Enhancing the Ductility of a Reinforced Concrete Beam using Engineered Cementitious Composite

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Abstract. A series of small-scale rectangular reinforced concrete beams made with different mix proportions were presented. The beams were fabricated using normal concrete designated as specimen control (NC), normal concrete blended with supplementary material using Class F fly ash (SMFA), and engineered cementitious composite (ECC). The beams comprised of similar reinforcement where the ratio of compression, tension, and transverse bars were 1.0%, 1.5%, and 1.0% respectively. To this end, the beams were tested under four-point bending and they were intended to fail in flexure mode. The tests also aimed to provide direct evidence regarding the improvement of beam ductility due to the use of ECC. Furthermore, the performance of test beams on the overall strength, crack pattern, and damage state was also assessed. To corroborate the experimental work, an analytical work employing nonlinear finite element analysis using Abaqus was also included. From this study, it was found that each beam demonstrated a discernible ductile plateau upon the post-cracking region with Beam ECC showing the largest ductility compared to the other two thereby suggesting that the use of ECC could enhance the beam ductility. It was also shown that the flexural cracks manifested in Beam ECC were less critical, signifying that ECC is a damage-tolerant composite. Furthermore, the overall results of predicted load-deflection and damage state obtained from Abaqus were also in a good agreement with the experimental results.

Keywords: reinforced concrete beam, ductility, ECC, flexural behaviour, cracks, Abaqus

1. Introduction

Concrete is a brittle material with a relatively high compressive strength and a low tensile strength. In the design of reinforced concrete members, it is of common practice to place steel reinforcement at locations where the concrete members are weakened by tensile forces [1]. This would allow the concrete element to have adequate cracking control which is essential for providing the required strength and ductility prior to failure [2-4]. To achieve this desired mode of failure, which is known as a flexural failure, it is of importance to design the beam with a relatively low reinforcing bar ratio, thereby allowing the steel reinforcements to yield prior to crushing of concrete [5].

When performing a design of doubly reinforced concrete member where a significant number of steel bars are required, however, the failure would likely to be accompanied by the crushing of concrete in the compression zone [6]. Although the load capacity tends to be higher, this certainly would affect the level of ductility of concrete elements as the drop of load capacity is considerable upon the manifestation of concrete crushing. As a result, the ductility performance may be less than that of a singly reinforced concrete member.
In order to improve the ductility and overall behaviour of concrete members, a new type of fibre reinforced concrete (FRC) was first introduced in the early 1970s with limited work undertaken on investigating the influence of glass fibre and steel fibre in concrete members [7]. Past research has shown the capability of these types of fibres to enhance the ductility and damage tolerance of concrete members, and the next type of fibre made of polyvinyl alcohol (PVA) was also introduced in the production of FRC [8]. This novel work was able to showcase a good performance of concrete under tension. It was found that the utilisation of PVA fibre employed in the mix design of FRC was able to exhibit a medium level of strain hardening during direct tension test of dog-bone shape FRC specimen which was followed by tension softening response prior to failure [9-10].

The resulting composite as described in the work above had led to another initiative which enabled the composite to exhibit a pseudo-ductile behaviour similar to that of steel or metal. This material is known nowadays as engineered cementitious composite (ECC). The discovery of ECC has benefited from pioneering research by IPC group [11], one of the first groups which applied fracture mechanics concepts to analyse fibre reinforced cementitious composite systems. The current advances in ECC technology would not have occurred without the active contributions of many international organisations.

ECC, in essence, is a unique class of high-performance fibre reinforced cementitious composite (HPFRCC) which is characterised by its high strain under direct tension, addressing the pseudo strain hardening response upon the first cracking [12-13]. The ultimate tensile strain attained by ECC is 3-6 per cent, which is 300-600 times greater than that of ordinary concrete. High tensile strain is achieved through multiple micro-cracking phenomena with typical tight crack widths below 80 µm when subjected to load [14]. ECC is commonly known as a bendable or flexible concrete. Its performance in structural members has proven to provide the ability to withstand high flexural and shear stresses [15]. In addition, previous studies have reported several assessments of ECC members on varying types of loading conditions such as monotonic flexure [16], repeated shear [17], fatigue [18], and reserved cyclic [19]. Recent research related to the application of ECC in Indonesia has also been introduced by Tambusay et al. [20].

