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Finite Element Analysis and Comparative Evaluation of ECC and Ordinary Concrete Shear Wall Under Cyclic Loading

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A B S T R A C T

The objective of this study is to evaluate the seismic performance characteristics of Engineered Cementitious Composite (ECC) and Ordinary Concrete (OC) shear walls subjected to cyclic lateral loading through finite element analysis (FEA) and comparative evaluation. ECC is a promising alternative to traditional concrete in seismic applications due to its superior ductility, strain-hardening behaviour, and crack control capabilities. Key performance parameters such as load-displacement hysteresis, energy dissipation capacity, stiffness degradation, and crack propagation patterns were captured by the simulation using ABAQUS, which was calibrated and validated against existing experimental data to ensure accuracy. In comparison to their OC counterparts, the results show that ECC shear walls have significantly improved ductility, delayed stiffness degradation, and improved energy dissipation. A parametric study was also carried out to examine the effects of wall thickness, reinforcement ratio, and axial pre-compression force on seismic behaviour, and the results highlight the potential of ECC as a high-performance material for seismic-resistant structural systems and offer useful insights for future design optimization. ECC walls maintain structural integrity under larger deformations, making them more resilient in earthquake-prone areas.

Engineered Cementitious Composites, Ordinary Concrete, Finite Element Analysis

1. Introduction

To withstand lateral loads and avoid structural collapse during seismic events, reinforced concrete (RC) shear walls are frequently used in mid- to high-rise structures. To improve seismic resilience, high-performance materials like Engineered Cementitious Composites (ECC) are being investigated since conventional RC walls are brittle and have limited elasticity during powerful earthquakes (Kang et al., 2021; Wang et al., 2022). In comparison to traditional concrete, ECC has demonstrated better energy dissipation and post-cracking performance because to its strain-hardening behavior and tight crack-width management (Yang et al., 2023; Lin & Ma, 2023). Although the improved ductility and hysteretic behavior of ECC shear walls have been verified by experimental study, few studies have combined experimental results with reliable numerical modelling for validation (Zhang et al., 2023). The behavior of composite and ECC-based shear walls, for example, was better understood in works by Hu et al. (2024) and Ahmed et al. (2023), but they lacked thorough parametric analyses incorporating wall thickness, reinforcement ratios, and axial pre-compression forces. Similarly, while cyclic behavior has been simulated using numerical models created by Li et al. (2024), few have verified these simulations against experimental evidence unique to ECC systems. Although Kim et al. (2023) and Tóth et al. (2021) investigated cyclic loading responses, they did not thoroughly investigate the impact of design elements such wall slenderness or SMA reinforcement. Additionally, Lee et al. (2022) added shape memory alloy (SMA) bars to ECC walls, although they skipped parametric research on structural configuration in favor of concentrating only on deformation properties\

1.1 Shear walls

Shear walls are vertical structural components that serve as the foundation for structural stability in dynamic situations. Their primary purpose is to withstand lateral stresses brought on by wind and seismic activity in multistory structures (Paulay & Priestley, 1992). Despite their superior strength and stiffness, traditional reinforced concrete (RC) shear walls are frequently constrained by brittle failure modes and insufficient energy dissipation capacity during powerful earthquakes (ACI 318-19, 2019; Wallace, 2012). Because of these drawbacks, there is increasing interest in using cutting-edge materials like Engineered Cementitious Composites (ECC), which are renowned for their tight crack-width control under cyclic loading, excellent ductility, and strain-hardening behavior (Li, 2003; Lepech & Li, 2008). When compared to traditional RC walls, ECC shear walls have shown noticeably better seismic performance, including better hysteretic behavior, less residual deformation, and delayed stiffness degradation (Kang et al., 2021; Wang et al., 2022). Additionally, ECC's microcrack dispersion and self-healing qualities improve durability and resilience after earthquakes (Zhang et al., 2020). Notwithstanding these benefits, most studies on ECC shear walls have been experimental in nature, with fewer focusing on numerical validation and parametric analyses to measure the impact of axial precompression, wall thickness, and reinforcement ratio (Hu et al., 2024; Ahmed et al., 2023). By combining experimental data with numerical modelling and performing a thorough parametric analysis to evaluate seismic performance improvements in ECC shear walls, the current work seeks to close this gap.

