Finite element analysis of seismic behavior of PVA-ECC pier columns based on ABAQUS

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Abstract. In order to study the seismic performance of PVA-ECC pier column, using the finite element analysis software ABAQUS as the main research means, combined with the measured data of two existing specimens, and taking the axial compression ratio, shear span ratio and stirrup spacing as changing parameters, the extended analysis of 13 specimens was carried out, and the influence of various influencing parameters on the seismic performance of pva-ecc pier column was discussed. The results show that the established ABAQUS finite element model has a high degree of coincidence in failure morphology, hysteretic curve, skeleton curve and stiffness degradation curve; The shear span ratio and axial compression ratio have a great influence on the type performance of PVA-ECC pier column. The influence of stirrup diameter on shear capacity is less than 5%.

Keyword：PVA-ECC; Bridge pier column; Seismic performance; finite element analysis.

1. Introduction

Bridge piers are critical components in bridges. In addition to bearing complex static and dynamic loads, outdoor temperature differences and water erosion often lead to cracking in bridge piers. Therefore, bridge piers require good seismic performance and crack resistance [1].

Engineered cementitious composites (ECCs) possess high ductility, toughness, and crack resistance, which can significantly improve the ductility, energy dissipation, corrosion resistance, impact resistance, and abrasion resistance of structures. Extensive research has demonstrated the mechanical properties of ECCs reinforced by various fibers, including polyvinyl alcohol (PVA), steel, and polypropylene fibers [2]. PVA-ECC exhibits high ductility and toughness, with ultimate tensile strain capacity over 4% and excellent strain hardening and multiple cracking abilities. Current research has investigated the seismic performance of ECC components, such as columns, beams, and shear walls. Finite element analysis shows ECC columns have ~25% higher energy dissipation and ~40% higher initial stiffness compared to concrete columns under the same seismic excitation [3]. Experimental results demonstrate ECC shear walls can improve the failure mode, damage tolerance, and post-earthquake reparability of low-rise shear walls [4]. Studies on eccentrically loaded ECC columns reveal PVA-ECC columns outperform reinforced concrete columns in ductility, energy dissipation, and seismic resistance, especially with reduced transverse reinforcement [5,6]. Torsion tests further prove PVA-ECC can effectively mitigate cracking in concrete [7,8]. Successful case studies have implemented PVA-ECC to partially retrofit bridge piers [9,10].

Despite the excellent potential of PVA-ECC, its application in bridge piers is still limited. In this study, we comprehensively analyze the seismic performance of ECC bridge piers based on previous experimental and numerical results [6]. Through extensive simulations of 13 specimens, we systematically investigate the effects of axial load ratio, shear span ratio, transverse reinforcement spacing, transverse bar diameter, and longitudinal bar diameter on the seismic behavior of ECC bridge piers. The results provide references for engineering applications.

2. Experimental programme

In the experimental study [6], two ECC bridge pier specimens were designed and fabricated with different PVA fiber volumes. The section details are shown in Figure 1. Table 1 summarizes the design parameters of the test specimens and additional specimens for extended analysis. All specimens have a cross-section of 200mm×200mm and a column height of 700mm. The cover thickness is 10mm. HRB400 grade rebars are used for longitudinal reinforcement, and HPB300 grade rebars for transverse confinement. For ECC with 1.2% PVA fiber volume, the cubic compressive strength fc = 42.9MPa, and the tensile strength ft = 3.53MPa. For ECC with 2% PVA fiber volume, fc = 46.3MPa, and ft = 4.83MPa.

