PERFORMANCE EVALUATION OF ECC-CONCRETE COMPOSITES UNDER IMPACT LOADS USING FINITE ELEMENT ANALYSIS

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ABSTRACT

Engineered Cementitious Composite (ECC) is made of limited fibers and a range of additional additives that enhance ductility, shock resistance, and other properties. Due to the fragile behavior of traditional and fiber-reinforced concrete, they shatter easily under environmental and mechanical pressures, reducing construction durability. Therefore, ECC came up with an effective approach to minimize the brittleness of concrete and increase its ductility. In this study, a concrete panel of 1 m × 1 m × 150 mm was used as a basic model to evaluate the displacement over time to identify shock absorption capacity. Finite element analysis was conducted during the simulation by utilizing Abaqus FEA software. Several trails were attempted as the concrete thickness was lowered and ECC layers were added. For every trial, the thickness of ECC-Concrete layers was increased, changing the impact forces. Results indicate that the inclusion of the ECC-Concrete layer greatly reduces distortion, increasing the shock absorption capacity, whereas increasing the depth of the double ECC layer enhances the shock-absorbing capacity marginally.

Keywords: *Engineered Cementitious Composite, Finite Element Analysis, C40 Concrete, Shape-memory alloy, Polyvinyl alcohol, Shock absorption capacity*

1. INTRODUCTION

Concrete has traditionally been the major building material for critical civilian infrastructure and defense constructions. Under dynamic stresses, concrete's low tensile strength promotes brittle disintegration, jeopardizing structural integrity and safety within and around protective systems. Engineered Cementitious Composite (ECC) is a fiber-reinforced cementitious composite that was first introduced in the early 2000s. ECC exceeds standard fiber-reinforced concrete (FRC) in terms of tensile properties, with a strain capacity of up to 8% (Li, 2003). ECC has demonstrated great potential for the building of protective structures due to its outstanding mechanical features, remarkable micro-cracking potential, energy absorption capacity, and shock resistance. Its high tensile ductility, compared to regular concrete, leads to superior impact resistance and energy absorption capacity, making it great for use in impact-resistant structures (Soe et al., 2013).

Uses of ECC include dynamically loaded shear members, mechanical components of beam and column composites, and primary structural maintenance. These ECC compounds are commonly used in dampers (Nagai et al., 2004), steel component junctions, and hybrid steel connectors in constructions with greater energy retention. It can also be used as a protective layer to improve the corrosive endurance of structures in addition to other structural purposes. Subsurface constructions, bridge decks (Li, 2014), and roadway pavements are probable targets for engineered cementitious composites.

Several studies have been conducted based on ECC material. In a study by Anil et al. (Anil et al., 2016), the behaviours of reinforced concrete beams made from various concrete kinds are explored experimentally and numerically under dynamic impact loads. Zhang & Baral (Zhang & Baral, 2018) demonstrated that the ECC material may be customized by combining local elements to obtain impact resistance behaviour. This research's ECC combination demonstrated good damage tolerance and energy dissipation capability, making it ideal for the intended application. A review (Singh et al., 2019) of existing research investigations on the characteristics of ECC with the addition of different mineral admixtures and fibers. In a investigation by Nehdi & Ali (Nehdi & Ali, 2019), shock loads applied to an engineered cementitious composite (ECC) with deformation recovery and microfibers of polyvinyl alcohol and shape memory alloy. The impact behavior of the composite was numerically simulated, and the simulation results matched the experimental results well. Whereas the actions of slab and column connectors in a flat slab construction under combination gravity-CLS (cyclic lateral stress) was investigated using a 3D finite element analysis (Tambusay et al., 2017). The structural approaches were then generated using shear wall orientations after establishing a close likeness to the prior study (Zahid et al., 2023). Another research (Hemmati et al., 2016) looked into the High-Performance Fiber Reinforced Cementitious Composites, which are cement matrices that have a strain hardening reaction when loaded under tension. Performance Hard Fiber Carbon can be utilized in key areas of reinforced concrete beams and frames to boost the capacity and longevity of the structures, according to the conclusions of the article. According to a team of researchers (Guan et al., 2018) that researched the flexural of ECC-concrete composite beams, the bound composite beam exhibited a stronger load-bearing capacity and better subsequent fracturing energy absorption than the fiber-reinforced composite beam. As a result, the unbounded composite beam might be used to construct bridges in abrasive environments to increase their service life (Zahid et al., 2023). The tendency of the plastic-damage factor strain curves produced using both approaches is the same, while the impact factor founded on the assumption of released soon develops faster; the uniaxial modelling approach was reduced, and piece-wise component curves of the concrete functionalization in formulae, which corresponded to the concrete damaged plasticity (CDP) models were generated (Xiao et al., 2017). There are also studies that focused on the effect of clay brick (Umama et al., 2023) and soft clay (Islam et al., 2023) during construction.

However, this current research is conducted with the purpose of determining how an ECC-concrete composite behaves when a sudden impact force is applied, as well as other parametric modifications, instead of a standard concrete. When exposed to dynamic stresses, an ECC-Concrete multiplayer composite could indeed withstand more impact than a concrete wall. Such, in this experiment, it will be figured out how various types of ECC-Concrete composite behave under different sudden impact forces. In order to address this research gap, a panel of 1 m x 1 m x 150 mm was designated for testing, and an impact force was delivered in the center. Numerous thicknesses of ECC and concrete panels were used in the suggested composite model, as well as different combinations. Then, by varying the ECC mixes, thickness of ECC, impact force, and so on, certain parametric investigations were carried out by doing Finite Element Modelling. The objectives of the research include the stress absorption capacity of several ECC-Concrete combination compositions is evaluated using FEM as well as to investigate the effects of varied impact-force on the ECC-Concrete composite to determine how different ECC compositions affect the ECC-Concrete composite's shock absorption capabilities.

