PREDICTIVE BEHAVIOUR FROM FINITE ELEMENT ANALYSIS ON PVC-DUCTED REINFORCED CONCRETE COLUMN

ABSTRACT

This research investigated the behaviour of square reinforced concrete columns with embedded PVC pipes, aiming to comprehensively analyze their performance. The study addressed the lack of significant research on the contributions and effects of embedded PVC pipes on structural performance compared to hollow columns. The objectives of the study sought to evaluate the contributions and effects of embedded PVC pipes on the structural performance of columns under loading conditions, determine how the presence of PVC pipes influenced the columns' ability to deform and dissipate energy, and identify the optimal size of PVC pipes to enhance column performance while maintaining stability and safety. Numerical analysis using ABAQUS CEA 2020 software was employed to simulate the behavior of reinforced concrete columns with embedded PVC pipes. The computational model used the same cross-sections with varying diameters of PVC pipes (50mm, 75mm and 100mm). The analysis focused on assessing load-bearing capacities, deformation characteristics, and energy dissipation patterns under axial vertical displacement loading scenario. Findings indicated that PVC-embedded columns exhibit higher load-bearing capacities and enhanced resilience. PVC pipes positively impact controlled deformation and energy dissipation, with smaller sizes resulting in better load-bearing performance. The study recommended meticulous attention to material composition and structural design during PVC-embedded column implementation, careful selection of PVC pipe sizes based on structural requirements and project specifications, further research on dynamic loading conditions to comprehensively understand column behavior, and implementation of stringent quality control measures during manufacturing and construction processes.

KEYWORDS:PVC embedded column, Perforated column, Force-displacement relationship, Plastic strains, Equivalent plastic strains, Magnetic potential energy.

1. INTRODUCTION

Columns are an essential part of any structural system as they support the beams and slabs and transfer loads to the foundations. In moment resisting structural systems, columns are considered critical members, and any failure or weakness can lead to the destabilization of the entire structure (Nilson et al., 2010). Hence, it is crucial to design and detail columns adequately to withstand both gravity and lateral loads (Ambrose et al., 2010). The ability of columns to bear loads depends on various factors such as the properties of materials used, their length, cross-sectional area, and upper and lower bracing (Mosley and Bungey, 1999).

In recent times, there has been a growing trend of modifying structural elements to enhance their functionality while maintaining the aesthetics of the structure (Hussien 2019). One such modification involves embedding Poly Vinyl Chloride (PVC) pipes into concrete structural elements to allow access for services such as electric wiring. Another practice involves positioning PVC pipes inside reinforced concrete (RC) columns to drain rain and waste water from high rise buildings and discharge at the ground (Bakhteri and Makhtar, 2002). However, these practices may lead to a reduction in strength, stiffness, ductility, and/or structural damage if not adequately considered during the design stage (Kani, 2013). Introducing drain pipes inside columns can make them hollow, thereby reducing the effective cross-sectional area and load carrying capacity of the column (Elmaguid et al., 2021). It is worth noting that current literature concerning the issue reveals a lack of coherent information and guidance in the codes of practice for ACI 318 (American) and BS8110 (British Standard) regarding this particular problem.

Research on these varieties of columns suggests that no significant investigations have been undertaken to examine the real discount in load carrying ability of these columns. Previous works in this regard have been limited to studying the effect of constant axial load and eccentric load on the behavior of rectangular and circular hollow reinforced concrete columns(Boukais, 1989, Basravi, 2010, Rajkumar and Madhavaraj, 2016). It has been found that columns constructed with PVC pipes embedded in them not only have reduced load carrying abilities but can also be dangerous to the safety of the entire building structure and reduce its useful life. Problems caused by this practice may include formation of honeycombs around the drain pipe and leakage from the joint lapping part of the pipe causing corrosion of reinforcement.

Variables such as the diameter and thickness of the PVC pipes, size and shape of the column, and the kind and amount of applied stresses may affect how reinforced concrete columns with PVC pipes embedded in them behave as hollow columns Kani, 2013). The presence of PVC pipes may also impact the bond between the concrete and the reinforcing steel, which can significantly affect the behavior of the column.

This analytical research aims to investigate the behavior of square reinforced concrete columns (models) having PVC pipes positioned inside them. The hysteric performance of the columns is evaluated using the same cross-sections with different diameters of PVC pipes.

2. MATERIALS AND METHODS

2.0. Study Overview

The primary aim of this study is to comprehensively analyze the behaviour of reinforced concrete columns embedded with PVC pipes and compare them with hollow columns without PVC pipes. The investigation utilizes a numerical simulation technique involving material characterization, column assembly, and testing under various loading conditions.The methodology involves modeling nonlinear mechanical analysis of concrete and reinforcement, treating them as time-independent. To address material non-linearity, the 3D Finite Element Analysis (FEA) software, ABAQUS FEA version 2020, was chosen.

2.1 Benchmark Validation

Solid Reinforced Concrete Column

A solid reinforced concrete column served as a benchmark or control for validation (see Table1). The model, developed within Abaqus, underwent rigorous evaluation against internal consistency and convergence criteria. Cross-verification involved adjusting parameters like mesh density, convergence criteria, and element types.

2.2ABAQUS Modeling of Reinforced Concrete Column

ABAQUS/CAE 2020 Overview

ABAQUS/CAE 2020, a finite element package, was chosen for its flexibility. ABAQUS offers various modes of execution, including ABAQUS/Standard for static, dynamic, linear, and nonlinear problems.

2.3 Material Modeling Pre-processing Data

Seven models were generated, each detailed in Table 1, encompassing three configurations featuring embedded PVC pipes, three perforated ones without PVC pipes, and a singular reference model. It also visually delineates the model identification, geometry, configuration specifics, reinforcement particulars, perforation diameters, and PVC pipe wall thicknesses for the varying PVC sizes.

Table 1 Material modeling pre-processing data (UPVC high pressure pipes & fittings, n.d.)

Column Model id	Model Geometry	Model Configuration	Rebar Details		Perforation Diameter	UPVC Wall Thickness
			Main	Stirrup		
FEM Validatio-Col.	300x300x2000	Solid	4R20	R8 165c/c	None	None
PVC-Embedded-50mm	300x300x2001	Hollow	4R20	R8 165c/c	60.32mm	6.20mm
Perforated-50mm	300x300x2002	Hollow	4R20	R8 165c/c	60.32mm	None
PVC-Embedded-75mm	300x300x2003	Hollow	4R20	R8 165c/c	88.90mm	8.53mm
Perforated-75mm	300x300x2004	Hollow	4R20	R8 165c/c	88.90mm	None
PVC-Embedded-100mm	300x300x2005	Hollow	4R20	R8 165c/c	114.30mm	9.58mm
Perforated-100mm	300x300x2006	Hollow	4R20	R8 165c/c	114.30mm	None

2.4Material Properties

Material properties, crucial for understanding material behaviour, were defined for concrete, steel, and UPVC (Table 2 and 3, Figures 1-5). These properties, such as mechanical, thermal, electrical, chemical, optical, density, and specific gravity, play a crucial role in defining a material's behaviour under various conditions. Mechanical properties, encompassing strength, stiffness, hardness, and elasticity, determine how a material responds to applied forces, influencing its structural integrity. Thermal properties, including thermal conductivity and heat capacity, provide insights into a material's ability to conduct heat and withstand temperature changes. Electrical properties, like conductivity and resistivity, detail a material's behaviour under electrical fields.

