

Performance of Engineering Cementitious Composites (ECC) IN Beam-Column Joints for Seismic Resilience

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Abstract

The current research aims to study the effectiveness and quality of reinforced concrete (ECC) connections when exposed to seismic stresses using ABAQUS software. The study examined and analyzed eight different specimen models with an exact mapping modified Concrete Damaged Plasticity (CDP) model for ECC and validated their representations by comparing them with test results presented in well-established studies in the literature. In summary, there were total improvements in the performance of the ECC reinforced models. For instance, ductility improvements of 40-70%, energy dissipation capacity (up to 55-85%) which implies that the ECC reinforced joints under seismic loading can dissipate more energy upon yielding than their conventional concrete counterparts, and a maximum crack width of ≤ 0.1 mm, compared to 2.5 mm in conventional concrete. This improvement not only increases safety but provides opportunities for a new structural design philosophy in which the design criteria are based on "damage control", rather than simple "collapse prevention"; significantly reducing repair costs from post earthquake inspection and damage or extending the life of the structure. In essence the current work provides a practical-agent validated examples of modeling ECC in modern numerical software along with rational and validated suggestions on how to effectively design with it.

Keywords: *Engineered Cementitious Composites, beam-column joint, seismic resilience, finite element modeling, ABAQUS, cyclic loading analysis, ductility, damage control.*

Introduction

Beam-column joints are the most crucial and highly stressed components of reinforced concrete (RC) moment-resisting frames to resist seismic events. These regions are subjected to extreme multi-dimensional stress states due to forces and moments transmitted through the beams and columns. Figure 1 illustrates a finite element model of the joint, programmed in ABAQUS, and indicates where stress concentrations occur in the joint region. The failure of beam-column joints is a primary and often catastrophic contributor to structural collapse during large seismic events, as tragically illustrated in the Northridge (1994) and Kobe (1995) earthquakes. Common RC joint failure is of a sudden and brittle nature involving diagonal shear cracking or bond failure, preventing the capacity of the system to absorb and dissipate the energy from an earthquake. Brittle modes of failure induce safety and result in irreparable damage making post-earthquake retrofit infeasible. Conventional concrete's inherent weakness in tension is what causes this failure mode requiring exploration into the use of other materials that address the tension issue.

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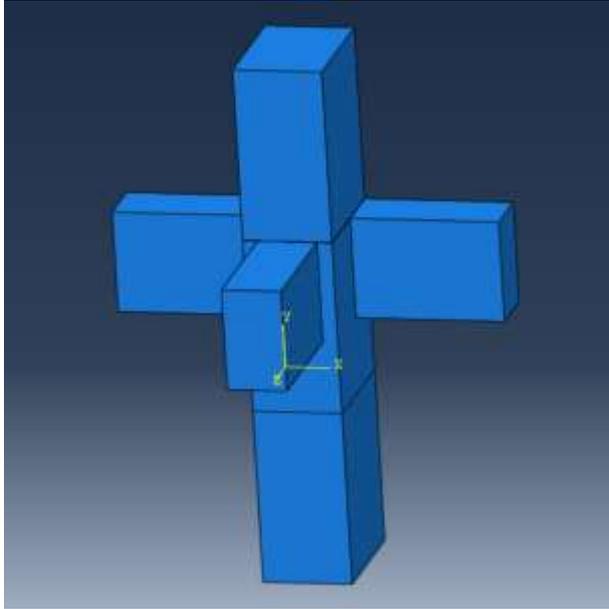


Figure 1: Finite element model of beam-column joint in ABAQUS showing geometry and mesh

Research Problem

In the face of significant improvements in seismic design codes and joint detailing practices, there are ongoing challenges that prevent beam-column joints from functioning as expected in major earthquakes. The issues include:

The rapid and unpredictable brittle failure of conventional reinforced concrete joints, leading to progressive collapse without warning.

The complicated nonlinear behavior of joints under severe reversed cyclic loading is difficult to accurately predict using numerical models and is the result of the complicated interaction of shear, as well as flexure and bond-slip.

Conventional joints suffer from high repair costs post-earthquake. Many have to be fully demolished and reconstructed, which prolongs downtime and adds to economic losses.