2. METHODOLOGY

A panel of 1 m x 1m x 150 mm was selected for testing purpose, then an impact force was applied at center. For proposed composite model, different thickness of ECC and concrete panels were taken, including different configurations. Then, some parametric studies were done by changing the ECC mixtures, thickness of ECC, and various impact force.

Using C40 concrete as a base model, different types of ECC-concrete models has been made for parametric studies. To determine displacement over time, an impact force has been applied in the mid portion of the surface of the models. By implementing this method shock absorption capacity is determined. All of the configuration and analysis was done using the Abaqus FEA software.

2.1 Research Flow

Figure 1 illustrates the research flow diagram, where the complete scenario of the study has been displayed. The literature review and setting of the objectives were the primary tasks during the process, followed by planning and methodology of the work. Then, data sets were collected from relevant literatures and were implemented through FEA modelling. After the overall analysis based on the models and data, comprehensive conclusions were made along with explanation of the results.

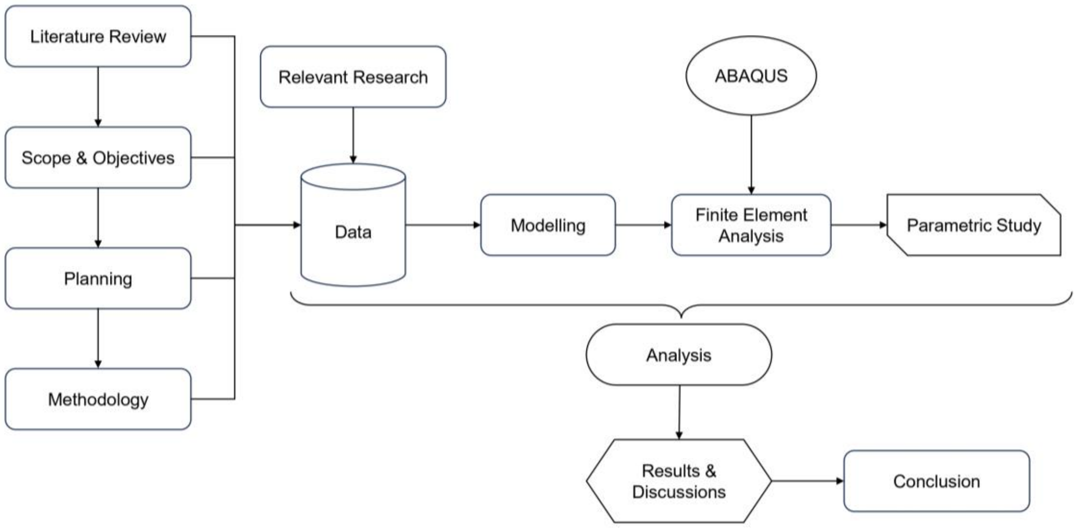


Figure 1: Research Flow Diagram

2.2 Configuration of Models

Figure 2 represents the configurations of the concrete panel, where S.V and F.V are indicated as side view and front view, respectively. The 1 m × 1 m × 150 mm concrete model is placed in the concrete section, where there is no ECC layer as this is the base model. In the second panel, the wall thickness was lowered to 100 mm, and in the third, the wall thickness was decreased to 90 mm.

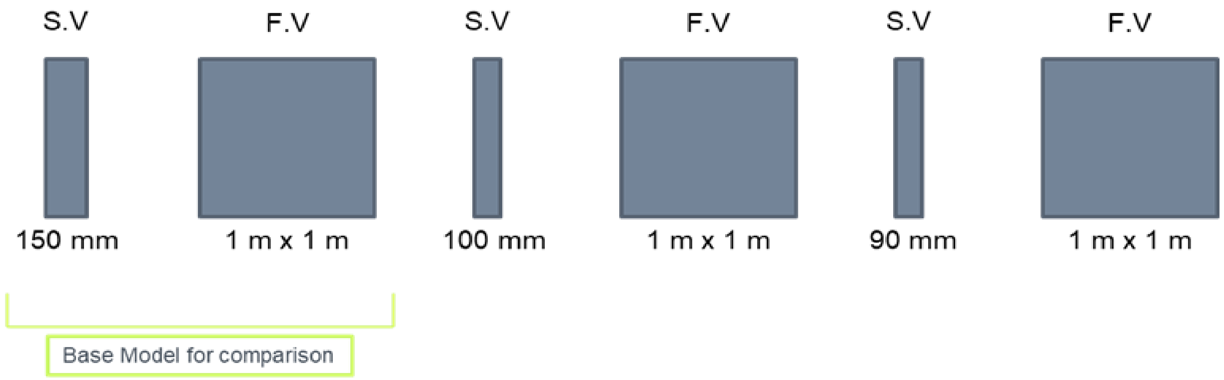


Figure 2: Configurations of Concrete

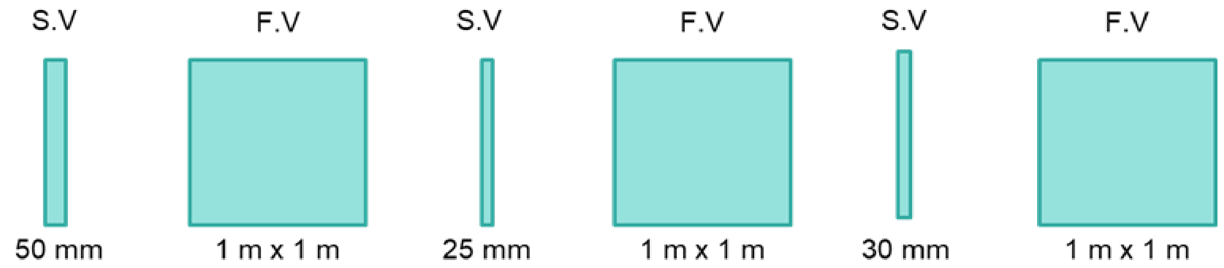


Figure 3: Configuration of ECC.