Chemical properties, such as reactivity and resistance to corrosion, are vital for assessing a material's durability and stability in different environments. Optical properties, covering transparency and reflectivity, focus on how materials interact with light. Additionally, density and specific gravity offer practical information about a material's mass and density concerning water, aiding in structural and design considerations. Overall, material properties guide decision-making processes in material selection, product design, and structural analysis, enabling the identification of the most suitable materials based on their performance attributes.

Table 2 Material properties for concrete (Elkady, 2023)

Material's parameters	**Concrete grade C25**	**Plasticity parameters**	
		Dilation angle	**33**
Concrete Elasticity		Eccentricity	0.1
Elastic Modulus (GPa)	30	fb0/fc0	1.16
Poisson's ratio	0.2	K	0.67
Density	2.40E-09	Viscosity parameter	0.0001

Concrete compressive behavior		Concrete compression damage	
Yield stress (MPa)	Inelastic strain	Damage parameter C	Inelastic strain
7.09252	0	0	0
14.0799	0.00032	0	0.00032
19.4175	0.00064	0	0.00064
22.8183	0.00095	0	0.00095
24.5305	0.00127	0	0.00127
25	0.00159	0	0.00159
24.2867	0.00191	0.02853	0.00191
22.5346	0.00222	0.09862	0.00222
20.2873	0.00254	0.18851	0.00254
17.9385	0.00286	0.28246	0.00286
15.7147	0.00318	0.37141	0.00318
13.7182	0.00349	0.45127	0.00349

Concrete tensile behavior		Concrete tension damage	
Yield stress (MPa)	Cracking strain	Damage parameter T	Cracking strain
4.16667	0	0	0
2.3116	0.00017	0.44522	0.00017
1.63771	0.00035	0.60695	0.00035
1.28244	0.00052	0.69221	0.00052
1.06088	0.0007	0.74539	0.0007
0.90857	0.00087	0.78194	0.00087
0.79699	0.00105	0.80872	0.00105
0.71148	0.00122	0.82924	0.00122
0.6437	0.00139	0.84551	0.00139
0.58856	0.00157	0.85875	0.00157
0.54276	0.00174	0.86974	0.00174
0.50406	0.00192	0.87902	0.00192