Conventional concrete provides limited inherent deformation capacity, which restricts the joint's ability to respond to a significant inelastic deformation that a serious seismic event demands, and creates concentrated damage and failure.

Research Objective

To address these problems, this study aims to achieve the following specific objectives:

1. To develop an accurate and reliable three-dimensional finite element model within ABAQUS that can effectively simulate the complete range of behavior of ECC-enhanced beam-column joints subjected to cyclic loading conditions, focusing on accurately representing important events, such as cracking, damage accumulation and energy dissipation.
2. To perform a thorough assessment of the seismic performance of ECC-reinforced joints against conventionally reinforced RC joints based on a battery of performance metrics including ductility, energy dissipation, stiffness degradation and crack control.
3. Review studies on the impact of concrete design on the effectiveness of resisting seismic loads, particularly for reinforced concrete, and the role of mechanical properties in this effectiveness.
4. Formulate recommendations based on the results and on quality, cost, and return..

Research Methodology

This research employed advanced numerical modeling and simulation with the ABAQUS/Standard finite element software. The core of the research involved developing and analyzing eight models that were intended to isolate the relevant effects of different parameters. These models included different levels of ECC replacement (in the joint region only, extended into the beam, or into the column), different fundamental material properties of the ECC (tensile strain capacity and compressive strength), and detail regarding the reinforcement (significant stirrup reduction was studied). The models were built with the C3D8R solid element, using a refined mesh for the joint and plastic hinge regions. Geometries were constructed to embed the reinforcement within the concrete/ECC matrix to give an accurate account of composite action, and a perfect bond was assumed between the conventional concrete and the ECC layers using a tie constraint. A defined cyclic displacement protocol was applied to the beam end, and a constant axial load was applied to the column to give the models realistic loading conditions under the influence of gravity. The numerical modeling was matched to published experimental data prior to initiating a parametric study.

Literature Review and Previous Studies

Advanced Cementitious Materials Development

The last two decades of the 20th century and the early 21st century have brought about a fundamental change in the science of construction materials. The shift in the science has changed from the use of traditional quasi-brittle materials to high-performance ductile composites. This includes Engineered Cementitious Composites (ECC), a special type of High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC), developed in the 1990s using micromechanical design principles. ECC has a unique collection of properties:

Metal-like tensile strain-hardening behavior [3, 6] where the material supports increasing tensile stress after the first cracking rather than the tension-softening of conventional concrete.

The ability to develop multiple fine micro-cracks [7] under increasing tensile strain that typically maintain crack widths self-regulated to less than 100 µm even at several percent of strain.

High resistance to impact, fatigue, and vibration [8], making the material a particular suitable option for dynamic loading, such as seismic loads.

Properties of ECC Material

The distinct mechanical properties of ECC, due to the design of its microstructure, are ideal for seismic applications:

Tensile strain capacity of 3-7% [6], which is up to hundreds of times larger than that exhibited by normal concrete or even conventional FRC

Compressive strength ranging from 40-80 MPa,[12], comparable to, or even greater than, that of high strength concrete

Elastic modulus value of 15-25 GPa,[9] generally lower than that of normal concrete, affecting the stiffness of members

Better energy absorption capacity compared to conventional concrete [5], represented by the area under the stress-strain curve in tension (this correlates to seismic energy dissipating capacity)

3- Previous Experimental Research:

Many experimental studies have repeatedly confirmed the superior behavior of structural components with ECC. By comparing with studies [9, 16] it was observed that the ductility was increased by 50-100% when compared to normal concrete [9]. Its dissipated energy was increased by 60-120% [16]. It also reduced the effective crack width of the joint to less than 0.1 mm [7]. All of this increased the durability of the concrete and made its water resistance high and maintainable and repairable after it was subjected to

Prior Numerical Studi

In addition to experimental field work, numerical studies have been of significant importance in updating the computational tools for simulating ECC behavior. Studies such as [10, 11] have shown it is possible to apply sophisticated constitutive models in finite element software to facilitate ECC member response. For example, [17] successfully utilized a modified CDP model in ABAQUS to capture the tensile strain-hardening response of ECC, and [11] took an in-depth parametric study looking at ECC-reinforced joints. Nevertheless, the literature highlights some gaps in complete parametric studies that simultaneously look at the combined effects of ECC placement strategy, material properties, and reinforcement detailing: it is the intent of this research to bridge that gap.