However, the ECC layer panels are displayed in Figure 3. In the ECC portion (Figure 4), 50 mm of ECC layer was implemented with a concrete wall thickness of 100 mm. In the second case, two ECC layers of 25 mm thickness were utilized on both sides. For the third case, two ECC layers of 30 mm thickness are used on both sides of a 90 mm concrete wall.

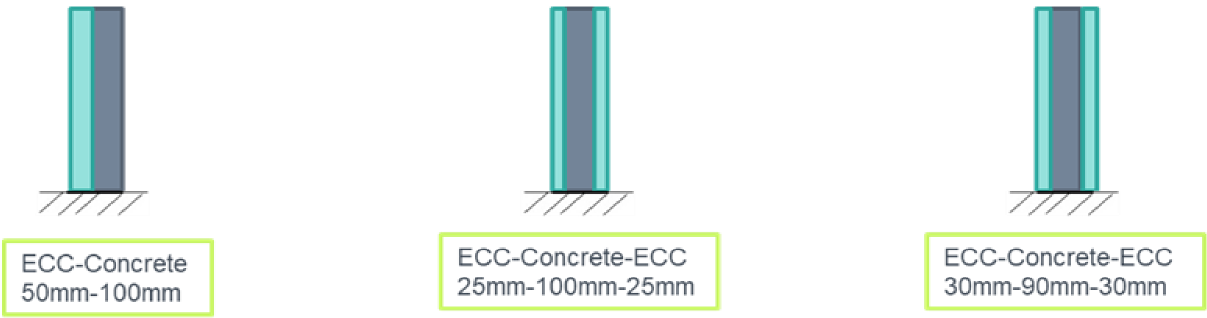


Figure 4: Configuration of ECC-Concrete Composites

2.3 Material Properties

In this section materials properties used in Abaqus finite element analysis is given in tabular and graphical formation. For the experimental data, C40 concrete (Xiao et al., 2017) and ECC mix (Nehdi & Ali, 2019) material properties are noted from different studies. In addition, for different types of ECC, the compressive Stress vs inelastic Strain data were generated using Carreira and Chu (1985) model (Carreira & Chu, 1985). In case of assigning material properties in Abaqus FEA software strain-rate effect of concrete were considered. So, compressive stress was multiplied with a factor of 1.1 and inelastic strain was multiplied with 10 to achieve accurate results.

2.3.1 C40 Concrete Properties

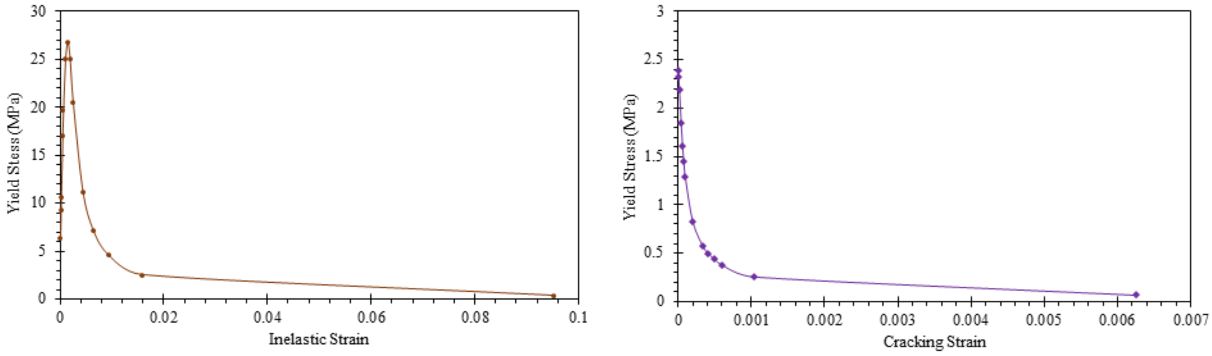
C40 concrete general properties as well as the damage plasticity properties has been presented in Table 1 and Table 2, respectively. These properties were used during the finite element analysis of the concrete. fb0 corresponds to the equiaxial compressive strength of concrete and fc0 the uniaxial ones. fb0/fc0 is a ratio of the strength in the biaxial state to the strength in the uniaxial state. The parameter ‘k’ indicates the development of tensile damage in the material.

Table 1: C40 Concrete Properties

Mass Density	**Young's Modulus (Pa)**	**Poisson's Ratio**
2300	27000	0.2

Table 2: C40 Concrete Damage Plasticity Properties

Dialation Angle	**Eccentricity**	**fb0/fc0**	**k**	**Viscosity parameter**
35	0.1	1.16	0.666666667	0.001



(a) (b)

Figure 5: C40 Concrete (a) Compressive stress vs. Inelastic Strain, (b) Tensile vs. Cracking Strain

Figure 5 depicts the compressive stress vs. inelastic strain and tensile vs. cracking strain plot for the C40 concrete. It can be observed that with the increase of inelastic strain, the yield stress goes up to 27 MPa and then drops eventually. On the other hand, with the increase in cracking strain, the yield stress decreases exponentially until the last point.

2.3.2 ECC Mixture Properties

The ECC mixture properties are shown in Table 3, whereas the properties of fibers are presented in Table 4.