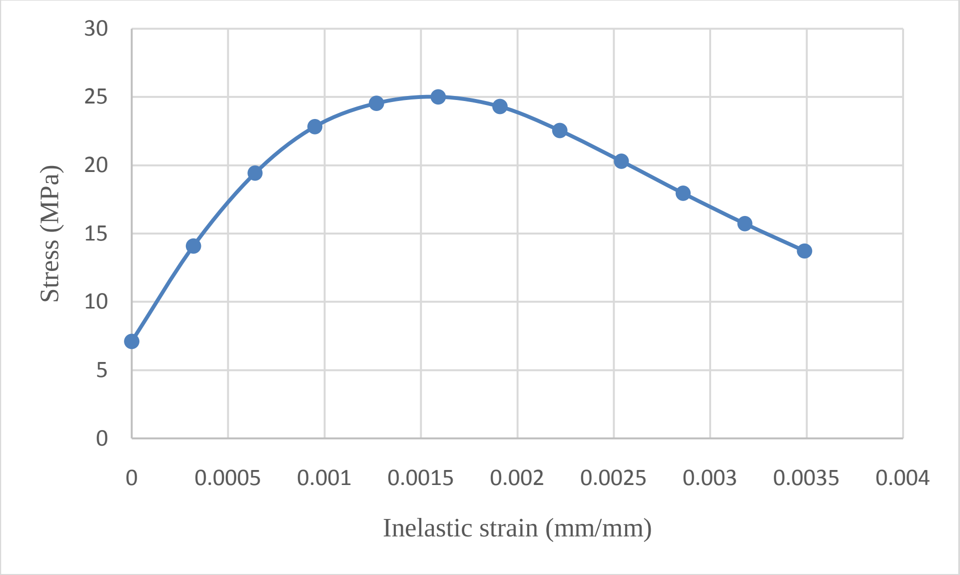


Figure 1: Concrete compressive strength

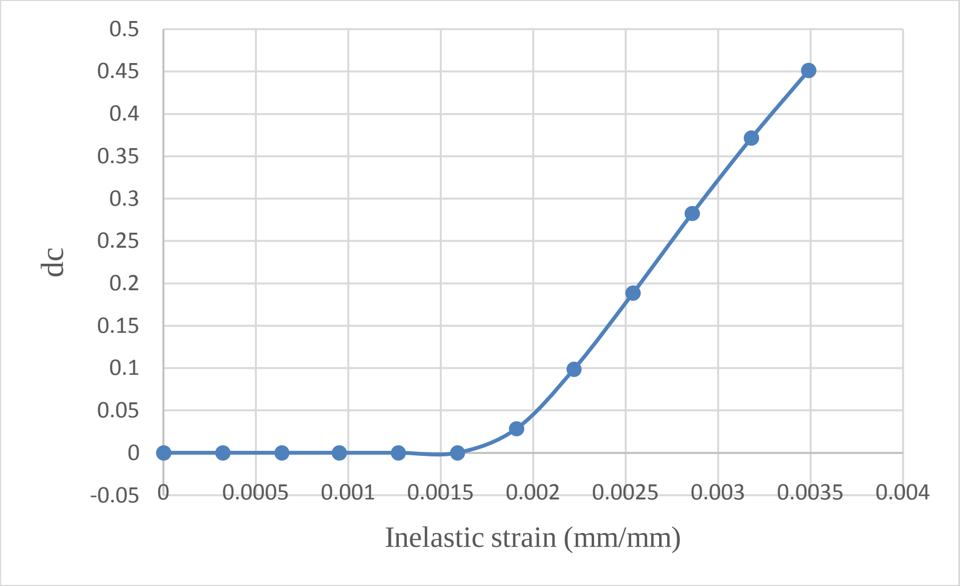


Figure 2: Compression damage of concrete

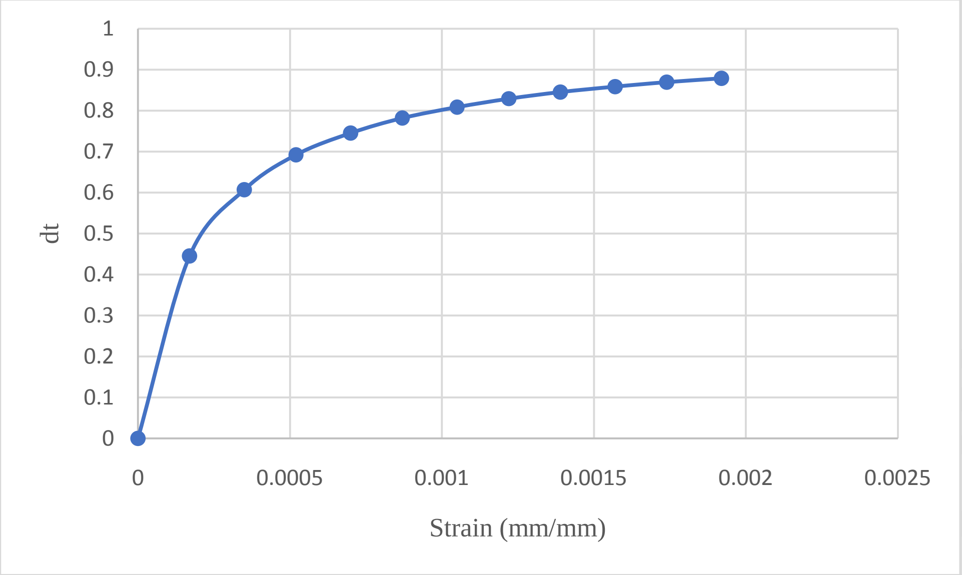


Figure 3: Tensile stress vs Cracking Strain

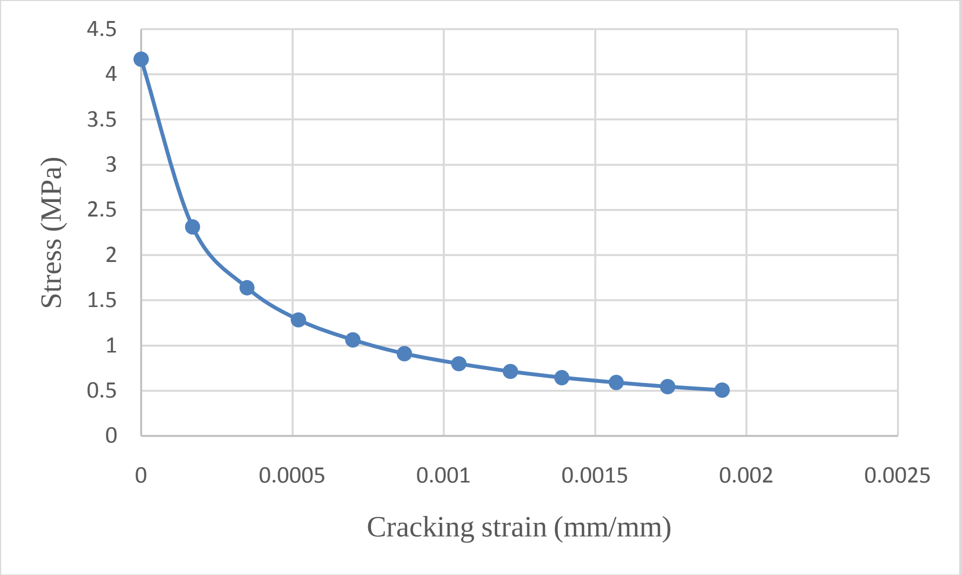
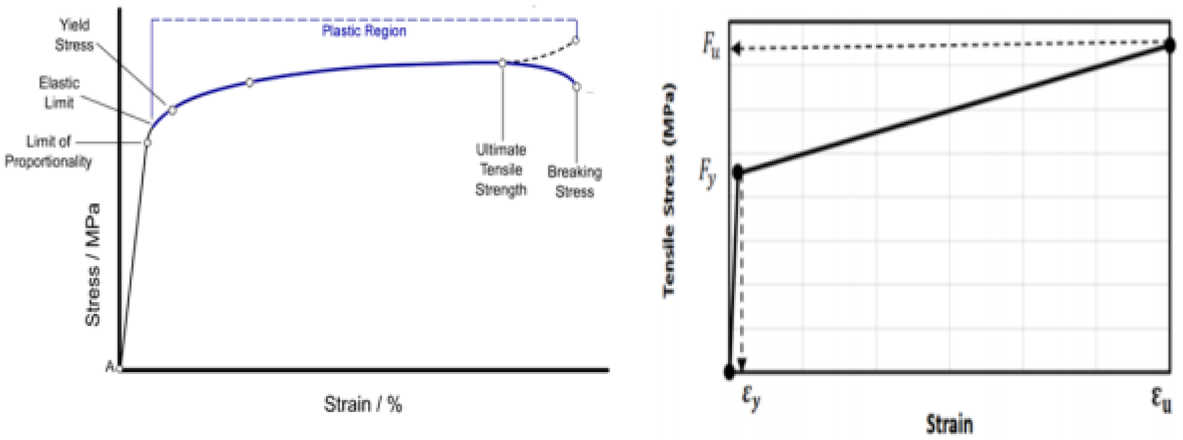


Figure 4: Concrete tension damage - Cracking strain of concrete

Table 3 Material properties for Steel and UPVC (Elkady, 2023; UPVC high pressure pipes & fittings, n.d.)

Material	Density	Elastic Behaviour		Plastic behaviour	
		Elastic Modulus E (GPa)	Poisson's ratio (v)	Yield Stress (MPa)	Plastic Strain
Steel	7.80E-09	200	0.3	159.458	0
				240.659	0.0227395
				271.991	0.0437627
				293.008	0.0648433
				309.155	0.0859509
				322.407	0.107075
				333.717	0.128209
				343.626	0.149351
				352.472	0.170499
				360.481	0.191652
				367.812	0.212809
				374.581	0.233968
UPVC	1.43E-09	3	0.4	45	0



a) Stress strain curve of mild steel **b) Simplified stress strain curve**

Figure 5: Typical uniaxial stress strain behavior of reinforcement(Mosley, Bungey, & Hulse, 1999)

2.5Element Type

Finite element analysis involved three-dimensional solid elements for concrete and truss elements for reinforcement. Two-node truss elements (T3D2) were used for reinforcement, and eight-node brick elements (C3D8) for plain concrete.

2.5.1 Step Module

A comprehensive analysis in the step module focused on detecting non-linearities. Two steps were present: the initial step defined boundary conditions and interactions, and the analysis step focused on static stress analysis.

2.5.2 Interactions and Kinematic Constraints

In constructing the finite element model, the focus was on establishing kinematic relationships to ensure strain compatibility among its components. This harmony in deformation was achieved through two key interaction types:

Embedded Constraints were crucial for defining interactions between concrete and steel reinforcement. The use of a beam-in-solid embedded relationship facilitated the embedding of the reinforcing bar within the inelastic concrete. However, caution was exercised to avoid over-constraining issues when extending this constraint to elastic portions at the column's extremes.

Surface Coupling Constraints played a vital role in ensuring proper interaction between different regions or surfaces within the model. Coupling column surfaces allowed for tie constraints, enabling realistic simulations of stress transfer, load distribution, and displacement compatibility. This approach effectively minimized stability issues often associated with combining nonlinear materials models with other interaction definitions.