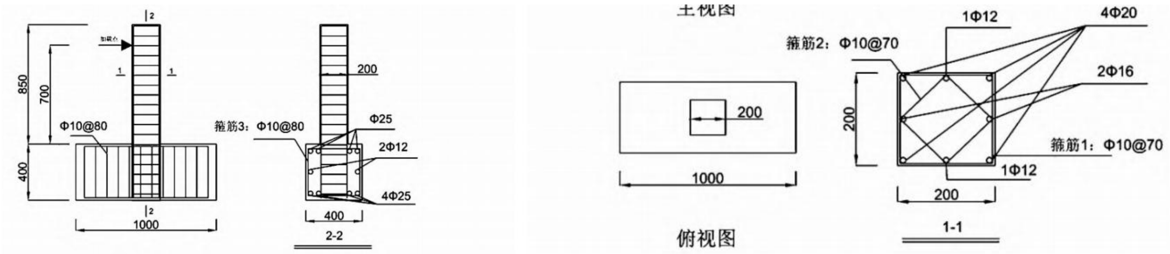


Figure 1 Schematic diagram of specimen structure

Table 1 Design parameters and test results of specimens

Specimen No	n	λ	S/mm	Pp/kN	μ	Note
ECC-1	0.2	3.5	70	161.5	3.01	Test specimen
ECC-2	0.2	3.5	70	178.7	5.62	
E-1	0.2	3.5	70	171.8	6.62	Change in axial compression ratio
E-2	0.3	3.5	70	190.0	5.46	
E-3	0.4	3.5	70	198.6	4.69	
E-4	0.5	3.5	70	197.2	3.80	
E-5	0.6	3.5	70	194.5	3.31	
E-6	0.2	4.5	70	135.7	4.75	Change in shear span ratio
E-7	0.2	5.5	70	107.1	3.01	
E-8	0.2	6.5	70	88.4	2.30	
E-9	0.2	7.5	70	73.9	2.34	
E-10	0.2	3.5	50	170.7	5.34	Change in stirrup spacing
E-11	0.2	3.5	100	178.9	6.78	
E-12	0.2	3.5	150	176.4	6.71	
E-13	0.2	3.5	200	174.8	6.85	

Note: Pp is the mean value of the positive and negative ultimate shear bearing capacity of the specimen; μ Is the mean of the positive and negative ductility coefficients, $\mu=\Delta u/\Delta y$[11], Δu and Δy represents the displacement of the failure point and yield point of the skeleton curve, respectively.

3. Finite element model

3.1 Constitutive relationships of the materials

3.1.1 PVC-ECC

Regarding the constitutive models of PVA-ECC under uniaxial compression and tension, the stress-strain relationships proposed by Meng [12] are adopted.

3.1.2 Steel

Steel reinforcement is modeled with truss elements to improve convergence. A bilinear elastic-plastic model [13] is used for the stress-strain relationship. The steel behaves linearly elastic before yielding. Between yielding and ultimate strength, the hardening stiffness is taken as 0.01Es. Here, fy and εy are the yield stress and strain, fu and εu are the ultimate stress and strain, E0 is the initial elastic modulus taken as 200 GPa, and Es is the hardening modulus taken as 0.01E0.

3.2 Interaction

The reinforcement is embedded in concrete using the "embed" constraint, which neglects bond-slip between rebars and concrete. A reference point is defined at the loading point and “coupled” with the top concrete surface to facilitate loading and boundary conditions.

3.3 Boundary conditions and loading method

According to the test setup, the bottom of the specimen is restrained against translations in three directions but allowed to rotate, simulating a hinged support. In the first analysis step, a constant axial load (n=0.2) is applied. Cyclic displacements are then imposed in the second step following the same loading protocol as in the tests [6]: 0.875mm, 1.4mm, 2.8mm, 4.66mm, 7mm, 14mm, 20mm, 28mm, 35mm.

3.4 Mesh

Based on preliminary analyses, a concrete element size of 15mm is adopted to achieve a balance between accuracy and efficiency. The completed finite element model is shown in Figure 2.

（a）PVA-ECC （b）Rebar cage

Figure 2 Component and grid division

3.5 Validation of the numerical simulation model

The proposed modeling method and material properties are utilized to simulate the two ECC pier specimens tested in [6]. The hysteretic curves and backbone curves from FE analysis are compared with test results in Figure 3. It can be observed that the computed hysteretic curves exhibit the same “ pinching ” behavior as the tests, with consistent envelope area and unloading stiffness. The backbone curves and ultimate shear capacities also agree well with the experiments. Figure 4 compares the failure modes between test and FE analysis. The computed tensile damage contours in concrete match well with the observed crack patterns, featuring cross-inclined cracks in the core and staggered cracks along the corners. Overall, the measured ultimate shear capacities are 161.5kN and 178.7kN for ECC-1 and ECC-2, with ductility coefficients of 3.01 and 5.62, respectively. The FE ultimate capacities are 165.4kN and 171.8kN, with ductility coefficients of 3.25 and 6.62. The average error is within 7%, demonstrating the FE model can reliably simulate the seismic behavior of PVA-ECC pier specimens.