Table 3: ECC Mixture Materials

Mixture Materials	**Accordance with code**
Type-I OPC (Ordinary Portland Cement)	ASTM C150
FA (Fly Ash)	ASTM C618
Micro silica sand (≤ 200 µm)	-
HRWRA (Polycarboxylate High Range Water Reducing Admixture)	ASTM C494
0.8 cm long PVA (Polyvinyl Alcohol) fibers	-
1.6 cm long Nickel Titanium SMA (Shape Memory Alloy) fibers	ASTM F2063

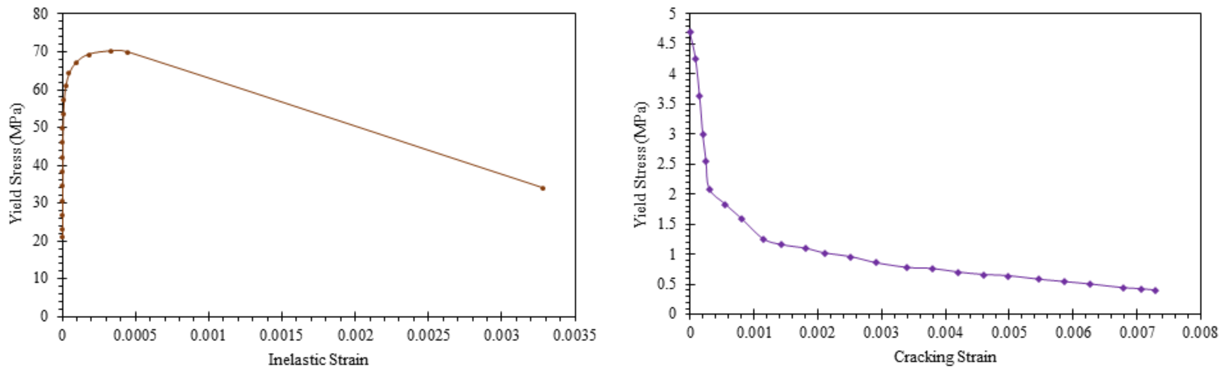
Table 4: Properties of fibers

Properties of fibers	**PVA**	**SMA**

Ultimate Tensile Strength	1620 MPa	869 MPa
Young's Modulus	43000 MPa	41000 MPa
Length	0.8 cm	1.6 cm
Diameter	0.0039 cm	0.0635 cm
Elongation	6%	38%
Density	1300 kgm^{-3}	6450 kgm^{-3}

2.3.2.1 ECC 2-0 Properties

By proportion ECC 2-0 contains, Cement: Fly Ash: Silica Sand: Water/Cement: HRWRA = 1: 1.2: 0.8: 0.26: 0.012 and 2% PVA fiber in volume fraction and 0% SMA fiber in volume fraction.



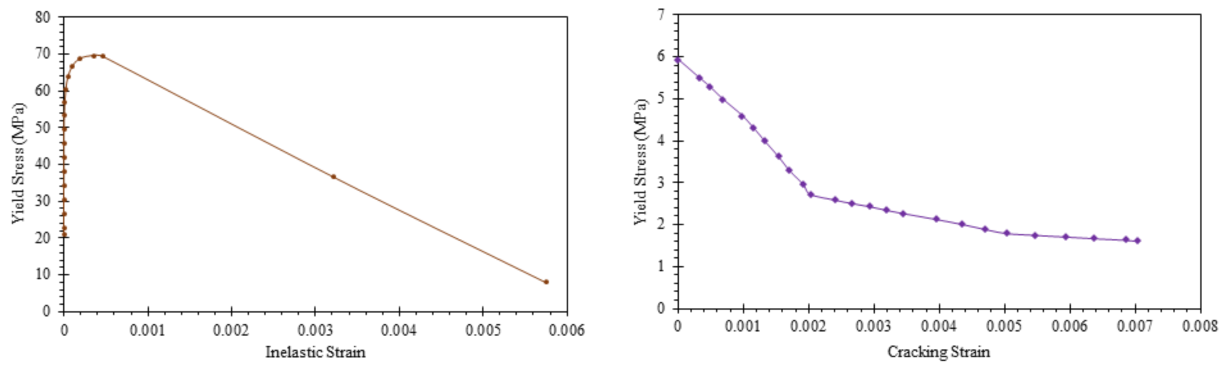
(a) (b)

Figure 6: ECC 2-0 (a) Compressive stress vs. Inelastic Strain, (b) Tensile vs. Cracking Strain

Figure 6 depicts the compressive stress vs. inelastic strain and tensile vs. cracking strain plot for the ECC 2-0. It can be observed that with the increase of inelastic strain, the yield stress goes up to 70 MPa and then drops eventually. On the other hand, with the increase in cracking strain, the yield stress decreases exponentially until 0.4 MPa.

2.3.2.2 ECC 2-0.5 Properties

By proportion ECC 2-0.5 contains, Cement: Fly Ash: Silica Sand: Water/Cement: HRWRA = 1: 1.2: 0.8: 0.26: 0.012 and 2% PVA fiber in volume fraction and 0.5% SMA fiber in volume fraction.



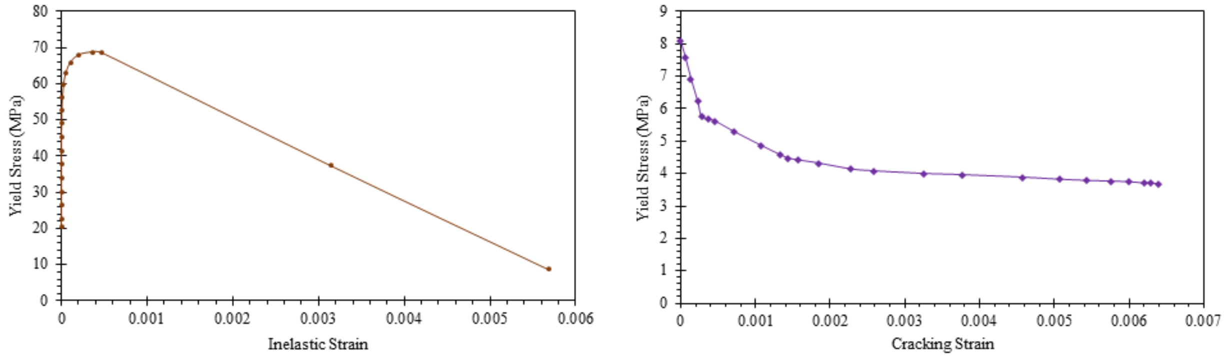
(a) (b)

Figure 7: ECC 2-0.5 (a) Compressive stress vs. Inelastic Strain, (b) Tensile vs. Cracking Strain

Figure 7 depicts the compressive stress vs. inelastic strain and tensile vs. cracking strain plot for the ECC 2-0.5. It can be observed that with the increase of inelastic strain, the yield stress goes up to 70 MPa and then drops to 9 MPa. On the other hand, with the increase in cracking strain, the yield stress decreases exponentially until 1.9 MPa.