In this present work, investigations are focused on the flexural behaviour of ECC beam along with other members made with normal concrete (NC) and concrete blended with supplementary materials using fly ash (SMFA) for comparative purposes. The fabrication of beams using these three different constituents is part of a big research project whose work focuses on improving the durability performance of marine infrastructure. Only the control specimens of this project are presented herein. In the experimental part, four-point bending tests on the ECC beam were carried out to obtain the overall performance accommodating its load-deflection responses and crack patterns compared to the other two counterpart beams. Furthermore, work using Abaqus was also done for verification purposes.

Table 1. Details of reinforcement and compressive strength

| Beam Specimen | Bottom Steel | Top Steel | Transverse Steel | $f'_c$ (MPa) |
|---------------|--------------|-----------|-----------------|--------------|
| NC            | 3D10         | 2D10      | D8-100          | 47.2         |
| SMFA          | 3D10         | 2D10      | D8-100          | 50.8         |
| ECC           | 3D10         | 2D10      | D8-100          | 46.2         |

Table 2. Mix proportions

| Beam | CEM I (kg/m³) | 10 mm (kg/m³) | Fine (<3mm) (kg/m³) | Silica Sand (kg/m³) | Fly ash (kg/m³) | Water (kg/m³) | HRWR (kg/m³) | PVA (kg/m³) | Water-to-Binder |
|------|---------------|---------------|---------------------|---------------------|----------------|--------------|--------------|-------------|-----------------|
| NC   | 525           | 1054          | 764                 | -                   | -              | 158          | 5.5          | -           | 0.3             |
| SMFA | 470           | 1052          | 731                 | -                   | 80             | 158          | 5.5          | -           | 0.3             |
| ECC  | 465           | -             | 390                 | 744                 | 338            | 3.25         | 26           | 0.28        |                 |
Table 3. Chemical properties of Class F fly ash

| Compound | Content (%) |
|----------|-------------|
| CaO      | 9.32        |
| SiO₂     | 43          |
| Al₂O₃    | 12.8        |
| Fe₂O₃    | 26.8        |
| MgO      | 0.17        |
| P₂O₅     | 0.81        |
| K₂O      | 2.36        |
| TiO₂     | 1.47        |
| V₂O₅     | 0.074       |
| Cr₂O₃    | 0.044       |
| CuO      | 0.05        |
| MoO₃     | 3           |
| BaO      | 0.25        |

Table 4. Chemical properties of CEM I

| Compound | Content (%) |
|----------|-------------|
| CaO      | 62.87       |
| SiO₂     | 20.33       |
| Al₂O₃    | 3.1         |
| Fe₂O₃    | 4.81        |
| MgO      | 0.1         |
| SO₃      | 2.5         |
| K₂O      | 0.45        |
| TiO₂     | 0.43        |
| V₂O₅     | 0.02        |
| CuO      | 0.075       |
| ZnO      | 0.027       |
| SrO      | 0.053       |
| ZrO₂     | 0.03        |
| BaO      | 0.06        |

Table 5. Properties of PVA fibre from Kuraray Japan

| Type   | Fibre diameter (µm) | Length (mm) | Specific gravity (g/cm³) | Tensile strength (MPa) | Elongation (%) | Young's modulus (GPa) |
|--------|---------------------|-------------|--------------------------|------------------------|----------------|-----------------------|
| RECS-15| 40                  | 8           | 1.3                      | 1600                   | 6              | 41                    |

Figure 1. Schematic drawing of beam geometry and loading setup
2. Experimental Programme

2.1 Test Specimens
The experimental programme involved the testing of three reinforced concrete beams under four-point bending. The summary of the test programme is provided in Table 1 with the schematic of the beam geometry, cross-section details, steel reinforcement layout, and loading setup shown in Figure 1. The beams were reinforced with five 10 mm longitudinal steel bars where two were positioned at compression zone and the other three at tension zone. The longitudinal bars were tied up and confined by 8 mm two-leg rectangular closed stirrups with a space of 100 mm thereby giving the total 20 Nos of stirrups embedded inside the concrete.