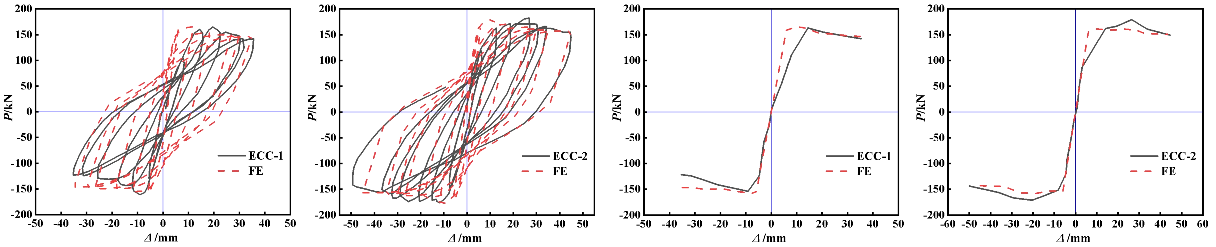
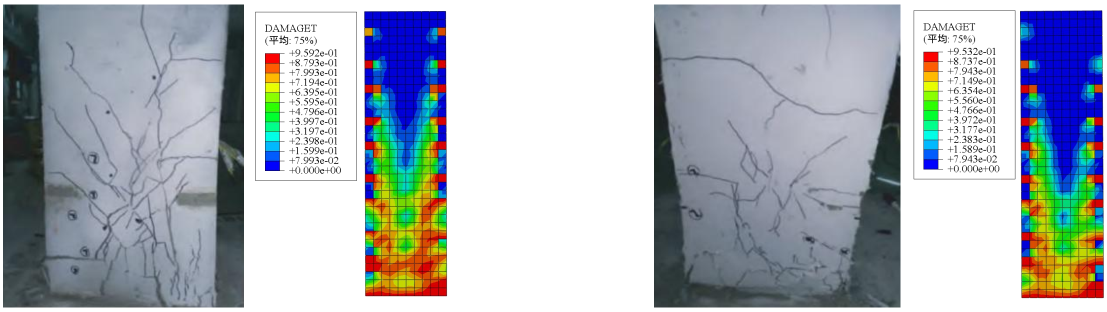


Figure3 Comparison between finite element results and experimental results

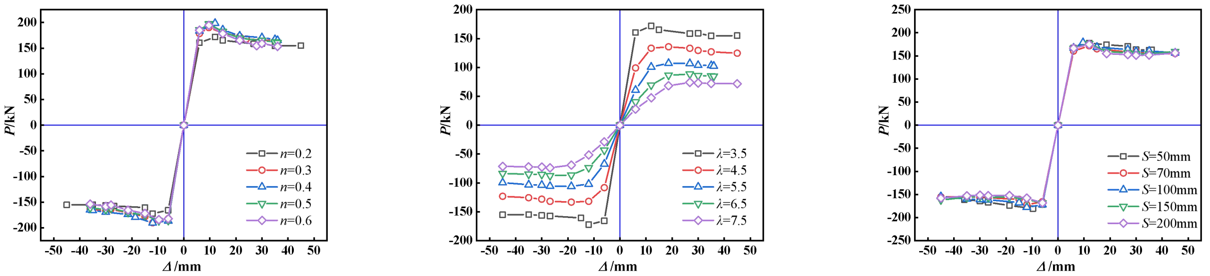


(a)ECC-1 (b)ECC-2

Figure 4 Comparison of failure modes between finite element results and experimental results