2.3.2.3 ECC 2-1 Properties

By proportion ECC 2-1 contains, Cement: Fly Ash: Silica Sand: Water/Cement: HRWRA = 1: 1.2: 0.8: 0.26: 0.012 and 2% PVA fiber in volume fraction and 1% SMA fiber in volume fraction.
Figure 8 depicts the compressive stress vs. inelastic strain and tensile vs. cracking strain plot for the ECC 2-0.5. It can be observed that with the increase of inelastic strain, the yield stress goes up to 70 MPa and then drops to 10 MPa. On the other hand, with the increase in cracking strain, the yield stress decreases exponentially until 3.9 MPa.

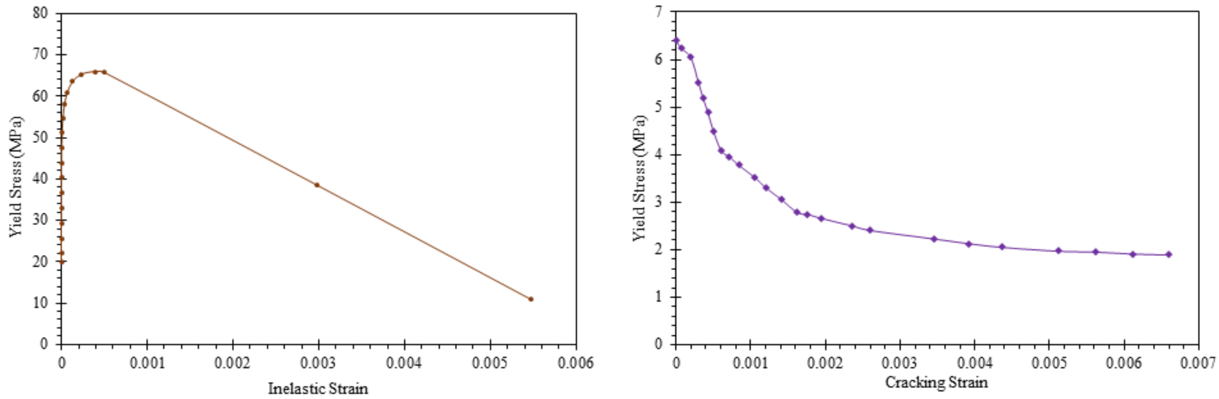


(a) (b)

Figure 8: ECC 2-1 (a) Compressive stress vs. Inelastic Strain, (b) Tensile vs. Cracking Strain

2.3.2.4 ECC 2-1.5 Properties

By proportion ECC 2-1.5 contains, Cement: Fly Ash: Silica Sand: Water/Cement: HRWRA = 1: 1.2: 0.8: 0.26: 0.012 and 2% PVA fiber in volume fraction and 1.5% SMA fiber in volume fraction.



(a) (b)

Figure 9: ECC 2-1.5 (a) Compressive stress vs. Inelastic Strain, (b) Tensile vs. Cracking Strain

Figure 9 depicts the compressive stress vs. inelastic strain and tensile vs. cracking strain plot for the ECC 2-1.5. It can be observed that with the increase of inelastic strain, the yield stress goes up to 70 MPa and then drops to 11 MPa. On the other hand, with the increase in cracking strain, the yield stress decreases exponentially until 2 MPa.

2.4 Method of Analysis

2.4.1 Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a mathematical approach for solving mathematical physics and engineering problems. In this study, FEA has been used for simulation. The FEA in this study, covers the whole range of physical behaviours and interactions of the created models. As well as it portrays mechanics as the interaction of a set of components with simplified physical behaviour. The SI unit system was considered during the whole analysis.

2.4.2 Concrete Damage Plasticity (CDP) Model

In this study, CDP model is considered while designing concrete and ECC models. The concrete damage plasticity (CDP) model was created for scenarios when the concrete is exposed to variable loading circumstances, involving cyclic loading, and when isotropic damage is assumed. The model accounts for the reduction of elastic stiffness caused by plastic straining in tension and compression. Likewise, it takes into account the impacts of stiffness recovery during cyclic loading.

2.4.3 Spatial Displacement Calculation

In this Figure 10, it can be seen that where the impact force has been applied and where the center point of the impacted region is chosen for the displacement vs time estimate. Different levels of dynamic loads have been applied to each of these formations, and the displacement is measured.

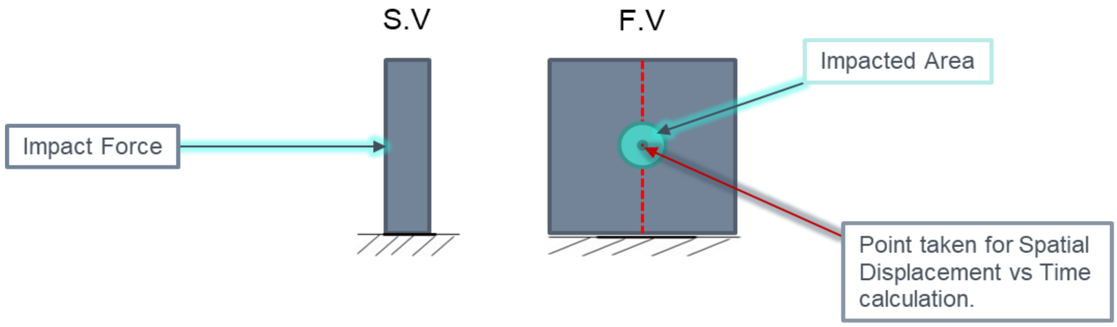
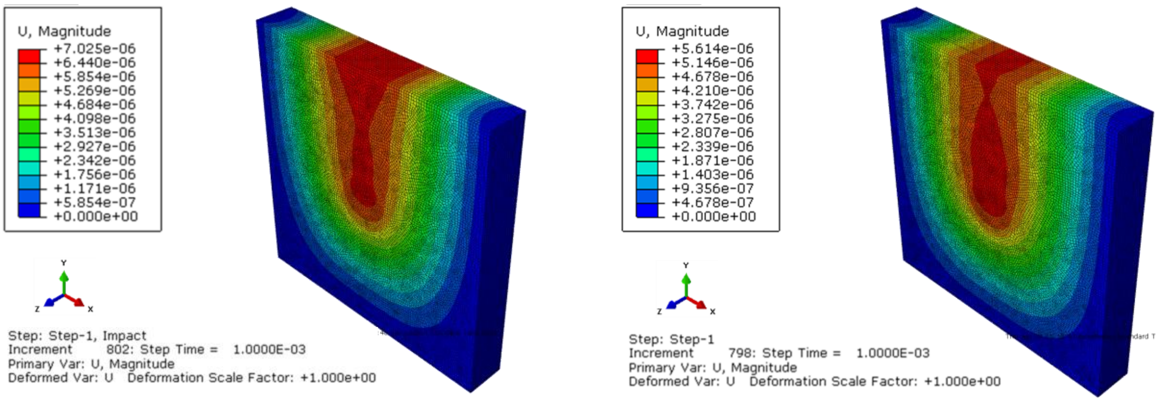


