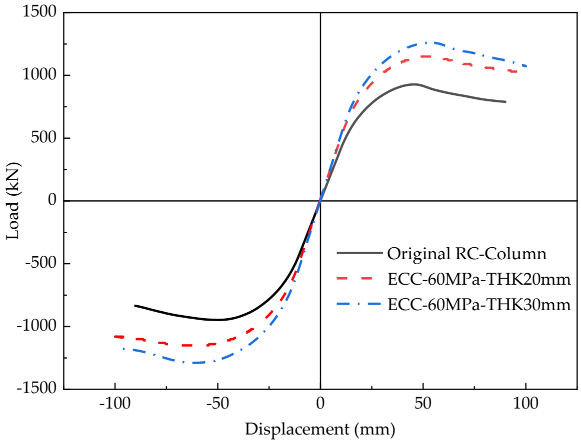
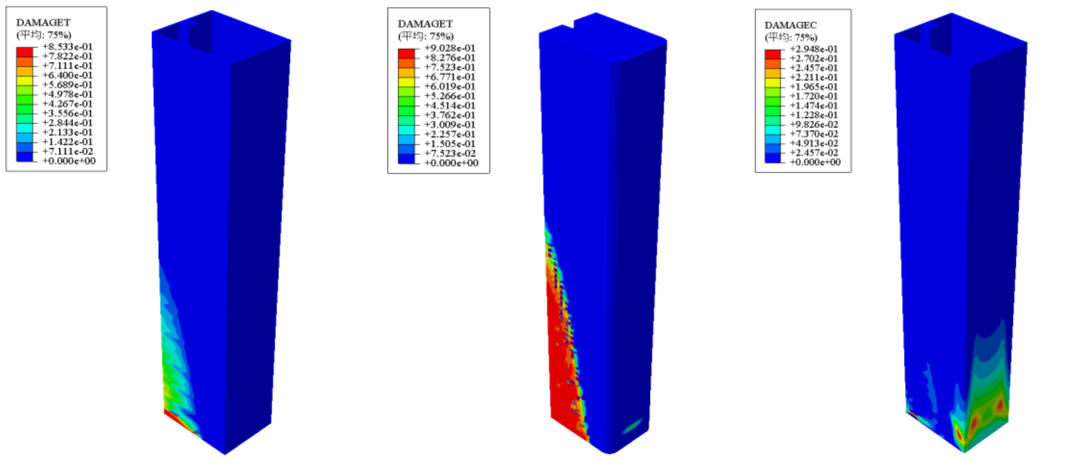
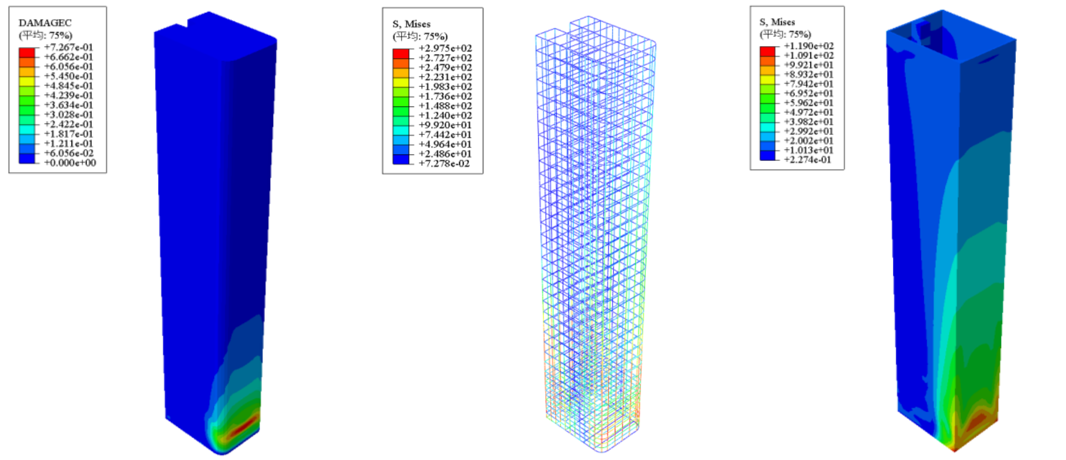