These interaction types collectively contributed to the consistent and accurate representation of structural behaviour and response throughout the analysis.

2.5.3 Mesh Density

Mesh density varied to reduce degrees of freedom. A fine mesh was applied to stress concentration zones, slots, notches, and holes (Figure 6). Meshing techniques differed for plain concrete with and without perforations.

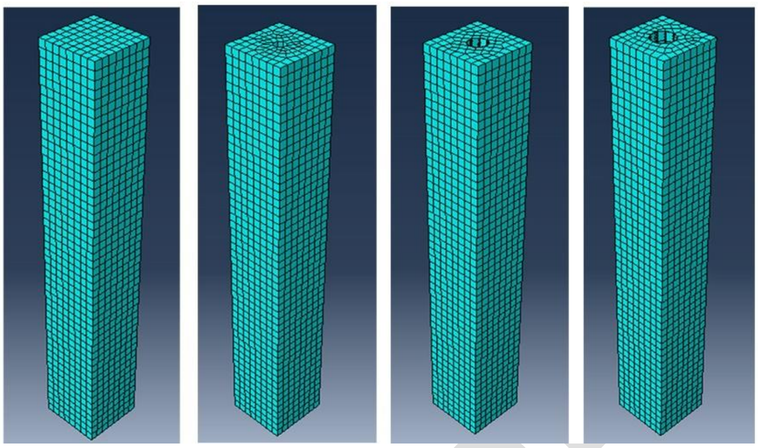


Figure 6: Meshing of reinforced concrete columns

2.5.4 Loading andBoundary Conditions

Constraints were established to prevent rigid body motion within the column structure. The base of the column was firmly fixed at the initiation of the simulation, restricting all six degrees of freedom to zero (U1=U2=U3=UR1=UR2=UR3=0).

Loading in the model was applied through a reference point on the upper surface of the column using displacement/rotation boundary conditions. This configuration facilitated the imposition of loads or fixed displacements at the reference point while capturing the corresponding reaction forces.

The loading process involved inducing a fixed axial displacement of -20mm vertically through the reference point in the static step of the simulation (U1= U3=UR1=UR2=UR3=0, U2= -20). The static analysis conducted in Abaqus aimed to understand the structure's response under constant loads, excluding dynamic forces or time-dependent effects. The analysis focused on assessing various structural responses, such as stresses, strains, and displacements, to evaluate the stability and strength of the structure under steady conditions. This methodology provided insights into how the structure would behave when subjected to specific applied forces or loads in a static scenario.

In summary, this comprehensive methodology, supported by Tables1-2 and Figures 2 to 7, ensures an accurate representation and analysis of reinforced concrete columns with embedded PVC pipes and hollow columns without PVC pipes.

3. RESULTS AND DISCUSSION

3.1 Benchmark column results

This section presents the outcomes of the solid column used as a reference point for the subsequent analyses, where reinforced concrete columns with embedded PVC pipes and hollow columns without PVC pipes were modeled from under consistent conditions.

3.1.1 Force-displacement relationship

The force-displacement relationship, depicted in Figure 7, demonstrates a substantial maximum force of 3092450 N applied to the column, resulting in a maximum negative displacement of -4.11699 mm. Notably, despite the magnitude of the load, the column exhibited remarkable resilience, with minimal deformation, illustrating its ability to withstand substantial axial forces without structural failure.

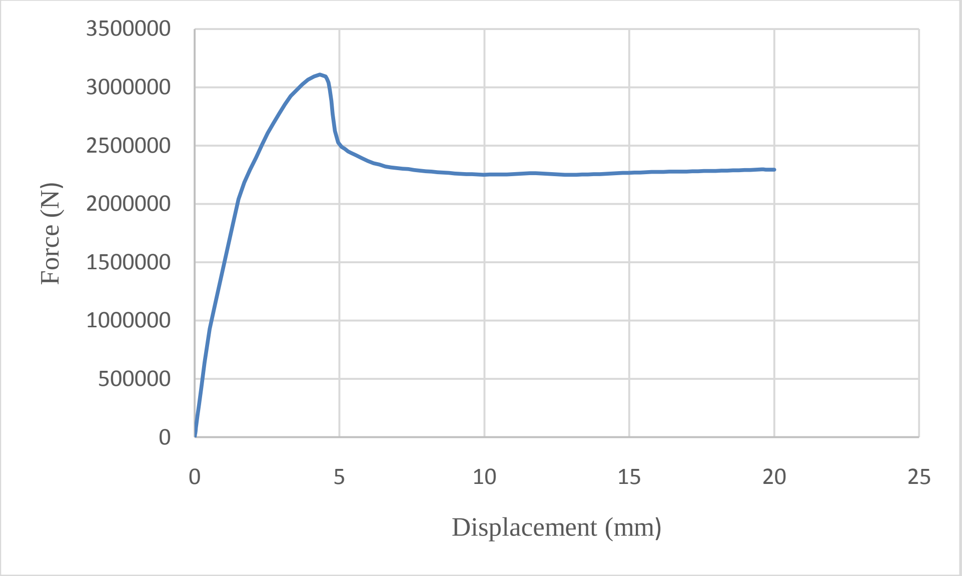


Figure 7 Maximum force-maximum displacementcurve

3.1.2 Plastic strains (LE)

Figure 8 illustrates the in-plane principal plastic strains, showcasing a discernible pattern of stress distribution within the column. The decreasing trend in stress values along the column's direction suggests varying stress concentrations, with higher values indicating potential areas prone to deformation or failure under extreme loading conditions.

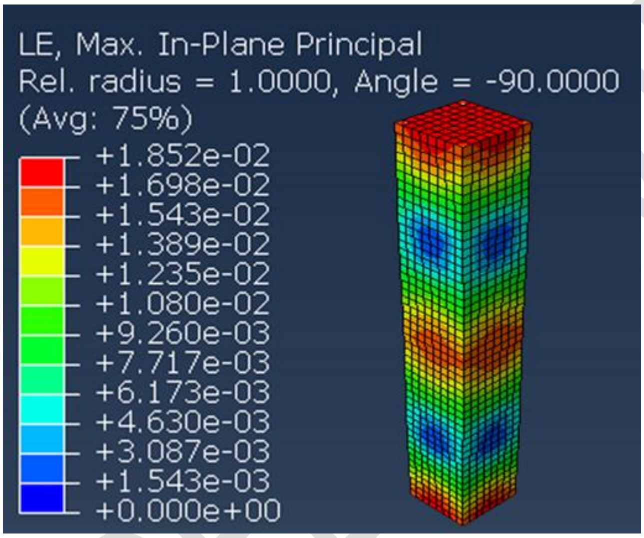


Figure 8Maximum in-plane principal plastic strains (LE)

3.1.3 Equivalent plastic strains (PEEQ)

Figure 9 presents the equivalent plastic strains, portraying the distribution of plastic deformation within the column. The decreasing trend in plastic strain values along the column indicates areas of varying plastic deformation, emphasizing regions susceptible to higher stress concentrations.