Figure 10: Method of Spatial Displacement Calculation

3. RESULTS AND DISCUSSIONS

3.1 Displacement in Different Configurations

In Figure 11, the changing the depth of ECC layers can be seen, the displacement over time is determined using finite element analysis to determine the best possible configuration of ECC-C40 concrete composite.



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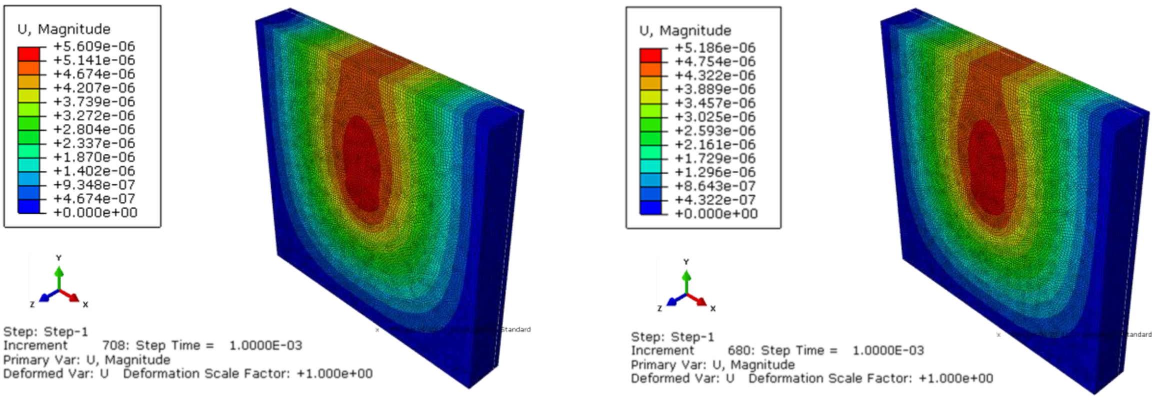


(c) (d)

Figure 11: 100KPa Impact Model Displacement (a) C40 150 mm, (b) ECC 2-0 50mm-100mm, (c) ECC 2-0 25mm-100mm-25mm, (d) ECC 2-0 30mm-90mm-30mm

From the graph shown in Figure 12, it is visible that adding ECC 2-0 panel over concrete greatly reduces displacement over time. C40 concrete base model has the highest displacement over time than other models. In case of ECC 2-0 – C40 50 mm - 100 mm model and ECC 2-0 – C40 25mm -100mm – 25mm model, the difference between displacement are moderately close. But instead of using ECC 2-0 in one layer, adding the same amount of ECC in both sides of concrete marginally helps to reduce the displacement over time.

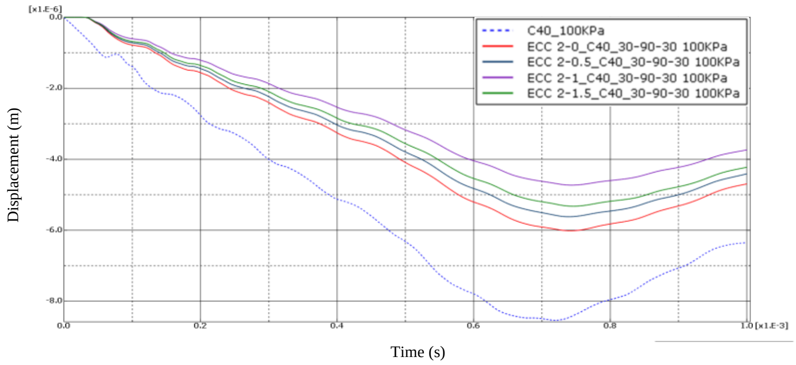
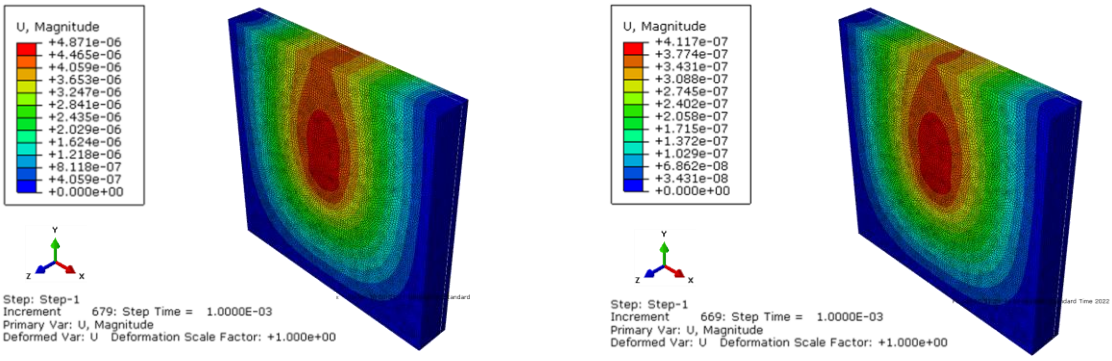