Figure 13 Load–displacement curves of reinforced concrete columns with different thicknesses of ECC layer

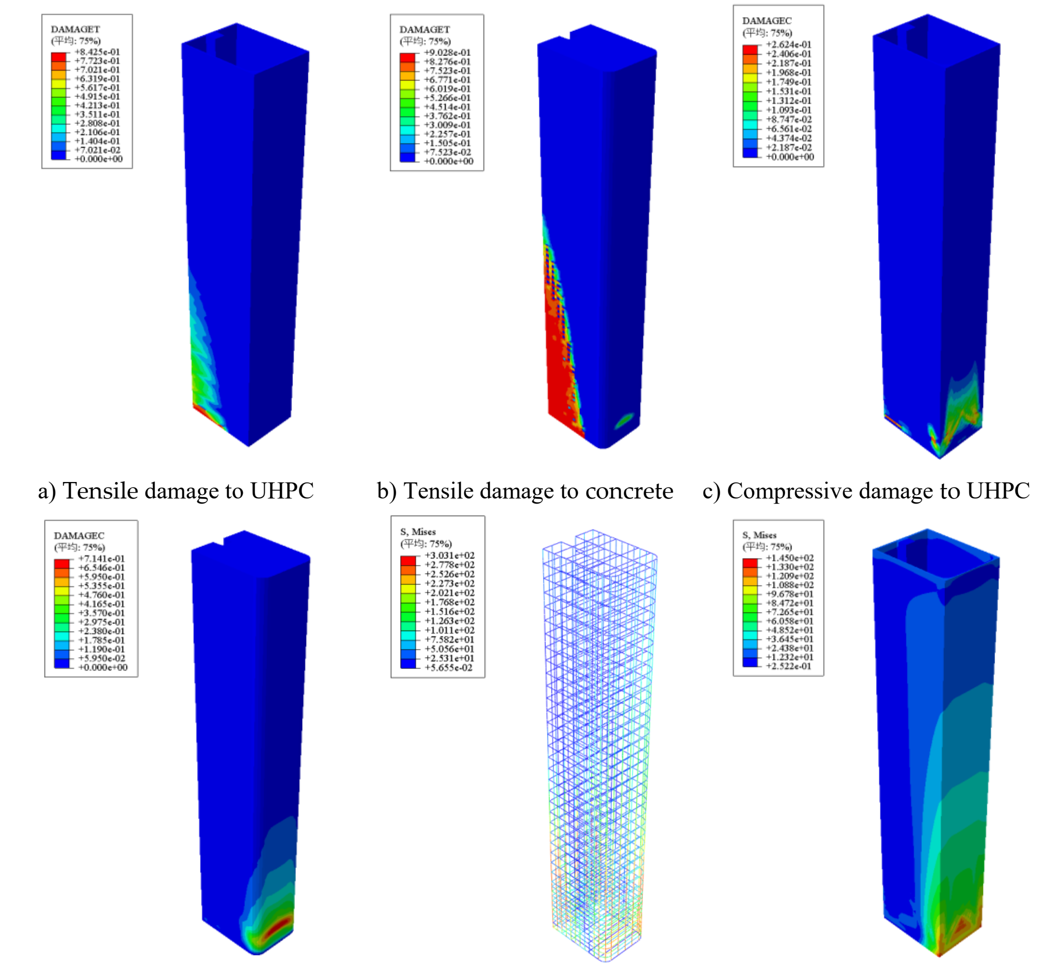


a) Tensile damage to UHPC b) Tensile damage to concrete c) Compressive damage to UHPC



d) Compressive damage to concrete e) Rebar stress f) UHPC stress

Figure 14 Damage contours and stress contours of columns reinforced with 100 MPa UHPC at peak loading