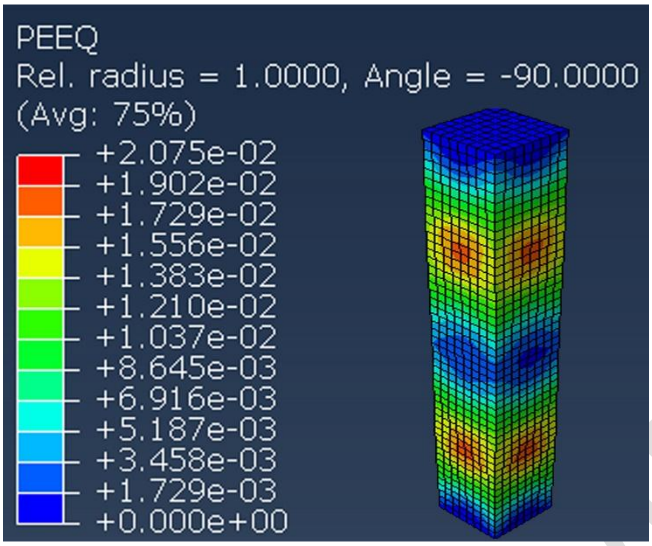


Figure 9Equivalent plastic strains (PEEQ)

3.1.4 Magnetic potential energy (PEMag)

Figure 10 illustrates the magnetic potential energy distribution along the column. The decreasing trend indicates a gradual dissipation of stored magnetic energy, with higher energy levels suggesting areas with stronger magnetic fields or increased energy storage.

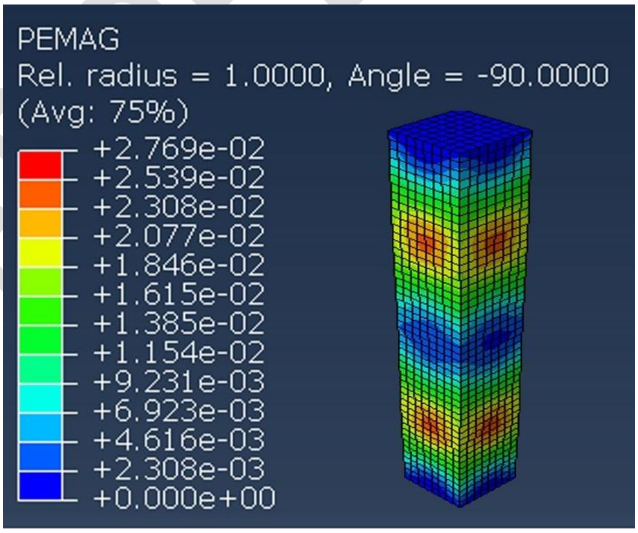
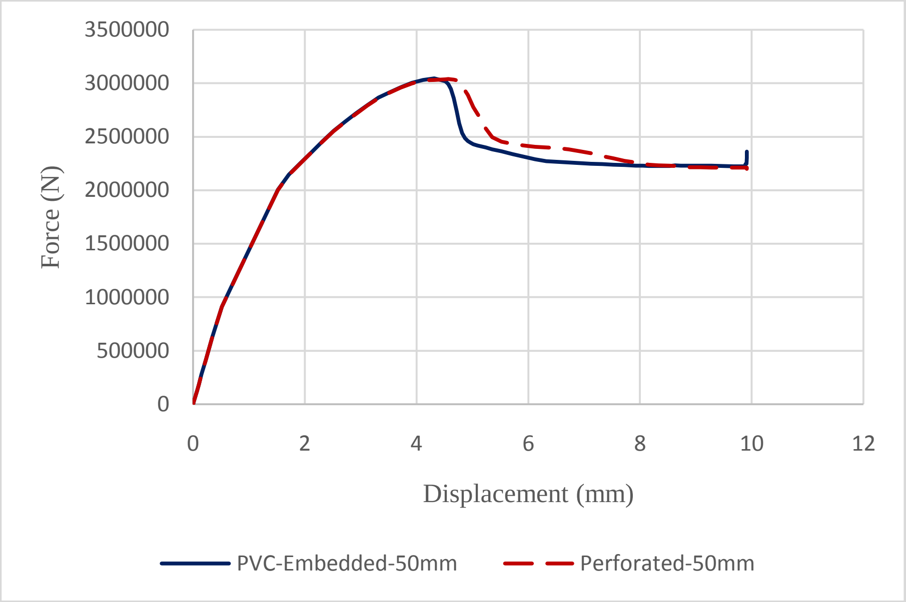
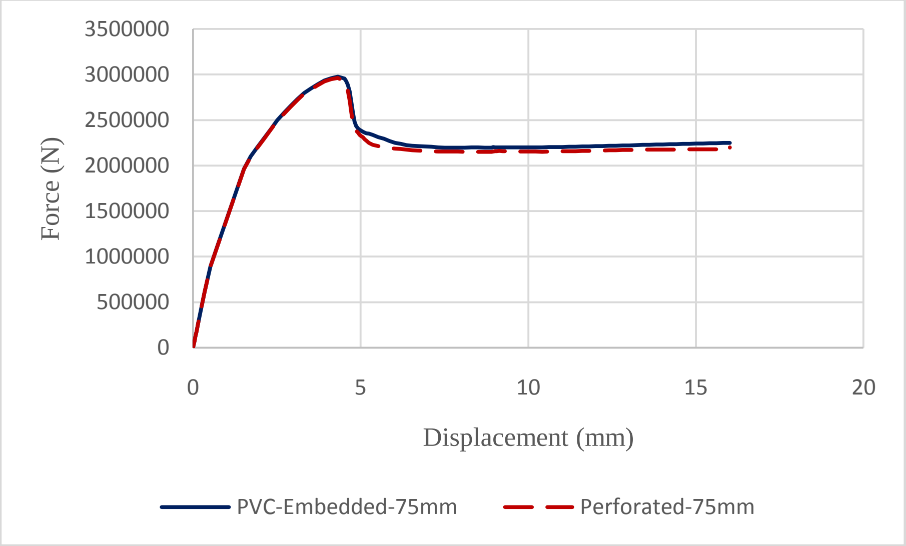


Figure 10 Magnetic potential energy (PEMag)

3.2 Comparison of Force-displacement relationship of PVC embedded columns and perforated columns without PVC

The force-displacement relationships of PVC-Embedded columns and Perforated columns without PVC are compared in Figure 11. Notably, PVC-Embedded columns consistently exhibit a slightly higher maximum force, indicating enhanced structural resilience across all lengths.