Figure 12: ECC 2-0 – C40 Models Displacement vs. Time (100KPa Impact)

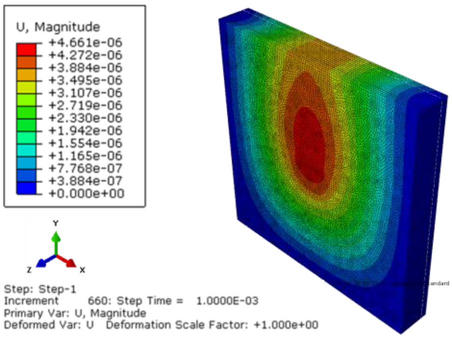
Again, in case of ECC 2-0 – C40 25mm-100mm-25mm model and ECC 2-0 – C40 30mm-90mm-30mm model, it has been observed that increasing the depth of ECC 2-0 in both side significantly helps to reduce the displacement over time. Thus, the ECC 2-0 – C40 30mm-90mm-30mm model has the least amount of displacement over time than the other models.

3.2 Displacement in Different ECC Materials

Since it has been observed that ECC 2-0 – C40 30mm-90mm-30mm model has the least amount of displacement which indicates higher shock absorption capacity. For the comparison of different types of ECC materials the ECC– C40 30mm-90mm-30mm model has been selected (Figure 13).



(a) (b)



(c)

Figure 13: 100KPa Impact Model Displacement (a) ECC 2-0.5 30mm-90mm-30mm, (b) ECC 2-1 C40 30mm-90mm-30mm, (c) ECC 2-1.5 30mm-90mm-30mm

From the Figure 14, it is noticeable that ECC 2-0 has the highest displacement over time than other ECC mixes. ECC 2-0 only has 2% PVA fiber in volume fraction and doesn't contain any SMA fiber. Where ECC 2-0.5 contains 0.5% of SMA fiber in volume fraction, and it significantly reduces the displacement over time.

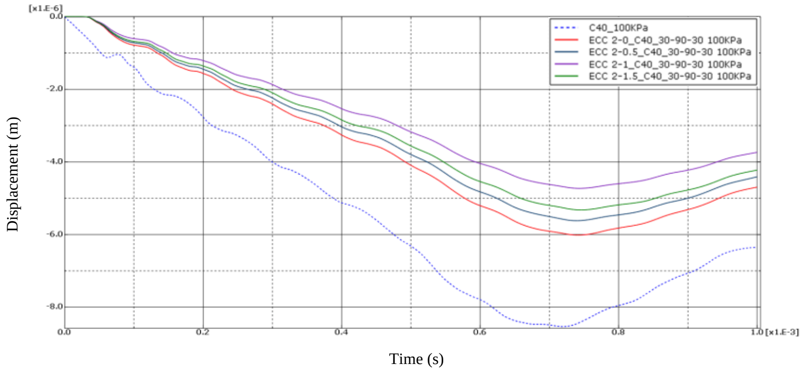
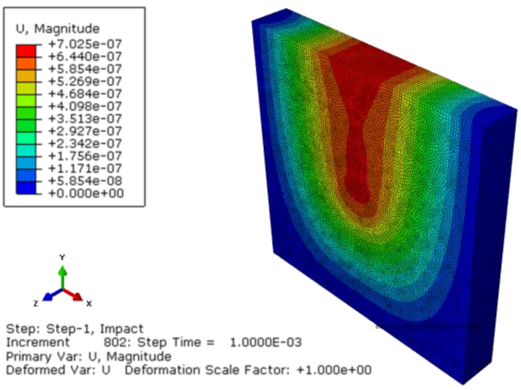


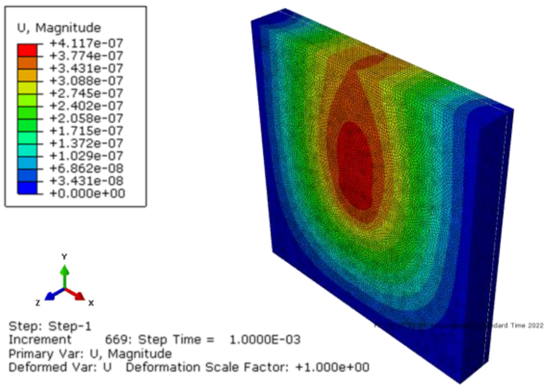
Figure 14: ECC – C40 30mm-90mm-30mm Model Displacement vs. Time (100KPa Impact)

In case of ECC 2-1.5, it contains 1.5% of SMA fiber in volume fraction. It improves the shock absorption capacity by reducing displacement over time but comparing ECC 2-1 it has lower shock absorption capacity. Therefore, ECC 2-1 reduces the displacement over time the most even though it has less SMA fiber in volume fraction than ECC 2-1.5. It is due to ECC 2-1 has the highest tensile strength than other ECC mixes.

3.3 Various Impact Forces

In case of ECC types, ECC 2-1 shows the highest shock absorption capacity than other ECC mixes and ECC-C40 30mm-90mm-30mm configuration shows the best results. For the comparison of various impact forces ECC 2-1 – C40 30mm-90mm-30mm Model has been selected.