1.2 Finite Element Analysis of Shear Walls

In structural engineering, finite element analysis, or FEA, has become a crucial method for assessing the nonlinear behavior of shear walls under seismic loads. It enables scientists to model intricate material reactions that are hard to capture through tests alone, such as yielding, cracking, and failure processes (Mazzoni et al., 2007). FEA is particularly useful for understanding and forecasting the ductile performance and energy dissipation capacity of ECC shear walls, which show strain-hardening and numerous fine-crack behavior (Li, 2003). To simulate the interaction of ECC material with reinforcement under monotonic and cyclic loads, sophisticated finite element models have been created utilizing programs such as ABAQUS, OpenSees, and ANSYS (Hu et al., 2024; Ahmed et al., 2023). These models frequently include nonlinear constitutive models, like the Concrete Damaged Plasticity (CDP) model, which considers anisotropic damage, tension stiffening, and stiffness degradation (Lee & Fenves, 1998). In studies such as those by Li et al. (2024), finite element simulations were validated against experimental data to ensure model accuracy and to explore a broader parametric space, such as varying wall thicknesses, axial loads, and reinforcement ratios. Nevertheless, despite these advancements, there are still research gaps, especially in the numerical validation of ECC-specific behavior, such as strain localization under cyclic loading, crack width control, and post-peak strength retention (Kang et al., 2021; Zhang et al., 2020). Few studies have carried out comprehensive parametric studies integrating wall geometry and loading conditions to optimize design guidelines.

2. Methodology

In this research finite element analysis is performed on ordinary concrete and ECC shear wall to investigate its seismic performance. Based on actual testing at the Structural Laboratory, the geometry of reinforced concrete shear walls was created for this study. For shear walls made of Ordinary Concrete (OC) and Engineered Cementitious Composite (ECC), different components were constructed. To duplicate the real test setup, loading zones, boundary components, and reinforcement details were all separately modelled. Each wall was discretized as a three-dimensional solid component, with reinforcement in the form of embedded truss components. The Concrete Damage Plasticity (CDP) model was used to predict the nonlinear behavior of concrete and ECC materials. Experimental data and literature were used to determine the material's characteristics (Tables 1, 2, and 3). Surface-to-surface contact qualities were assigned at possible separation planes, and embedded constraints were used to characterize the interaction between concrete (or ECC) and reinforcement. To replicate the test setting, boundary conditions were applied by anchoring the wall's base in all directions. To simulate seismic loading, lateral force was applied at the top of the wall using a cyclic displacement-controlled methodology, adhering to accepted testing practices like FEMA 461.

Table 1: Ordinary concrete and ECC Linear properties

Wall	Compressive strength, σ_c (MPa)	Poison Ratio, ν	Density, (tonne/mm^3)
OC	21.78	0.2	2.4e-09
ECC	26.22	0.2	2.4e-09

Table 2: Input CDP parameters for ordinary Concrete

Dilation Angle	e	fc'/fb	K	V
38.5	0.1	1.16	0.67	0.0001

Table 3: Input CDP parameters for ECC

Dilation Angle	e	fc'/fb	K	V
37	0.1	1.16	0.67	0.0001

3. Results and Discussions

3.1 ECC Shear Wall

The distribution of the maximum in-plane principal strains in an ECC (Engineered Cementitious Composite) shear wall underloading is shown in Figure 1, which offers important information about the deformation behavior of the wall and the location of strains. The strain values range from 0 (blue) to about 7.559e-4 (red), with the largest strains concentrated near the bottom right edge of the wall and progressively decreasing as they move upward. This distribution pattern indicates that the most critical tensile strains are developing at the lower part of the wall, most likely as a result of flexural effects caused by lateral loads. As is typical of ECC materials, the presence of a gradual color transition—from red through yellow, green, and blue—indicates that the strain is smoothly distributed over a region rather than being abruptly localized. ECC can withstand greater deformations while retaining its integrity because of its ability to experience controlled microcracking and strain-hardening behavior. Furthermore, the strain distribution demonstrates that ECC shear walls can support large in-plane deformations, which is especially advantageous when it comes to fending off lateral pressures brought on by earthquakes. In accordance with lateral loading situations, the vertical alignment of the greater strain bands indicates that the wall is largely deforming in flexure with some shear effect. In summary, the picture demonstrates the better ductile behavior of ECC, demonstrating its ability to increase structural resilience in seismic applications with widely dispersed in-plane primary stresses that show a capacity for deformation without brittle failure.