Three different mix proportions with the details presented in Table 2 were used to produce the test beams. The coarse aggregate used for NC and SMFA specimens was a 10 mm graded crushed granite. A well-graded fine aggregate with 3 mm maximum particle size was used throughout. A high range water reducer (TamCem 60 RA) was also used to maintain the workability in addition to achieving high compressive strength. In SMFA mix proportion, fly ash was included with an amount of 15 per cent by mass of ordinary Portland cement. Unlike NC and SMFA mix proportions, ECC constituents employed the use of a high volume of Class F fly ash (see Table 3), silica sand in the form of powder, ordinary Portland cement Grade 42.5 referred to as CEM I 42.5 R-NA in DIN 1164 (see Table 4) [21], a high range water reducer (HRWR), and 2% by volume of PVA fibres (see Table 5).

Each beam was fabricated separately at PT. Wijaya Karya Beton Tbk. in Pasuruan and cast in a steel mould with a dimension of 100×200×2000 mm³ along with 50 mm cubes for ECC beam and 300 mm standard cylinders for the other two. Mixing was done in a single batch using a 150-litre pan mixer. To assess the quality of ECC, three dog-bone shaped specimens, with details of the geometry shown in Figure 2, were fabricated using a similar mix as provided in Table 2. Casting was done manually using an internal vibrating poker to ensure no air bubble would be trapped inside the concrete which would affect the concrete strength. In ECC specimens, however, the use of an internal poker was limited in order to prevent fibres from flocking to the bottom side of the mould. Immediately after casting, the top surface of each beam, cylinder cubes, and dog-bones were covered with plastic wrap and they were all stripped after 24 hours and transported to a curing chamber. To ensure water hydration throughout the curing period (typically 28 days after casting), the fabricated specimens were frequently wetted with water until required for testing.

![Figure 2. Test setup of a ECC dog-bone specimen](image1)

![Figure 3. Test setup and instrumentation of a test beam](image2)
2.2 Test Setup
Prior to testing the beams, direct tensile tests were undertaken on dog-bone shaped ECC specimens with the typical setup depicted in Figure 2. The dog-bone specimens were tested in the Laboratory of Concrete and Building Materials at Institut Teknologi Sepuluh Nopember using a Universal Testing Machine (UTM) Shimadzu Autograph AG-X with the capacity of 5 kN. 50 mm linear variable displacement transducer (LVDT) was attached vertically and parallel to the specimen using acrylic mounting blocks. The measurement of the tensile load was obtained from the built-in load cell in the UTM machine. The dog-bone ECC shaped specimens were tested under displacement control with a rate of 0.5 mm/min.

For each test beam, the specimen was prepared and transferred next to the test rig one day before testing. The front surface of the beam was sprayed white along with the production of 5 mm square gridlines at half of the beam length for easy crack identification. The other half was prepared with randomly speckled pattern for automated crack mapping employing the application of a low-cost digital image correlation (DIC) system as per [22-24]. However, the DIC results are not presented herein.

The photo of the test setup of the beam and the measuring instrumentation is shown in Figure 3. Each beam was placed onto two roller supports with a span of 1700 mm and subjected to monotonic two-point loads at 700 mm centres, giving a shear span-to-effective depth ratio of 3.2. The load was applied using a mechanical hydraulic jack with 50 psi (344.5 kN/m²) pressure increments until failure occurred. Given the piston area of hydraulic jack of 0.02 m², the load that corresponded with the 50 psi pressure was equivalent to 6.89 kN. The vertical beam deflection was measured using a 100 mm LVDT positioned underneath the beam at midspan where the maximum flexural moment occurred. The load and deflection data were acquired continuously at a sampling rate of 1 Hz using the Data Logger TDS-630. Throughout the course of testing, cracks were also observed and marked using coloured permanent markers at each loading increment until the failure occurred.