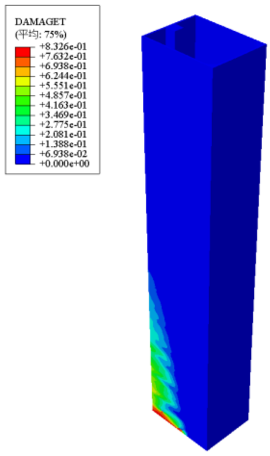
a) Tensile damage to UHPC b) Tensile damage to concrete c) Compressive damage to UHPC

d) Compressive damage to concrete e) Reinforcement stress f) UHPC stress

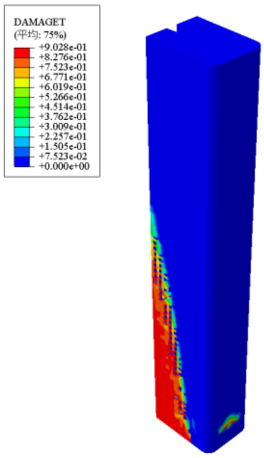
Figure 15 Damage contours and stress contours of columns reinforced with 130 MPa UHPC at peak loading

Load-displacement curves, peak loads, displacements, and stiffness degradation under monotonic loading for concrete columns reinforced with varying-strength UHPC (100, 130, 160 MPa; 30 mm thickness) are presented in Figure 17. The results demonstrate significantly higher peak loads and displacements in UHPC-reinforced columns relative to original concrete columns, confirming superior deformability. Notably, the peak load enhancement substantially exceeds that achieved with ECC reinforcing. This cross-sectional size augmentation also amplified initial stiffness, elevated residual strength, and increased structural redundancy. The larger area enclosed by the load-displacement curves of UHPC-reinforced columns signifies greater energy dissipation capacity compared to conventional concrete columns, with progressively enhanced dissipation observed at higher UHPC strengths. Furthermore, all strengthened specimens exhibited progressively increasing stiffness exceeding original RC columns, coupled with greater damage resistance characterized by slower strength degradation.

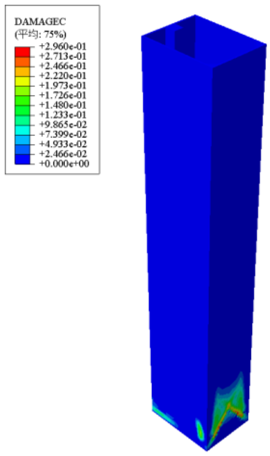
Concrete columns reinforced with 130 MPa compressive strength UHPC were investigated at two bonded layer thicknesses (20 mm and 30 mm) to assess thickness effects on mechanical performance. As revealed by the load-displacement curves in Figure 18, progressive enhancement of load-bearing capacity and amplified initial stiffness occurred with increasing UHPC layer thickness.