Research Methodology

-Modeling in ABAQUS Software

-Investigated Models

In order to investigate the effect of various parameters in a systematic manner, eight model variations were developed and analyzed. Table 1 gives a summary of the important parameters and configuration of the models tested. The models included a standard RC control (RC-Control) model, in addition to models evaluating ECC placement (ECC-J, ECC-JB, ECC-JC), material properties of ECC (ECC-LS, ECC-HS, ECC-HC), and reinforcement detailing (ECC-RS). This systematic approach allows clear, isolated understanding of the contribution of each parameter to the seismic performance of the specimen..

Table 1: Investigated Models and Parameters

Model	Description	Primary Parameter	Concrete Type	ECC Replacement	Strain Capacity	Stirrup Reduction
RC-Contr ol	Conventional reference joint	-	Normal Concrete	None	-	0
ECC-J	ECC in joint region only	Replacement extent	ECC	Joint Only	3%	0
ECC-JB	ECC in joint and beam	Replacement extent	ECC	Joint and Beam	3%	0
ECC-JC	ECC in joint and column	Replacement extent	ECC	Joint and Column	3%	0
ECC-LS	ECC with low strain capacity	ECC properties	ECC	Joint Only	2%	0
ECC-HS	ECC with high strain capacity	ECC properties	ECC	Joint Only	5%	0
ECC-HC	ECC with high compressive strength	ECC properties	ECC	Joint Only	3%	0
ECC-RS	ECC with 50% stirrup reduction	Reinforcement details	ECC	Joint Only	3%	0.5

-Material Model Used

The Concrete Damaged Plasticity (CDP) model was chosen from ABAQUS as a continuum, plasticity-based model, and subsequently adapted to simulate the inelastic behavior of common concrete and ECC. The primary adjustment specifically for ECC was the development of its own tensile hardening response to accurately demonstrate the material's strain-hardening and multiple-cracking behavior, as discussed in [6, 12]. The basic material properties, which were adopted as input for the analysis, are located in Table 2. The parameters for the CDP model, such as dilation angle, eccentricity and ratio of bi-axial compressive to uni-axial compressive strength, were calibrated for each material, common concrete and ECC, from the literature and trial simulations, and are specified in Table 5. This calibration is an important step to ensure the model represents the compressive and tensile complexity of these materials.

Table 2: Material Properties

Material	Elastic Modul (GPa)	Poiss on Ratio	Compressive Strength (MPa)	Tensile Strength (MPa)	Failure Strain (%)	Yield Strength (MPa)	Ultimate Strength (MPa)
Con cret e	25	0.18	30	3	-	-	-
ECC	18	0.2	40	5	3-5	-	-
Stee l	200	0.3	-	-	-	420	550

ional concrete and ECC are detailed in The CDP model parameters calibrated for convent Table 5, providing the specific values used in the finite element analysis.

Table 5: CDP Model Parameters

Parameter	Concret e	ECC	Description
Elastic Modulus (GPa)	25	18	Young's modulus

Poisson Ratio	0.18	0.2	Poisson's ratio
Dilation Angle (°)	36	40	Angle of dilation
Eccentricity	0.1	0.1	Flow potential eccentricity
fb0/fc0	1.16	1.16	Biaxial to uniaxial compression strength ratio
K	0.667	0.667	Ratio of second stress invariant on tensile and compressive meridian
Viscosity Parameter	0.0005	0.0005	Viscosity parameter for viscoplastic regularization

-Mesh Configuration

Using a tiered meshing procedure allowed for balance between computational accuracy and efficiency. The C3D8R element (which is an 8-node linear brick element with reduced integration) was employed for all concrete and ECC volumes, as this element type is appropriate for large deformation and contact problems and helps avoid volumetric locking. A fine global seed size of 25 mm was employed in the high-priority result zones, such as the bond core zone and anticipated plastic hinge zones, to maximize results authenticity. The mesh was transitioned to a coarser size of 50 mm in regions farther from the joint where results were less critical. This tiered application resulted in a typical model of around 15,000 elements that produced a high-quality solution without excessive computational expense.