![Test Setup Diagram](image)

**Figure 4.** Stress-strain responses of three ECC dog-bones under direct tension
3. Results and Discussion

3.1 Tensile stress-strain relationships and crack pattern of dog-bone specimens
To provide a bigger picture regarding the quality of ECC used in this experiment, the tensile stress-strain relationships of three test dog-bone shaped ECC specimens shown in Figure 4 along with one example of observed final multiple micro-crack patterns at failure are discussed herein. The response of each specimen can generally be divided into three different types of branches:

(i) An initial linear elastic (ascending) branch which forms when the tensile load first initiates and then ends when the first crack(s) formed;

(ii) A transitional strain hardening branch (plateau) deviating from linearity when the specimen deforms. During this stage, the progressive formation of closely spaced fine cracks which were bridged by the rupture of PVA fibres occurs, causing fluctuations of the stress-strain response;

(iii) A steep strain softening (descending) resembling vertical lines which initiates after the peak stress is reached. At this stage, one to two failure places forms as a result of fibre bridging failure.

Based on the stress-strain relationships provided, it is noticeable that ECC is capable of exhibiting nonlinear strain hardening response up to a strain of 5 per cent, suggesting ECC is classified as an ultra-ductile cement composite. The strain obtained when the first cracking occurred is typically similar to that of normal concrete. However, in the strain hardening branch (see point (ii)), it can be seen that the tensile stress also increases following the increase of strain.

It is relatively challenging to spot the cracks occurring on the surface of an ECC member with merely naked eyes. It is due to high tight crack breadth which is typically less than 80 μm. To deal with this, the use of image subtraction employing the application of image editing functions as an innovative technique to provide enhanced quality and a clear picture of the cracks. An example of an edited image of a photo of cracked dog-bone which provides direct evidence regarding the advantage of this technique is shown in Figure 4. It can be seen that there are a number of closely spaced cracks developing throughout the weakened section. Regardless, it is worth mentioning that the location of fibre bridging failure in the dog-bone specimen does not always occur over the centre of the weakened section. In some tests, the fibre bridging failure would also occur at the edge of the weakened section.

Figure 5. Observed and predicted load-deflection responses for all beams
Note: Numbers shown in the crack patterns are in psi (please refer to Section 2.2 for conversion)

Figure 6. Observed and predicted load-deflection responses for all beams

3.2 Load-deflection responses and crack patterns
A comparison of observed and predicted load-deflection responses of the beams is presented in Figure 5, followed by the crack patterns obtained after failure in Figure 6. With regard to the curves presented, the three test beams generally comprise of three main regions: (i) the first region is a linear zone that specifies the response prior to the occurrence of initial crack(s); (ii) the second region is also a linear zone that represents the response until the yield of longitudinal reinforcing bars; and (iii) the third zone signifies the response beyond the yielding of reinforcement. At this region, the high rate of the rapid increase in deflection occurs for successive loads. From the overall results presented in the figure, it is apparent that Beam ECC develops a discernible ductile plateau compared to the other two beams. Accordingly, Beam NC and SMFA are also capable of demonstrating rational ductility with an increase in load capacity in the post-cracking region.

During the initial stage of loading, it is apparent that the beams exhibit similar initial stiffness until the first flexural cracks start to form on the tension face at a load of ~13.7 kN, ~20.7 kN, and ~20.3 kN for Beam NC, SMFA, and ECC respectively, when the curves slightly deviated from linearity. The
load upon these first cracks is still, in many respects, proportional to the deflection, suggesting the reinforcements are yet yielded. As the load further increased, more significant development of new flexural cracks and progression of previous cracks are apparent, propagating toward the neutral axis of the cross-section. At this stage of loading, no crack widening is observed in all test beams during testing which can be attributed to the fact that the reinforcement has not yielded. This then continues until the linear curve shifts to nonlinear at a load of 80 kN, 85 kN, and 77 kN respectively for Beam NC, SMFA, and ECC. Upon this stage, the significant reduction of stiffness is apparent which can be associated with the yielding of bottom steel bars. As the load further continued, a high rate of increasing deflection occurs which is accompanied by extensive crack widening over the centre of the beam. The increased load at this stage, however, is not proportional to the deflection.