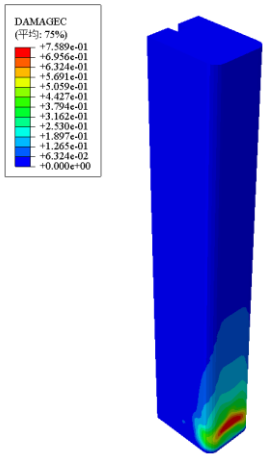
a) Tensile damage to UHPC



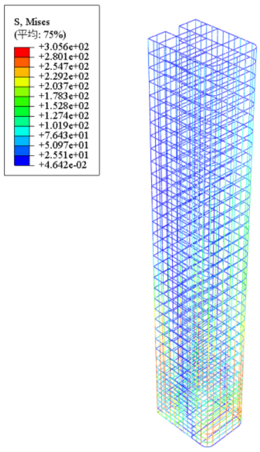
b) Tensile damage to concrete



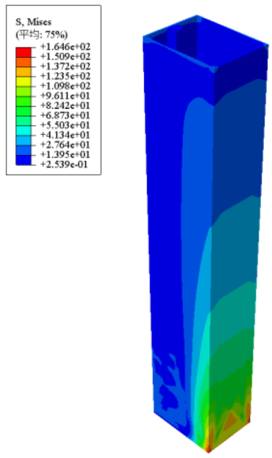
c) Compressive damage to UHPC



d) Compressive damage to concrete

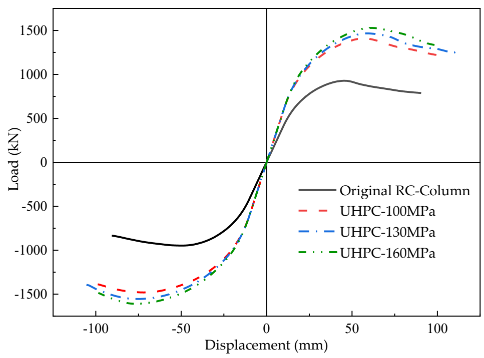


e) Reinforcement stress

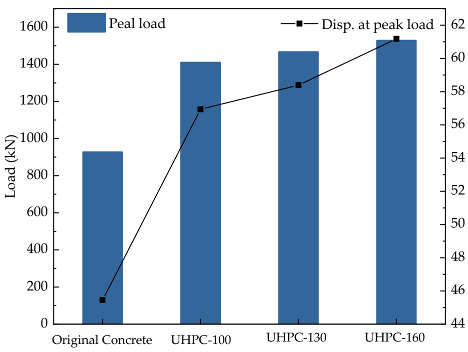


f) UHPC stress

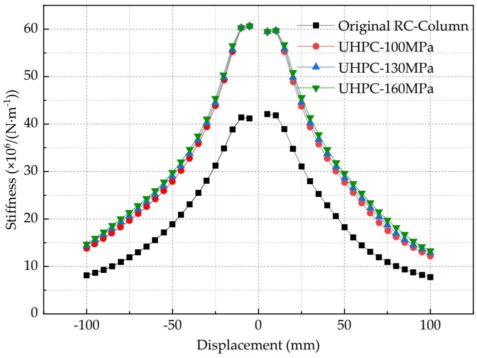
Figure 16 Damage contours and stress contours of columns reinforced with 160 MPa UHPC at peak loading



a) Load–displacement curves



b) Peak loads and displacements



c) Stiffness–displacement curves

Figure 17 Mechanical properties of UHPC reinforced columns with different strength

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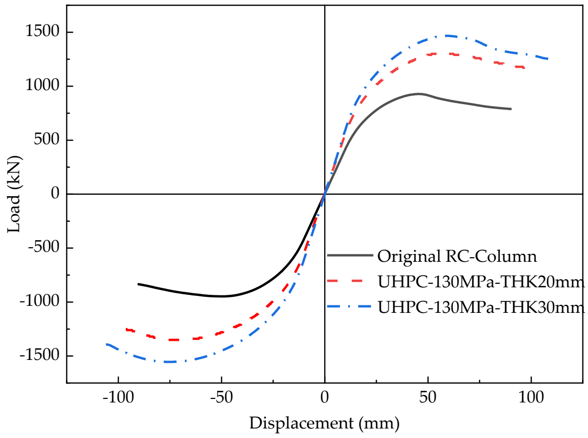

Figure 18 Load–displacement curves of reinforced concrete columns with different thicknesses of UHPC layer

3.4 Comparison of Reinforcement Effect

The effects of FRP, ECC, and UHPC externally bonded composites on the mechanical properties of concrete columns are summarized in Table 1, including load-bearing capacity, ductility factor, energy dissipation, and ultimate drift ratio. The ductility factor is defined as the ratio of ultimate displacement to yield displacement, where ultimate displacement corresponds to the point at which load drops to 85% of peak load [16]. Yield displacement is averaged using three methods: geometric graphics method, equivalent elastoplastic energy method, and R. Park method. Energy dissipation is quantified by the area enclosed by the skeleton curve and displacement axis.