4. Parameter analysis

As validated in Section 3.5, the established FE model can accurately simulate the seismic behavior of ECC bridge piers. The ECC-2 model with better matched hysteretic curves, backbone curves, and stiffness degradation is selected as the baseline. 21 additional models are created by varying the axial load ratio n, shear span ratio λ, stirrup spacing S, stirrup bar diameter dst, and longitudinal bar diameter dl. Figure 5 shows the influence of different variables on the skeleton curve. The detailed parameters and key analysis results are summarized in Table 2. Based on the parametric study, the influences of these factors on the seismic behavior of ECC piers can be quantified. The axial load ratio and stirrup configuration have significant effects on the shear strength and ductility. Increased axial load improves the confinement and shear transfer capacity, while reduced stirrup spacing and larger bar diameters enhance the shear resistance and deformation capability. The shear span ratio primarily affects the failure mode and ductility. Overall, these parametric studies can provide guidance for optimal seismic design of ECC bridge piers.



(a)The influence of axial compression ratio (b)The influence of shear span ratio (c)The influence of stirrup spacing

Figure 5. Effect of Different Parameters on Skeleton Curve

4.1 The influence of axial compression ratio

As the axial load ratio increases, the ultimate shear capacity of ECC piers gradually increases, and the peak point on the backbone curve shifts upwards and leftwards with a more pronounced convex shape. Compared to the specimen with 0.2 axial load ratio, the ultimate capacities for axial load ratios of 0.3, 0.4, 0.5 and 0.6 are increased by 10.5%, 15.5%, 14.7% and 13.2%, respectively. However, the ductility decreases by 17.6%, 29.2%, 42.6% and 50.1%, respectively. This indicates that higher axial load ratio improves the shear strength of PVA-ECC piers, but is detrimental to ductility.

4.2 The influence of shear span ratio

The shear span ratio has a significant influence on the backbone curves of ECC piers. As the ratio increases, the ultimate shear capacity and shear stiffness exhibit apparent degradation, and the post-peak descending branch becomes more gradual. Compared to the specimen with shear span ratio of 3.5, the ultimate capacities decrease by 21.1%, 37.7%, 48.6% and 56.9% for shear span ratios of 4.5, 5.5, 6.5 and 7.5, respectively. The ductility reduces by 28.3%, 54.6%, 65.3% and 64.7%, respectively. This demonstrates that the shear span ratio is a crucial factor affecting the seismic performance of PVA-ECC piers. A larger shear span ratio leads to reduced shear resistance and energy dissipation capability.

4.3 The influence of stirrup spacing

The change in stirrup spacing does not have a significant influence on the backbone curves of ECC piers. Compared to the specimen with 50mm stirrup spacing, the ultimate shear capacities increase by 0.6%, 4.8%, 3.3% and 2.4% for spacings of 70mm, 100mm, 150mm and 200mm, respectively. The ductility improves by 23.9%, 26.9%, 25.6% and 28.2%, respectively. This indicates that larger stirrup spacing can effectively enhance the ductility of PVA-ECC piers, but the impact on shear strength is minor. In summary, increased stirrup spacing mainly benefits the deformation capability and energy dissipation of PVA-ECC piers, while having marginal influence on the shear resistance. This is likely because the ECC material itself has high tensile ductility, so the confinement effect from stirrups is less crucial compared to regular concrete.

5. Conclusion

Through finite element modeling and analysis on 13 ECC bridge piers, the following conclusions can be drawn:

The established ABAQUS finite element model can reliably simulate the seismic behavior of tested ECC bridge piers, with good agreement achieved in failure mode, hysteretic curves, backbone curves, and stiffness degradation.

The ultimate capacity of PVA-ECC piers increases with higher axial load ratio and lower shear span ratio. The effects of stirrup spacing on capacity improvement are minor, within 5%. Among these factors, shear span ratio has the most significant influence.

Increased axial load ratio and shear span ratio all contribute to reduced ductility of PVA-ECC piers, while larger stirrup spacing effectively improve the ductility. Axial load ratio and shear span ratio have more pronounced effects on ductility.

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