It is worth mentioning, despite all the similarity these three beams have, the Beam SMFA shows a greater increase of load-carrying capacity compared to the other two, albeit the limited deflection (ductility) due to sudden crushing of concrete in the compression zone. Accordingly, it is shown that the overall response of Beam NC is similar, in many respects, to Beam SMFA. Despite somewhat lower load capacity and higher beam deflection found in Beam NC, the ductility is also limited due to sudden concrete crushing near the point load.

Unlike Beam NC and SMFA, the response of Beam ECC in the post-cracking regime can further withstand the applied load with large deflection plateau up to 64 mm, highlighting the improvement in ductility. At this stage, the load does not increase as the load transfer mechanism is ceased due to a significant widening of several cracks upward the neutral axis which propagates toward the loading point. Throughout the course of the testing, it was found that no crushing of concrete manifested in the compression zone, confirming the high damage tolerance of Beam ECC. These beams eventually failed in a ductile manner with flexural capacity reaching a load of 84 kN, 90 kN, and 78 kN respectively for Beam NC, SMFA, and ECC.

Apart from the experimental results of Beam ECC, it is found that the predicted load-deflection response from this limited preliminary analysis using Abaqus package shows a reasonable agreement with the experimental results, in terms of overall response and stiffness, although both predictions slightly underestimate the actual load capacity and deflection. The constitutive model used for ECC should be further evaluated with wide-ranging parameters. On the other hand, the predicted load-deflection response found in modelled Beam NC showed more accuracy in terms of stiffness and load at yield level, resembling a similar curve to that of the test beam. As seen in Figure 7, the contour of damage state obtained from Abaqus shows that ECC is much more damage-tolerant compared to the normal concrete.

![Figure 7. Visualisation of damage state from predicted beams (NC and ECC)](image-url)
4. Conclusions
The experimental investigations into the flexural behaviour of reinforced concrete beams are presented. Emphasis has been made on studying the enhancement of ductility using engineered cementitious composite, and to check whether or not the material would provide damage tolerance throughout. The results from nonlinear finite element analysis have also been included in this paper for comparative purposes. Based on the experimental and analytical work presented, some conclusions are drawn:
1. This work demonstrates that the application of ECC is capable of enhancing the ductility of the reinforced concrete beam. It is shown that in the post-cracking regime, the extensive deflection plateau that occurs is also accompanied by the formation of closely-spaced flexural cracks.
2. It is shown that ECC is a damage-tolerant composite where the typical crack width is limited. In addition, the influence of fibre-matrix interaction is proven to maintain the integrity of the structure throughout the course of loading, preventing the beam to experience concrete crushing at the compression zone.
3. In general, the overall response of Beam NC and SMFA is similar in terms of strength, stiffness, crack pattern, and mode of failure.
4. The load-deflection responses obtained from the nonlinear finite element analysis shows a reasonable agreement with the experimental results.