Table 1 Mechanical parameters of concrete columns reinforced with different materials

Material	Thickness (mm)	Material Strength (MPa)	Load-Bearing Capacity (kN)	Ductility Factor	Energy Dissipation ($\times10^6$ N·mm)	Ultimate Drift Ratio
Original Column	0	-	928	3.2948	75.08	1/74
FRP	1	700	988	3.2069	79.87	1/69
	1	1400	988	3.3403	80.16	1/66
	1	2100	988	3.3403	80.16	1/66
ECC	20	60	1,150	3.4155	95.14	1/66
	30	30	1,161	3.5381	94.58	1/67
	30	60	1,260	3.3155	102.76	1/66
	30	95	1,345	3.3759	109.75	1/63
UHPC	20	130	1,310	3.4728	106.97	1/59
	30	100	1,410	3.4251	114.35	1/60
	30	130	1,467	3.6282	118.68	1/59
	30	160	1,528	3.2669	123.20	1/59

All three reinforcing materials had some enhancement effects on the ductility of the concrete columns, but the ECC- and UHPC-reinforced columns generally presented greater ductility. The ductility coefficients of the samples decrease with increasing ECC strength, which was primarily because the deformation capacity of the ECC material itself decreased with increasing strength of the substrate, resulting in a weakening of the deformation restraining capacity of the outer thin layer. For

UHPC, a similar trend is observed, where the ductility factor of the 160 MPa strength UHPC-reinforced concrete columns is lower than that of the 130 MPa strength UHPC-reinforced columns.

All three reinforcement materials have some enhancement effects on the energy dissipation capacity of concrete columns, although the enhancement effect of FRP is relatively weak. FRP reinforcement increases the energy dissipation of the concrete columns from 75 × 10^6 N·mm to approximately 80 × 10^6 N·mm, with an enhancement rate of only 6.7%, whereas the energy dissipation rates of the ECC- and UHPC-reinforced columns are in the 95–110 × 10^6 N·mm and 105–125 × 10^6 N·mm, with minimum energy dissipation enhancement rates of 26.7% and 40%, respectively. In other words, the UHPC-reinforced columns had the highest energy dissipation, followed by the ECC-reinforced columns, and the FRP-reinforced columns had the lowest energy dissipation, which was mainly due to the higher compressive strength of the UHPC. In addition, the ultimate load bearing capacity and energy dissipation of the samples gradually increased with the increasing thickness of the ECC and UHPC layer. According to the specimen load bearing capacity and ductility requirements, FRP, ECC and UHPC reinforcement materials with different strengths and thicknesses can be used. Owing to the high strength of FRP layer, the number of layers should not be too high in the actual reinforcement to prevent material waste.

The ultimate drift ratios of the concrete columns reinforced with all three materials are larger than those of the original concrete columns, where the ultimate drift ratios of the FRP- and ECC-reinforced concrete columns are similar. The ultimate drift ratios of the UHPC-reinforced concrete are significantly larger, indicating that the outsourced UHPC-reinforced members have a greater ultimate deformation capacity.

4 Conclusions

(1) Despite FRP's superior tensile strength, increasing its strength yields negligible improvements in load-bearing capacity, stiffness, or deformation capacity. FRP selection should therefore align with the existing concrete strength and reinforcement grade to optimize tensile performance utilization.

(2) The bonded ECC layer exhibits significantly less tensile damage than UHPC due to ECC's exceptional deformation capacity. Conversely, UHPC provides more substantial load-bearing capacity enhancement owing to its higher compressive strength.

(3) Both ECC and UHPC bonded layers yield enhanced energy dissipation capacity, with progressive improvement observed as material strength increases. While both ECC and UHPC specimens offer higher ductility compared to the original columns, the differences in ductility between ECC and UHPC specimens are not pronounced. Furthermore, increasing the layer thickness enhances load capacity and energy dissipation, while also increasing initial stiffness.

Conflict of interest: All the authors disclosed no relevant relationships.

Data availability statement: The data that support the findings of this study are available from the corresponding author, Duan, upon reasonable request.

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