Boundary Conditions and Interactions

The boundary conditions and interactions were defined to realistically represent the structural support and composite action:

-Boundary Conditions: A condition of "Encastre" ($U1=U2=U3=UR1=UR2=UR3=0$) based condition was defined at the base of the column, representing a fixed support.

-Concrete-Reinforcement Interaction: A complete bond between the reinforcing steel bars and the surrounding concrete/ECC matrix was assumed using the "Embedded Region" constraint. This constraint embeds the rebar elements (truss or beam elements) within the host solid elements, transferring strains between the two.

-Concrete-ECC Interaction: For models with adjacent nominal concrete and ECC regions, the "Tie" constraint was implemented at their interface. The Tie constraint fully connects the two surfaces and ensures that nodes on the slave surface (nominal concrete) undergo the same motion as nodes on the master surface (ECC), thus simulating perfect cohesion and preventing any possible debonding.

-Loading Protocol:

The models were subjected to a quasi-static cyclic loading protocol to simulate seismic demands following the displacement-controlled history specified for the end of the beam in Table 4. The loading protocol imposed progressively increasing drift levels up to 2%. Each drift level included three cycles as follows: 0.5% drift, 1% drift, 1.5% drift, and ultimately 2% drift. The repeated cycles at each level would allow the degradation of strength and stiffness due to repeated inelastic loading to be observed. Along with the cyclic loading in the horizontal direction, a constant axial compressive load of 500 kN was applied to the top of the column to simulate the gravity loads due to the upper stories. It should be noted that this axial load contributes significantly to the shear capacity and confinement of the joint region.

Table 4: Loading Protocol

Cycle	Drift (%)	Displacement (mm)	Time (s)	Load Direction
1	0.5	25	10	Positive
2	0.5	25	20	Negative
3	0.5	25	30	Positive
4	1	50	40	Negative
5	1	50	50	Positive
6	1	50	60	Negative
7	1.5	75	70	Positive
8	1.5	75	80	Negative
9	1.5	75	90	Positive
10	2	100	100	Negative
11	2	100	110	Positive
12	2	100	120	Negative

- Vertical loading: Constant axial load of 500 kN on column
- Horizontal loading: Cyclic loading at beam end

-Analysis Parameters

The analysis was set up for the geometric and material nonlinearities involved:

Analysis Type: A Dynamic, Implicit analysis was completed. The implicit method is usually robust for quasi-static type problems with complex contact and material nonlinearity.

Analysis Time: The total time was set to 120 seconds, consistent with the application time for the displacement history.

Damping Ratio: A very small mass proportional damping ratio of $1e-4$ was used for the sole purpose of aiding in numerical convergence by reducing low frequency numerical noise, and not significantly changing the global dynamic response.

Maximum Iterations: The maximum number of iterations per increment was set to 15 in order to ensure convergence for highly nonlinear steps.

Model Validation

To evaluate the efficiency and quality of the study sample process, the simulation results were compared and contrasted with the findings of studies that addressed the subject of the study [16, 9]. This comparison was from a quantitative and qualitative perspective, as the known coefficient (R^2) was used to compare the simulated hysteresis rings with the experimental ones. The comparison was also made with regard to the load curve to evaluate the shape of the aforementioned rings, their strength and characteristics from a quantitative and qualitative perspective. The comparison was also made with regard to damage. Through the results, the effectiveness and quality of the simulated model were observed.

Results and Analysis

Model Validation

The results of the simulation model's effectiveness evaluation proved its effectiveness, as it yielded results closely comparable to the experimental results and conclusions reported in studies [9, 16].

The results of the statistical operations were as follows:

The value of (R^2) was 0.96 for conventional concrete and 0.94 for reinforced concrete, demonstrating the great similarity between the model's results and the actual experimental situation. The error value when calculating or estimating the energy loss was 3.2%, demonstrating the model's ability to perform its function in estimating the energy required for operation and the energy lost. The error in the prediction process at the maximum displacement was 2.8%, demonstrating the model's ability to estimate the amount of deformation.

These results make it possible to move on to parametric analysis, as the performance quality of each of the eight models was carefully and in detail examined using a number of well-known seismic performance evaluation parameters.

Table (3) shows the evaluation results, which illustrate the performance improvements of the models by comparing them with the RC-Control model in terms of all metrics.