References
[1] Gribniak V, Kaklauskas G, Torres L, Daniunas A, Timinskas E and Gudonis E 2013 Comparative analysis of deformations and tension-stiffening in concrete beams reinforced with GFRP or steel bars and fibers Composites : Part B 50 158–70
[2] Nadir W, Dhahir M K and Naser F H 2018 A compression field based model to assess the shear strength of concrete slender beams without web reinforcement Case Stud. Constr. Mater. 9 e00210
[3] Ulzurrun G S D and Zanuy C 2017 Enhancement of impact performance of reinforced concrete beams without stirrups by adding steel fibers Constr. Build. Mater. 145 166–82
[4] Higgins L, Forth J P, Neville A, Jones R and Hodgson T 2013 Behaviour of cracked reinforced concrete beams under repeated and sustained load types Eng. Struct. 56 457–65
[5] ACI 318-11 2011 Building Code Requirements for Structural Concrete and commentary
[6] Bentur A and Mindess S 1983 Concrete beams reinforced with conventional steel bars and steel fibres : properties in static loading Int. J. Cem. Comp. Lightw. Conc. 5 3 pp 199–202
[7] Poon C S, Shui Z H and Lam L 2004 Compressive behavior of fiber reinforced high-performance concrete subjected to elevated temperatures Cem. Concr. Res. 34 2215–22
[8] Noshehini A, Samali B and Vessalas K 2013 Effect of polyvinyl alcohol (PVA) fibre on dynamic and material properties of fibre reinforced concrete Constr. Build. Mater. 49 374–83
[9] Li W Q, Zhu J H, Chen P Y, Xing F, Li D and Su M 2019 Evaluation of carbon fiber reinforced cementitious matrix as a recyclable strengthening material J. Clean. Prod. 217 234–43
[10] Homma D, Mihashi H and Nishiwaki T 2009 Self-healing capability of fibre reinforced cementitious composites J. Adv. Concr. Technol. 7 217–28
[11] Li V 2003 On Engineered cementitious composites (ECC): A review of the material and its applications J. Adv. Conc. Tech. 3 pp 215-230
[12] Yu K Q, Yu J T, Dai J G, Lu Z D and Shah S P 2018 Development of ultra-high performance engineered cementitious composites using polyethylene (PE) fibers Constr. Build. Mater. 158 217–27
[13] Komara I, Tambusay A, Sutrisno W and Suprobo P 2019 Engineered Cementitious Composite as an innovative durable material: A review ARPN J. Eng. Appl. Sci. 14 822–33
[14] Huang T and Zhang Y X 2014 Simulation of material behaviour of engineered cementitious composites under uniaxial tension (Woodhead Publishing Limited) 539-43
[15] Shanour A S, Said M, Arafa A I and Maher A 2018 Flexural performance of concrete beams
containing engineered cementitious composites *Constr. Build. Mater.* 180 pp 23–34
[16] Yuan F, Pan J and Leung C K Y 2013 Flexural behaviors of ECC and concrete/ECC composite beams reinforced with basalt fiber-reinforced polymer *J. Compos. Constr.* 17 pp 591–602
[17] Sahmaran M, Anil O, Lachemi M, Yildirim G, Ashour A F and Acar F 2015 Effect of corrosion on shear behavior of reinforced engineered cementitious composite beams *ACI Struct. J.* 112 771–82
[18] Liu Y, Zhang Q, Bao Y and Bu Y 2019 Static and fatigue push-out tests of short headed shear studs embedded in Engineered Cementitious Composites (ECC) *Eng. Struct.* 182 pp 29–38
[19] Qudah S and Maalej M 2014 Application of engineered cementitious composites (ECC) in interior beam-column connections for enhanced seismic resistance *Eng. Struct.* 69 pp 235–245
[20] Tambusay A, Suprobo P, Faimun, Arwin A 2015 Finite element analysis on the behaviour of slab-column connections using PVA-ECC material *J. Tek.* 79 5 pp 23–32
[21] DIN EN 197-1 *Special cement composition and conformity evaluation* 2000
[22] Suryanto B, Tambusay A and Suprobo P 2017 Crack mapping on shear-critical reinforced concrete beams using an open source digital image correlation software *Civ. Eng. Dimens.* 19 2 93–8
[23] Tambusay A, Suryanto B and Suprobo P 2018 Visualization of shear cracks in a reinforced concrete beam using the digital image correlation *Intr. J. Adv. Sci. Eng. Inf. Tech.* 8 2 573-8
[24] Suryanto B, Staniforth G, Kim J, Gebreyouhannes E, Chijiwa N, Chikako F and Woodward P K 2019 Investigating the mechanism of shear fatigue in reinforced concrete beams subjected to pulsating and moving loads using digital image correlation *MATEC web Conf.* 258 03015

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