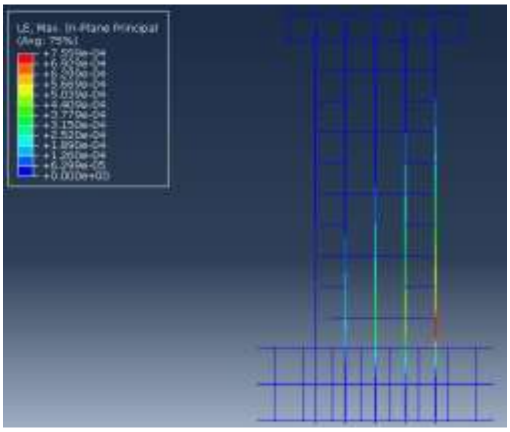

Figure 1 In-Plane Principal ECC Shear wall

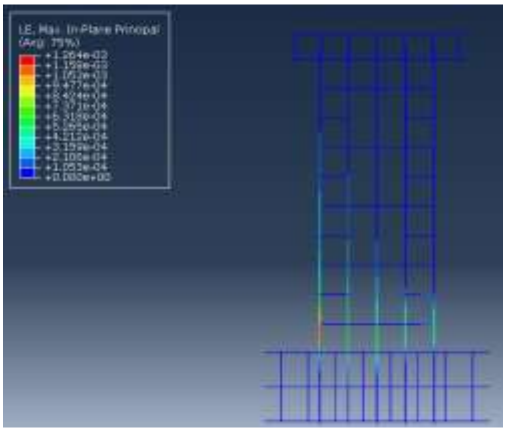

Figure 2 In-Plane Principal OC Shear wall

3.2. Ordinary concrete Shear wall

Figure 2 shows the finite element analysis (FEA) result for a reinforced concrete shear wall, specifically the distribution of the maximum in-plane principal strain (LE, Max. In-Plane Principal) across the wall structure. The color contour offers insight into the strain behavior under loading, with a gradient scale from blue to red indicating increasing levels of strain. Higher strain values, shown by green, yellow, and faint red, are seen at the bottom portion of the wall, particularly close to the base where it joins the foundation. This indicates that the wall is undergoing substantial deformation and is a crucial zone for possible cracking or failure start. This is to be expected as lateral loads usually cause the base of the wall to carry the maximum moment and shear demand. As we proceed up the height of the wall, the strain gradually lessens, as seen by the change from warmer to cooler colors, which indicates less deformation. The vertical alignment shows that the wall serves as a key lateral load-resisting element, and the mesh pattern, which is made up of rectangular components, permits a clear distribution of strain data.

4. Conclusions

The ECC shear wall's tensile damage contour shows a finely grained, widely dispersed damage pattern, suggesting that there are numerous microcracks scattered throughout the wall, particularly in the vicinity of the base and mid-height areas. This behavior is consistent with ECC materials' well-known strain-hardening and crack-bridging properties, which postpone the onset of localized failure and enable the wall to withstand greater deformations while retaining load support. A characteristic of brittle shear failure, the tensile damage seen in the typical concrete shear wall is more localized and forms a clear "V"-shaped diagonal fracture pattern. Limited ductility and a greater vulnerability to abrupt collapse under lateral pressures are reflected in the fractures, which start at the base and move towards the center of the wall. Strains in the ECC wall are evenly distributed, with moderate values spreading over a larger region, especially close to the base, indicating regulated deformation for energy dissipation. On the other hand, the typical concrete wall shows a steep gradient to lower strain values higher up, with high strain concentrations in a narrower zone near the base. When exposed to seismic or lateral loads, this implies restricted energy dissipation and an increased risk of early-stage cracking and structural damage. When compared to conventional concrete walls, ECC walls exhibit better ductility, strain tolerance, and fracture management. They are perfect for buildings in high-risk earthquake zones because of these features, which greatly increase their seismic resistance. Ordinary concrete walls are more vulnerable during strong seismic events because they have a reduced energy absorption capacity and restricted post-cracking behavior, even though they are structurally sufficient for certain loading situations.

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