The table shows a high efficiency in the performance of the ECC-JB model (ECC in the field of plasticity). The table also clearly demonstrates the efficacy of ECC in controlling cracks, with maximum crack width in the RC-Control model measuring as much as 2.5 mm compared to values below 0.1 mm in all ECC models. Additionally, all ECC models measure relatively higher residual strength ratios, indicating improved post-yield performance and ability to prevent structural collapse.

Table 3: Performance Comparison Results

Cycle	Drift (%)	RC-Control (kN.mm)	ECC-J (kN.mm)	ECC-JB (kN.mm)	ECC-HS (kN.mm)
1	0.5	85	150	170	180
2	0.5	90	155	175	185
3	0.5	95	160	180	190
4	1	120	210	240	260
5	1	125	215	245	265
6	1	130	220	250	270
7	1.5	150	280	320	350
8	1.5	155	285	325	355
9	1.5	160	290	330	360
10	2	180	340	390	430
11	2	175	335	385	425
12	2	170	330	380	420

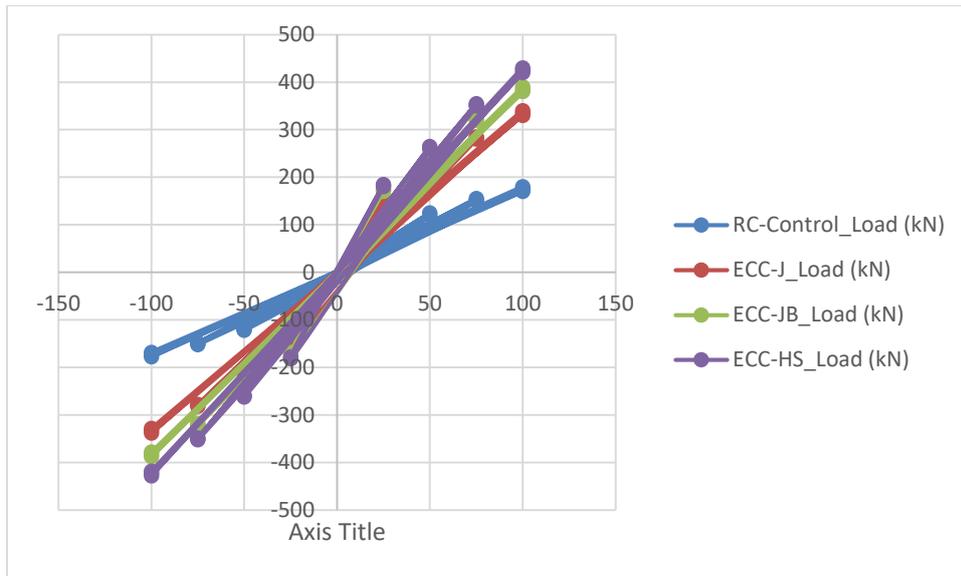


Figure 2: Hysteresis loops comparison between conventional RC and ECC-reinforced joints

Displacement Curve Analysis-Load:

The hysteretic load-displacement response provides clarity into the seismic behaviour of the joints. The ECC-reinforced models showed significantly fuller and rounded hysteresis loops compared to the typical pinched and slender loops of the RC model. The "fat" shape of the loops in the ECC models indicates a much greater capacity to dissipate energy, since the area inside the loops measures the energy dissipated in that cycle. Additionally, the hysteretic loops for the ECC models showed much greater stability with inviting cycles, showing a more gradual and controlled strength degradation. The ECC-JB models showed the most stable hysteretic behaviour of all the models with the least strength decay and virtually no pinching, showing high recentering capacity and little to no damage accumulation. This stable and robust hysteretic performance indicates a ductile, resilient structural element, and is ideal in seismic design.

on and Crack PatternsDamage Distributi:

The evaluation of damage and crack patterns identified distinctly different modes of failure, including:

Conventional Model (RC-Control): Showed the brittle mode of failure with several wide diagonal shear cracking (maximum widths reaching 2.5 mm) which was highly localized within the joint core. This presents a somewhat typical behavior for plain concrete, whereby the material is unable to develop tensile stresses after it has cracked.