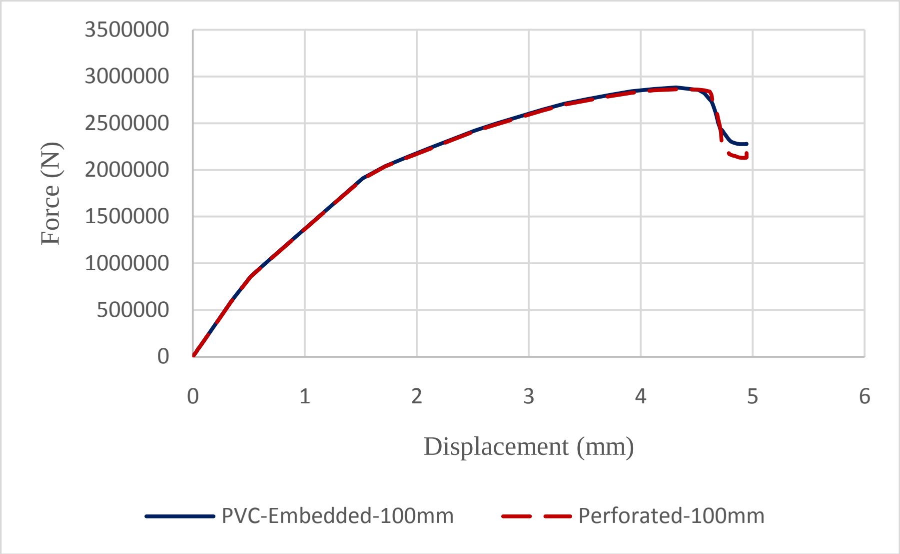
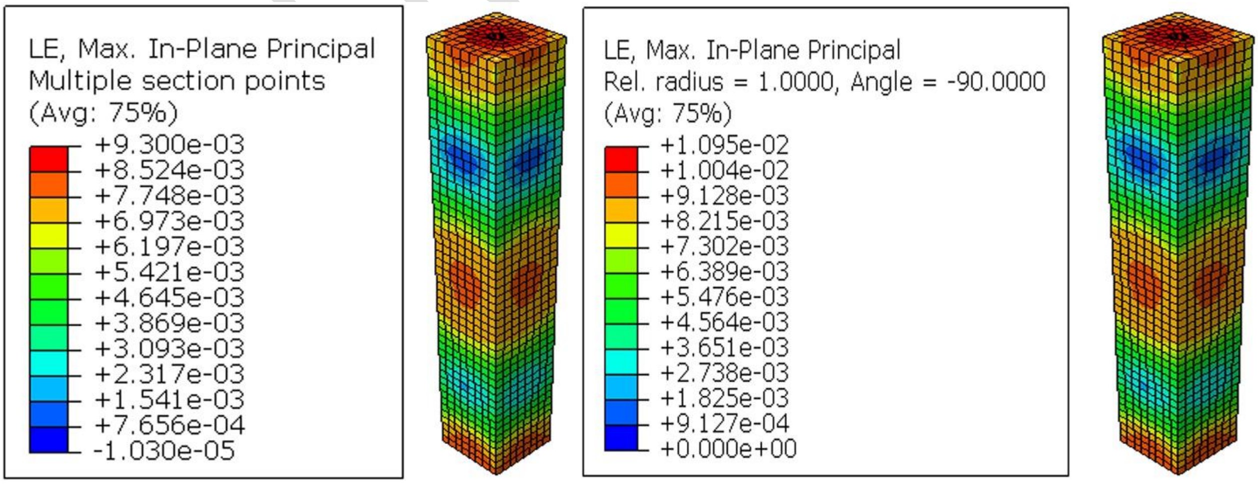


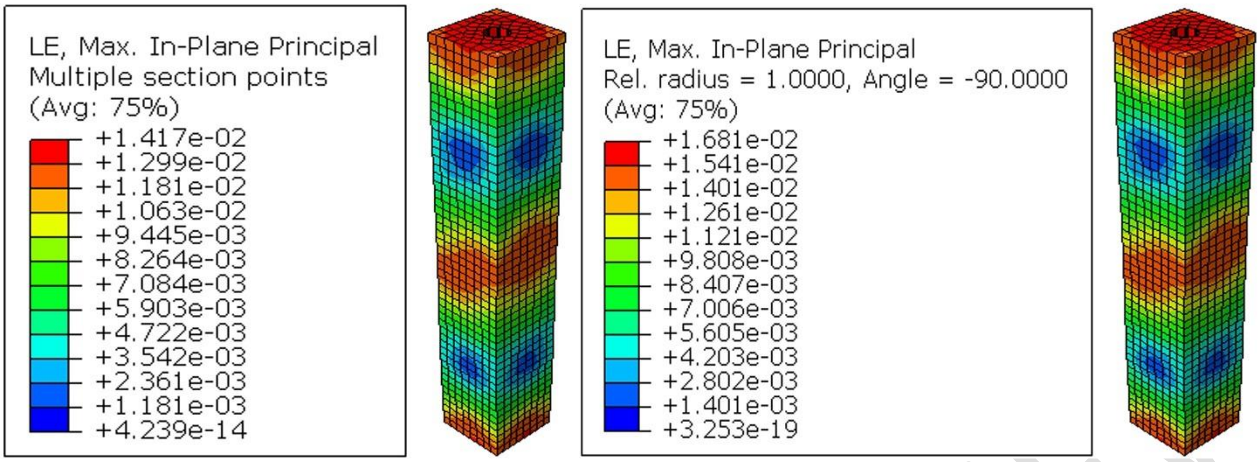
Figure 11. Force-displacement relationship of PVC embedded columns and perforated columns without PVC

3.3Comparison of Plastic strains (LE) of PVC embedded columns and perforated columns without PVC

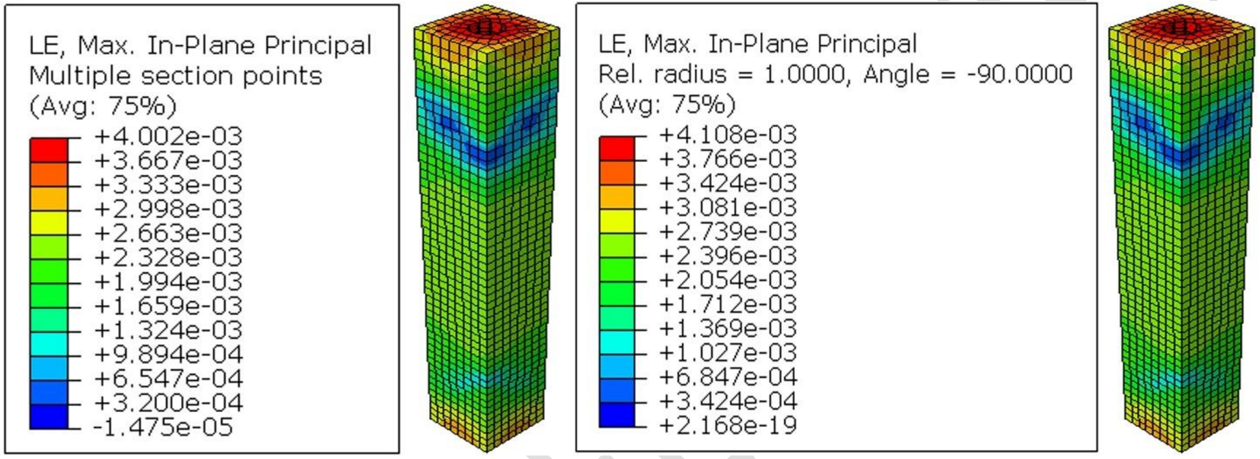
Figure 12 provides a detailed comparison of plastic strains (LE) in PVC-Embedded and Perforated columns without PVC. The results reveal that PVC-Embedded configurations tend to undergo, on average, less plastic deformation, indicating potentially more robust and resilient behavior across all diameters.