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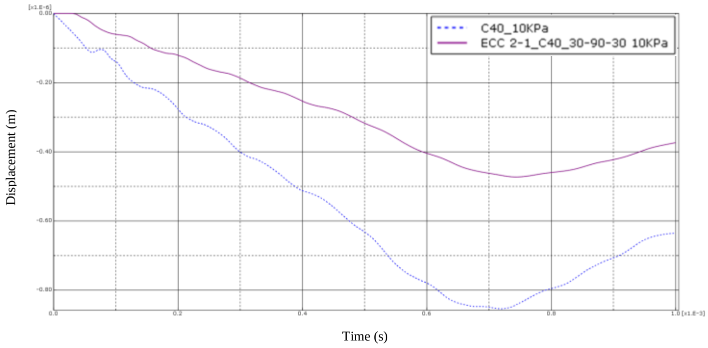
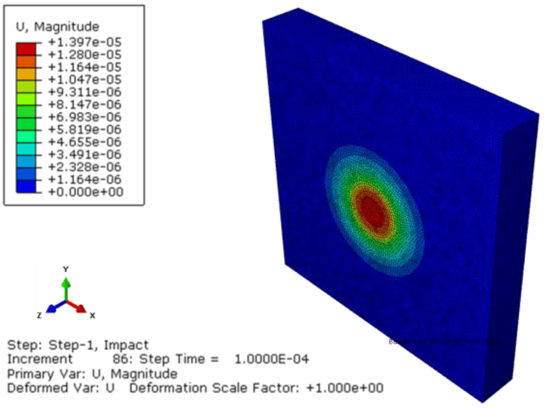
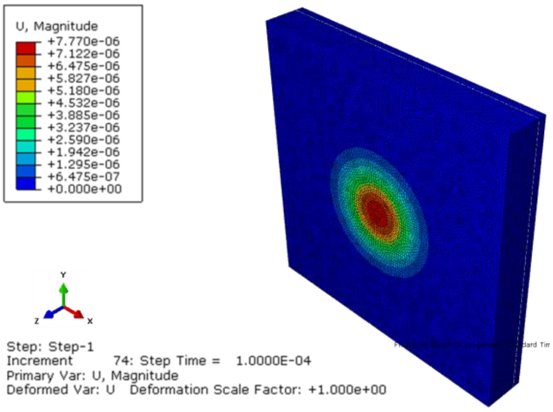


(c)

Figure 15: 10 KPa Impact Model Displacement (a) C40 150 mm, (b) ECC 2-1 – C40 30mm-90mm-30mm, (c) C40 Concrete Model and ECC 2-1 – C40 30mm-90mm-30mm Model (10 KPa Impact)



(a)



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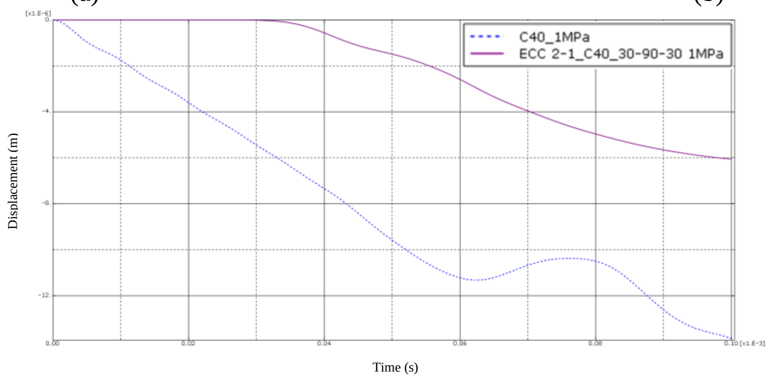

(c)

Figure 16: 1 MPa Impact Model Displacement (a) C40 150 mm, (b) ECC 2-1 – C40 30mm-90mm-30mm, (c) C40 Concrete Model and ECC 2-1 – C40 30mm-90mm-30mm Model (1 MPa Impact)

For 1MPa impact it has been observed some changes in the analysis. In case of C40 concrete the displacement curve goes downward till a certain point. Then it goes upward again, then straight downward again. It is due to C40 losing its shock absorption capacity and creating damage on the model's impact surface. But in case of ECC 2-1 – C40 30mm-90mm-30mm model the curve goes downward like C40 concrete but displacement over time, as expected is way less than C40 concrete base model. Thus, in case of various impact forces the ECC-Concrete has higher shock absorption capacity than C40 concrete.

4. CONCLUSIONS

As previously stated, three models were built which include four types of ECC in order to achieve the goal of this research. Some conclusions may be drawn after studying the findings of these models. The main purpose of this study was to find out what the best ECC-Concrete layer composition configuration and thickness were for withstanding impact forces. Analyzing all the data, the following conclusions are made:

- The inclusion of an ECC layer to concrete greatly reduces distortion, indicating a greater shock absorption efficiency.
- When comparing the ECC-Concrete 50mm-100mm and ECC-Concrete-ECC 25mm-100mm-25mm model configurations, the ECC-Concrete 50mm-100mm model has a somewhat larger displacement than the ECC-Concrete-ECC 25mm-100mm-25mm model. Even though the same amount of ECC was utilized in the experiment, adding a second layer (front and rear) of ECC increases the experimental wall's shock absorption capability.
- In all sorts of impact situations, ECC-Concrete-ECC 30mm-90-30mm outperforms the alternatives.
- But the difference between displacement of ECC-Concrete-ECC 25mm-100mm-25mm and ECC-Concrete 50mm-100mm has not been observed much comparing ECC-Concrete 50mm-100mm and ECC-Concrete-ECC 30mm-90-30mm / ECC-Concrete-ECC 25mm-100mm-25mm and ECC-Concrete-ECC 30mm-90-30mm.
- As a result, increasing the depth of the double ECC layer enhances the shock absorbing capacity marginally.
- The addition of shape memory alloy (SMA) fibers with polyvinyl-alcohol (PVA) fibers in ECC mixes significantly enhances shock absorption capability of the composite.
- But adding more than 1% by volume fraction of SMA fiber in ECC mix can lower the tensile strength of ECC mix. Therefore, the perfect ECC mix ratio would be 2% PVA and 1% SMA fiber for gaining the highest tensile strength of the model.
- In case of different impact forces ECC-Concrete composite outperforms C40 concrete in every scenario.

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