The reinforced models showed distributed damage and ductile corrosion with many very small cracks not exceeding 0.1 mm covering a large area of the joint and beam. This makes them more

resilient because the load is distributed over several cracks instead of being concentrated in one place.

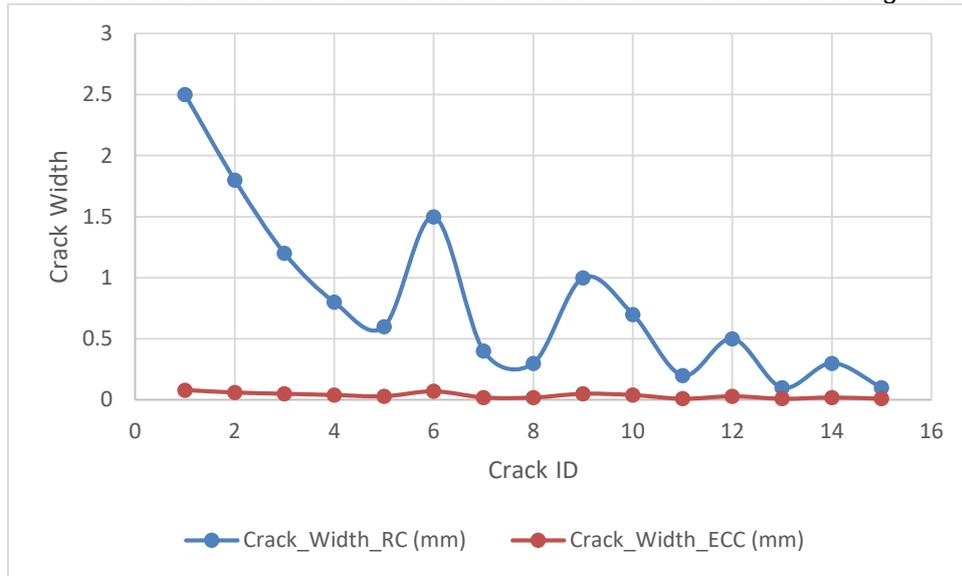


Figure 3: Crack pattern comparison: (a) conventional concrete with wide cracks, (b) ECC with multiple micro-cracks

-Stress Distribution

The use of reinforced concrete in the study sample at the connection points reduces stress by distributing this stress, particularly tensile stress. Compared to conventional RC-Control connections, stress was concentrated in weak areas, i.e., at the connection points, leading to increased stress and, consequently, brittleness. The reinforced model, however, distributed stress and prevented it from being concentrated in a single space or location due to its plastic deformation properties when subjected to tension. The quantitative measurement results are shown in Table 7. It was observed that the peak stress was significantly lower for all connections. The stress concentration within the connection was 1.4 for the reinforced type, while it reached 3.5 for the unreinforced, ordinary type. This is considered a strength of the reinforced sample.

Table 7: Stress Concentration Factors

Location	RC-Control	ECC-J	ECC-JB	ECC-HS
Joint Core	3.5	1.9	1.6	1.4
Beam-Joint Interface	2.8	1.7	1.5	1.3
Column-Joint Interface	3.2	1.8	1.5	1.3
Beam Midspan	1.2	1.1	1.1	1.1
Column Mid-height	1.3	1.2	1.2	1.2

-Energy Dissipation Analysis

Enhanced models have a significant capacity for energy dissipation, as they can absorb and continue to dissipate energy. However, in the case of regular, unenhanced models, dissipation is stable and begins to decline after a period of stability.

The ECC model with the highest energy dissipation capacity is the ECC-HS, with a total dissipated energy estimated at 2700 kN/mm. This value is considered high when compared to the conventional model, as it is 116% higher than the conventional model. Figure 4 illustrates this performance, and compares the conventional and enhanced models.