(a)PVC-Embedded-50mm (b) Perforated-50mm



(c)PVC-Embedded-75mm (d)Perforated-75mm

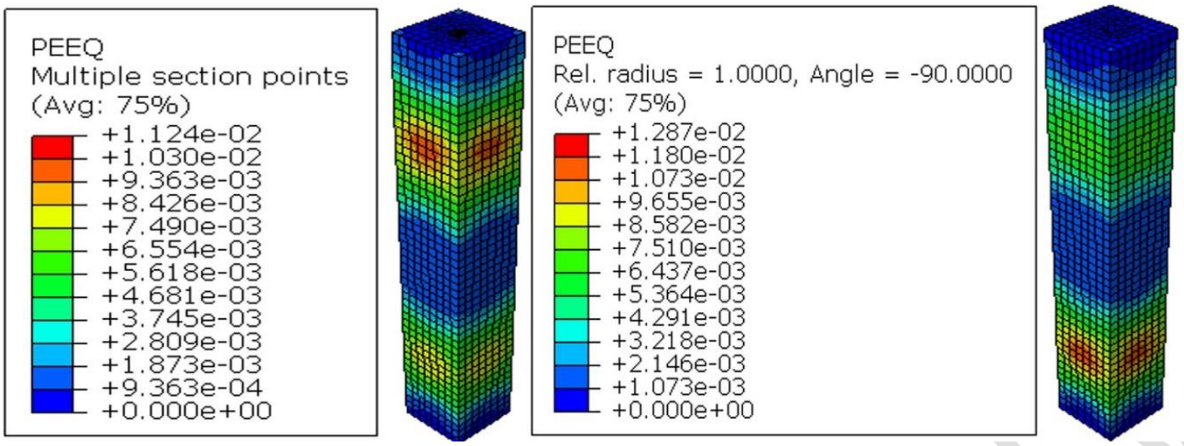


(e)PVC-Embedded-100mm (f)Perforated-100mm

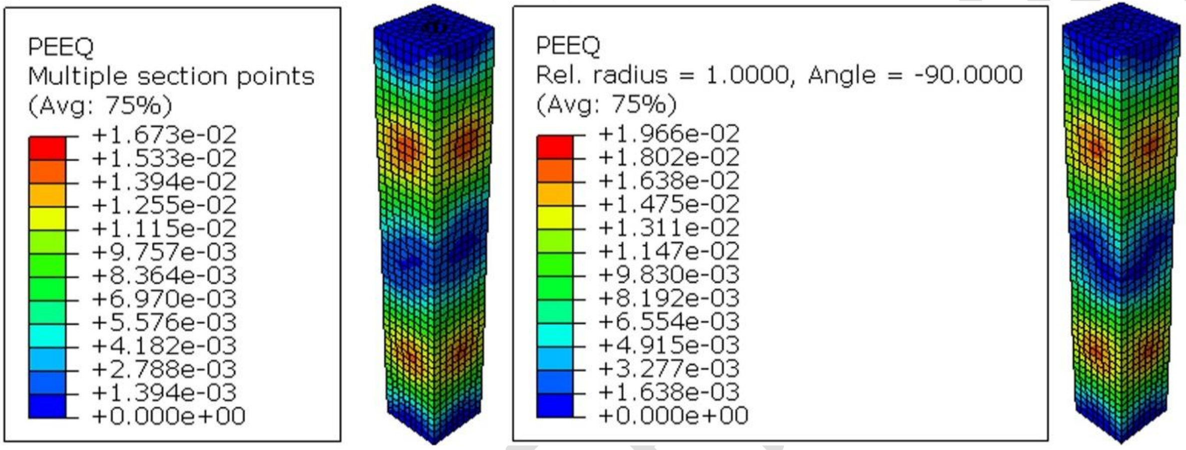
Figure 12 Plastic strains (LE)of PVC embedded columns and perforated columns without PVC

3.4 Comparison of Equivalent plastic strains (PEEQ) of PVC embedded columns and perforated columns without PVC

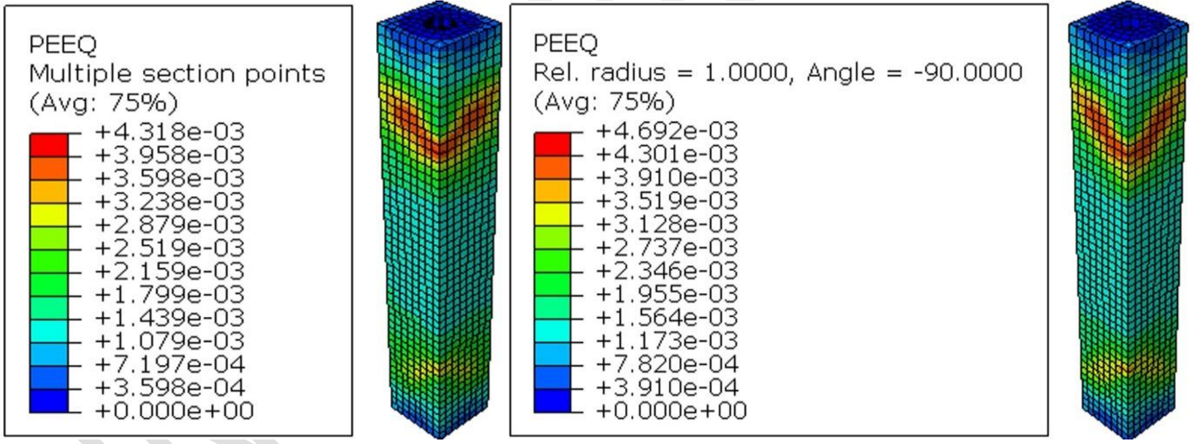
Figure 13 provides a detailed comparison of plastic strains (LE) in PVC-Embedded and Perforated columns without PVC. The results reveal that PVC-Embedded configurations tend to undergo, on average, less plastic deformation, indicating potentially more robust and resilient behavior across all diameters.



(a)PVC-Embedded-50mm (b)Perforated-50mm



(c)PVC-Embedded-75mm (d)Perforated-75mm



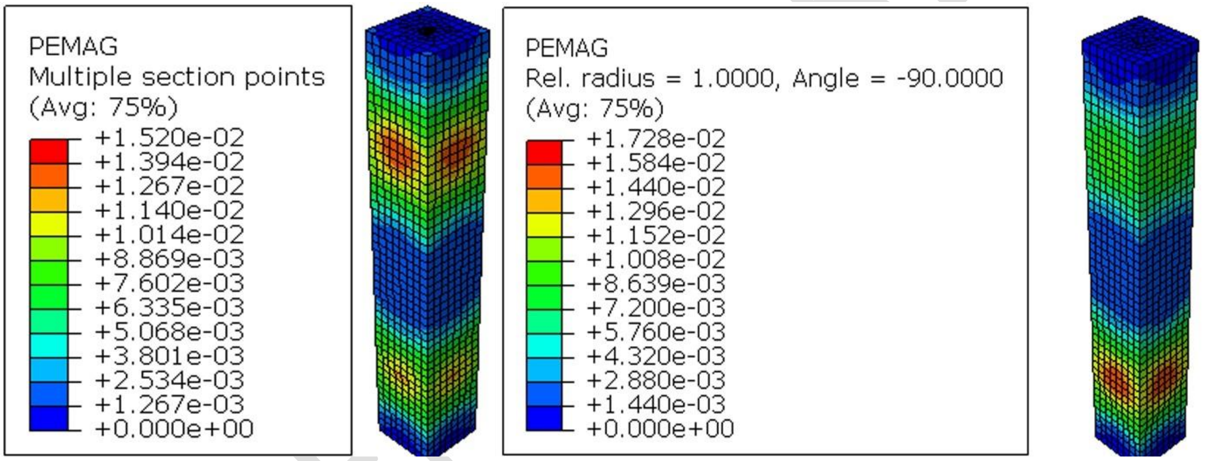
(e)PVC-Embedded-100mm (f)Perforated-100mm

Figure 13 Equivalent plastic strains (PEEQ)of PVC embedded columns and perforated columns without PVC

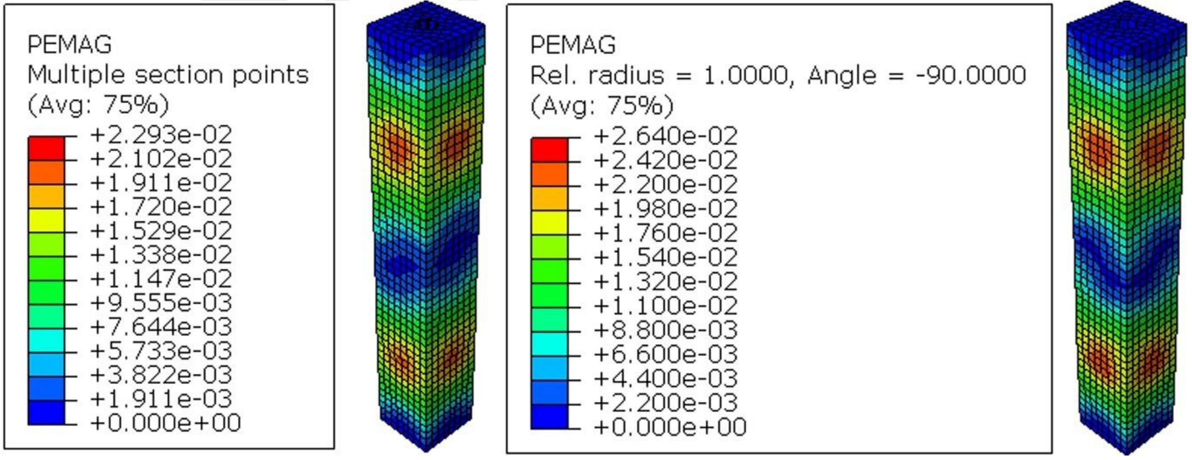
3.5 Comparison of Magnetic potential energy (PEMag) of PVC embedded columns and perforated columns without PVC

Figure 14 highlights the differences in magnetic potential energy (PEMag) across various column configurations. PVC-Embedded configurations generally exhibit moderate magnetic potential energy, indicating balanced magnetic interactions within the material. In contrast, Perforated configurations show slightly higher magnetic potential energy, suggesting increased magnetic interactions.

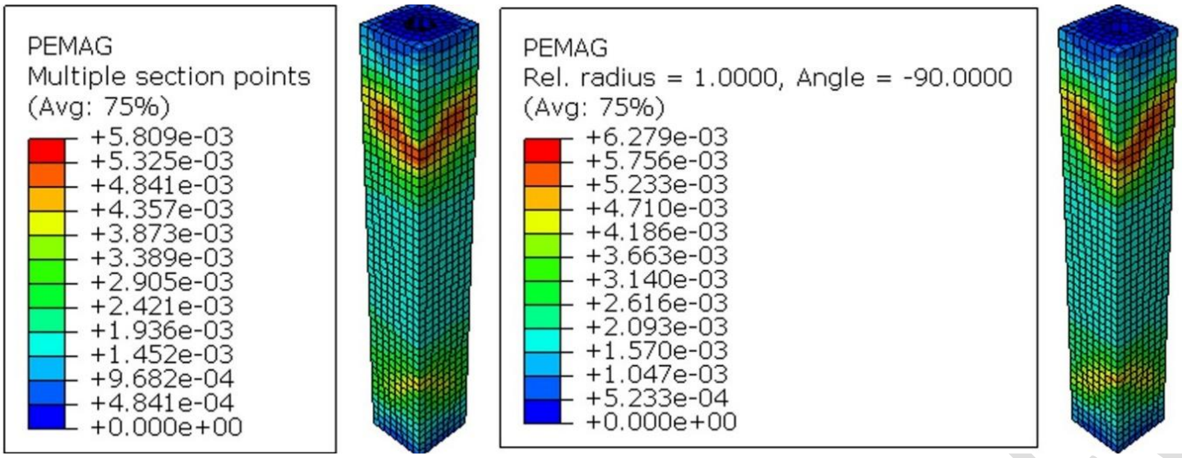
The results indicate a consistent advantage of PVC-Embedded configurations, demonstrating enhanced structural resilience and controlled deformation across all lengths and diameters. The choice between configurations should align with specific project requirements, considering factors such as structural integrity and flexibility in deformation response.



(a)PVC-Embedded-50mm (b)Perforated-50mm



(c)PVC-Embedded-75mm (d)Perforated-75mm



(e)PVC-Embedded-100mm (f)Perforated-100mm

Figure 14 Magnetic potential energy (PEMag) of PVC embedded columns and perforated columns without PVC

4. CONCLUSION

1. The investigation revealed that PVC-Embedded columns consistently exhibited higher load-bearing capacities and enhanced structural resilience compared to hollow or Perforated columns without PVC across all diameters (50mm, 75mm, and 100mm)
2. The findings of plastic strains (LE), Equivalent Plastic Strains (PEEQ) and Magnetic Potential Energy (PEMag) collectively suggest that the presence of PVC pipes positively influences the columns' ability to deform with limited plastic strain and dissipate energy efficiently. PVC-Embedded columns, while maintaining structural stability, tend to offer a more controlled and resilient response under loading conditions compared to Perforated columns without PVC. The observed patterns in plastic strains, equivalent plastic strains, and magnetic potential energy underscore the importance of PVC pipes in enhancing the overall performance and behavior of the columns during loading scenarios.
3. Based on the findings presented in the Force-displacement relationship, it can be concluded that smaller sizes of embedded PVC pipes result in better performance in terms of load-bearing capacity.

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