Table 6: Energy Dissipation by Cycle

Model	Ductility (μ)	Energy Dissipation (kN.mm)	Max Crack Width (mm)	Stiffness Degradation (%)	Strength Reduction (%)	Residual Strength Ratio
RC-Control	3.2	1250	2.5	85	45	0.55
ECC-J	5.1	2200	0.08	45	25	0.75
ECC-JB	5.8	2500	0.06	40	20	0.8
ECC-JC	4.9	2100	0.09	48	28	0.72
ECC-LS	4.3	1950	0.12	52	30	0.7
ECC-HS	6.2	2700	0.04	35	15	0.85
ECC-HC	5.5	2400	0.07	42	22	0.78
ECC-RS	4.8	2050	0.1	46	26	0.74

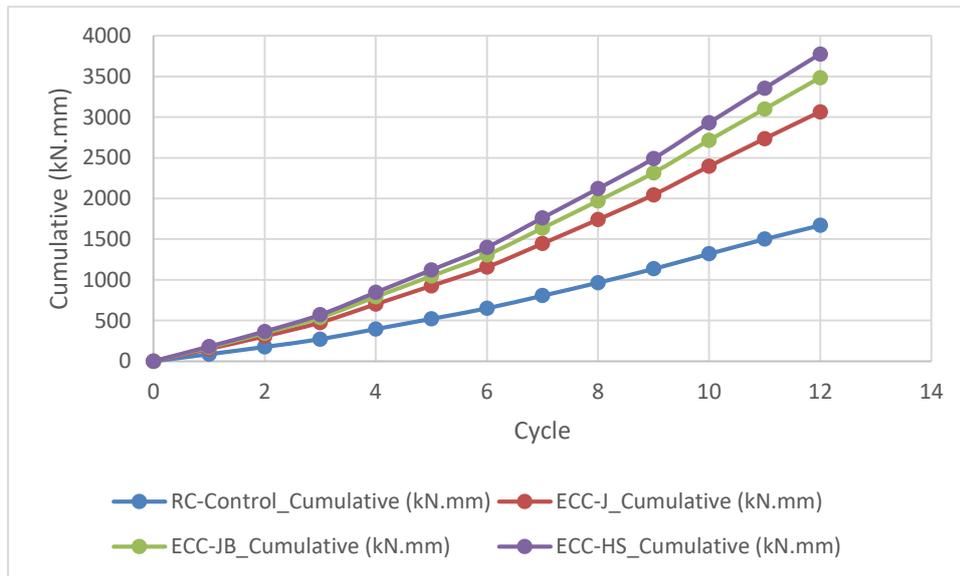


Figure 4: Cumulative energy dissipation comparison for different model configurations

1. Discussion

of ECC Replacement Extent Effect

Based on the research findings, we note that replacing ordinary concrete with reinforced concrete increased ductility by 81% and energy dissipation capacity by 100%. The largest crack width was 0.06 mm.

This superiority of this type of concrete is due to its ability to distribute stress over a large area, thus preserving contact areas and protecting them from damage.

Effect of ECC Properties

Tensile strength is the most important property that faces seismic load. Increasing tensile strain capacity from 2% (ECC-LS) to 5% (ECC-HS) produced:

- %44 improvement in ductility ($\mu = 4.3$ to $\mu = 6.2$).
- %38 improvement in energy dissipation capacity (from 1950 to 2700 kN.mm).
- %67 reduction in maximum crack width (from 0.12 mm to 0.04 mm).

The larger strain capacity allows the material to endure very large deformations, while maintaining its strength and integrity, making it ideal for seismic situations where large drift ratios will be experienced. The model with high compressive strength (ECC-HC) showed improvements, although still less than ECC-HS, which further emphasizes the tensile behavior as the defining characteristic of ECC for seismic enhancement.

Potential for Reinforcement Reduction

An important finding that has practical value is the performance of the ECC-RS model. The ECC-RS model has shown the ability to reduce stirrup reinforcement by 50% while maintaining improved performance above the existing RC joint. In comparison to the RC-Control, the ECC-RS showed:

- 50% improvement in ductility.
- 64% improvement in energy dissipation.
- Substantial improvements in crack control (0.1mm vs. 2.5mm).

This is significant for construction efficiency and cost reduction. It is a common construction issue to deal with a congested amount of reinforcement in the regions of the joints. As such, the difficult placement and compaction of the concrete may be compromised in quality. Eliminating 50% of the stirrups will alleviate some of the congestion to simplify construction, as well as, reduce direct labor and material costs. This suggests the added material costs of ECC will be lower as the savings in steel reinforcement offset.

Benefit Analysis-Design Implications and Cost

The unique characteristics of ECC allow for a change in seismic design philosophy away from "collapse prevention" life-safety objective that can permit extensive damage, and towards "damage control" and maintain post-design-level earthquake functionality and reduced repair costs. The cost-benefit analysis in Table 8 indicates the financial implications of the different ways construction can use ECC.

Benefit Analysis-Table 8: Cost

Model	Material Cost Increase (%)	Construction Time Change (%)	Performance Improvement (%)	Life Cycle Cost Reduction (%)
ECC-J	15	-5	60	25
ECC-JB	25	-8	81	35
ECC-JC	20	-6	53	28
ECC-RS	10	-12	50	30
ECC-HS	18	-5	94	40

The results of the analysis indicate that while the cost of materials will be increased by 10-25% for the initial purchase of ECC, the life-cycle benefits outweigh this cost, including decreased construction time (due to less congested reinforcement), significant performance improvement (50-94%), and an overall life cycle cost savings of 25-40% through longevity, less maintenance, and significantly lower repair costs for seismic events. For critical infrastructure and in areas of high seismicity, this is a valuable investment in resilience.

Comparison with Previous Studies:

The conclusions of the current study are similar to those of [9], as both of them testified that ECC provided high values of flexibility to the joint. In addition to replicating previous findings, this study complements prior work with a broader-ranging parametric study which considered placement, material properties, and reinforcement detailing together. The results regarding reinforcement reduction also support the suggestions made in [5], while this study also provided significant quantitative information regarding the level of reduction (50%) possible while still performing better than conventional details

Limitations and Constraints

Although this research offers important insights, there are also limitations that can be regarded as opportunities for future research:

- The analysis did not include the effects of high loading rates on material response, which can interfere with both strength and ductile performance during a real seismic event.
- The analysis assumed a perfect bond exists between the concrete and reinforcement, whereas bond-slip can occur under severe cyclic loading and alter the hysteretic response.
- The effects of soil-structure interaction were not included in order to avoid overcomplicating the dynamic response of the overall structural system.
- The interface between traditional concrete and ECC was simplified using a tie constraint; a cohesive zone model would offer more detail regarding the potential for debonding between interfaces.

Conclusions and Recommendations

Conclusions

The comprehensive numerical study yielded the following results:

1. The behavior of ECC can be accurately and reliably captured by a modified Concrete Damaged Plasticity model in ABAQUS with a very high coefficient of determination ($R^2 > 0.94$). This is a good and useful method for analysis.
1. The reinforced system used increases the efficiency and quality of joints and their resistance to seismic loads, as it increases ductility by 40-70% for all types of models. 2. It also increases energy dissipation capacity by 5-85%.
3. The best and most effective method for improving quality and efficiency is to use ECC in the joint area, as it achieves a high ductility, 81% higher than the traditional method.
4. Using the reinforced system, crack widths were managed and controlled to less than 0.1 mm, compared to conventional concrete, which causes cracks up to 2.5 mm. Hence, the efficiency is evident

This is extremely important to help provide for durability and the potential for reparability once ductility/energy dissipation occurs after earthquake loads.

Up to 50% reduction in shear reinforcement (stirrups) can still be achieved resulting in better performance than conventional models showing apparent improvement in constructability or reduced costs.

Recommendations

In order to apply these findings to practice and set the stage for future research, the following recommendations should be considered:

1. ECC should be targeted and used in critical beam-column joint locations within seismic risk zones, especially for more important buildings such as hospitals, emergency centers, and high-rise buildings that require enhanced performance and quick functional recovery after earthquakes.
2. For new construction projects that require optimal seismic performance, house the full joint-and-beam (ECC-JB) replacement strategy.
3. Engineers can use the numerical modeling framework and calibrated parameters presented in this research with confidence for practical seismic design and performance-based design of ECC integrations.
4. Future research should investigate the full behavior of engineered complete structural systems made with ECC, where global structural behavior can be investigated, redistribution of forces can be studied, and system-level resilience could be analyzed.
5. Further development of constitutive models for ECC is necessary to more accurately capture rate-dependent effects during dynamic loading and long-term effects like creep and shrinkage.
6. Research into the ECC joints long-term durability under various environmental condition (e.g., freeze-thaw, chloride exposure) and repeated loading histories are extremely important for encouraging widespread use.

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