Experimental study on Shear behaviors of RC beams strengthened with ECC layers

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Abstract. The experimental study on shear behaviors of reinforced concrete (RC) beams externally strengthened with Engineered Cementitious Composite (ECC) layers were conducted and analyzed. The RC beams were designed and fabricated without stirrups. ECC was sprayed onto the sides of the beams to the designed thicknesses which were 20 mm, and 40 mm. A series of four-point bending experiments were performed to study and analyze the shear behavior of the specimens. The thickness of ECC layers and shear span-to-depth ratios were considered and analyzed. It is an effective way for the shear strengthening of RC beams with ECC layers. The ECC layers’ thickness should be restricted to override the debonding between ECC layers and RC beam or to strengthen an RC beam into an under reinforced one. Fibre Bragg Grating sensors can be used to measure the development of shear strain of the strengthened specimens.

1. Introduction
It is well known that Engineered Cementitious Composite (ECC) is a class of ultra-ductile fiber reinforced cementitious composite. The tensile ductility can reach more than 3% with multiple cracks distributing in the interface [1-2].

Many pieces of research on the strengthening effect of ECC have been conducted, and it has been regarded as a suitable material for strengthening reinforced concrete (RC) structures [3-5]. Kim and Yun conducted the research on the beams repaired with ECC. The strengthened beams showed no concrete crushing or spalling until final flexural failure but showed a great number of hair cracks [6]. The crack damage mitigation and shear behavior of shear-dominant RC beams repaired with ECC were also conducted. The use of an ECC layer leads to a substantial increase in the shear strength and ductility of the RC beams after the peak load. The results also indicate that ECC layers can be effective repair material for enhancing the control of cracking to help protect the concrete from the migration of aggressive agents in severe environments [7]. Yuan conducted the research on the mechanical behavior of steel reinforced ECC or ECC/Concrete composite beams under reversed cyclic loading. It is found that the steel-reinforced ECC beams show better seismic performance in terms of load-carrying capacity. Beams failed in shear showed more significant improvement than those failed in flexure [8]. Afefy and Mohamed placed pre-cast and cured ECC strips in the tension cover zone of one-way reinforced RC slabs beside the main steel reinforcement. Test results showed that the ECC strips enhanced the structural performance of the slabs at both service and ultimate limit states [9].

In this paper, four-point bending experiments for control specimens, specimens strengthened with 20 mm, and 40 mm ECC layers were conducted and analyzed. The load, deflection at mid-span, and
shear strain development on the sides of the beams were recorded and compared. The thickness of ECC layers and the shear span-to-depth ratios were taken into consideration.

2. Four-point bending experiments

2.1. Materials properties and the test setup
The properties of the materials used in the experiments including concrete, ECC and steel rebars are shown in table 1.

| Type    | Diameter (mm) | Net Area (mm²) | $f_c$ (MPa) | $f_t$ (MPa) | $f_y$ (MPa) | $\varepsilon_y$ | $f_u$ (MPa) | $\varepsilon_u$ | $E$ (GPa) |
|---------|---------------|----------------|--------------|-------------|-------------|-----------------|--------------|---------------|-----------|
| Concrete| ---           | ---            | 32           | 2.6         | ---         | ---             | 258          | 20            | 203.8     |
| ECC     | ---           | ---            | 56           | 4.0         | ---         | ---             | ---          | 478           | 0.013     |
| Rebar   | 16            | 201            | 386          | 0.00189     | 478         | 0.013           | 203.8        |               |           |

$^a f_c$ means compressive strength of concrete or ECC
$^b f_t$ means tensile strength of concrete or ECC
$^c f_y$ means yield stress of rebar
$^d \varepsilon_y$ means yield strain of rebar
$^e f_u$ means ultimate stress of rebar
$^f \varepsilon_u$ means ultimate strain of rebar
$^g E$ means young’s modulus of rebar

Concrete was mixed at a concrete station and then poured into wood molds, where the rebars were already located according to design. As shown in figure 1, only four steel stirrups with a diameter of 8 mm were placed at each end of the beams with a spacing of 50 mm. Sprayed ECC layers with a thickness of 20 mm and 40 mm were used to strengthen the beams. The sides of the beams were chiseled and cleaned before ECC layers were sprayed. After the ECC layers were applied, the strengthened specimens were covered with a polyethylene sheet and water was sprayed onto the surfaces of ECC layers during the curing stage, which lasted 28 days. The details of the specimens are shown in table 2.

2.2. Fabrication of specimens and experimental setup

| Specimen ID | Length (mm) | Span (mm) | $b \times h$ (mm x mm) | $\rho$ (%) | $L_0$ (mm) | $t_{ECC}$ (mm) | $\lambda$ |
|-------------|-------------|-----------|------------------------|------------|------------|----------------|----------|
| C-2         | 2100        | 1800      | 150 x 300              | 0.89       | 772        | 0              | 2        |
| C-3         | 2100        | 1800      | 150 x 300              | 0.89       | 258        | 0              | 3        |
| S-20-2      | 2100        | 1800      | 190 x 300              | 0.71       | 772        | 20             | 2        |
| S-20-3      | 2100        | 1800      | 190 x 300              | 0.71       | 258        | 20             | 3        |
| S-40-2      | 2100        | 1800      | 230 x 300              | 0.58       | 772        | 40             | 2        |
| S-40-3      | 2100        | 1800      | 230 x 300              | 0.58       | 258        | 40             | 3        |

$^a b$ means the width of the beam’s cross-section
$^b h$ means the height of the beam’s cross-section
$^c \rho$ means reinforcement ratio of beam
$^d L_0$ means loading span
$^e t_{ECC}$ means the thickness of the ECC layer
$^f \lambda$ means the shear span-to-depth ratio

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Four-point bending experiments were conducted. All specimens were simply supported with a span of 1800 mm. The loading spans were 772 mm for the specimens which have the shear span-to-depth ratio ($\lambda$) of 2.0, and 258 mm for the specimens which have $\lambda$ of 3.0. The specimens were loaded until final failure with an MTS hydraulic servo loading system (MTS-1000 kN) under a load control
manner. Three Linear Variable Differential Transformers (LVDTs) were used to measure the deflections at the mid-span and two loading points. The initiation and propagation of cracks in the concrete were observed during the experiments. Strain gage was stick on the main rebar at the middle location to measure the development of tensile strain. In this test, two strain rosettes which were formed with three Fiber Bragg Grating (FBG) sensors with a gauge length of 15 cm were used to measure the shear strain in the side of the specimen.

![Figure 1. Sketch of the specimens (mm)](image)

3. Experimental results and discussion

3.1. Behaviors between load and deflection at mid-span

The load and deflection at mid-span curves of the specimens are shown in figure 2 and the results are demonstrated in table 3.

As observed from figure 2, the ultimate load of the specimen strengthened with 40 mm ECC layers even lower than that of the specimen strengthened with 20 mm ECC layers when $\lambda$ is 2. And, when $\lambda$ is 3, the ultimate loads of the strengthened specimens are almost the same. It can be found from table 2 that the reinforcement ratio of the specimens after the reinforcement with 40 mm ECC layers is 0.58%. It is lower than the minimum limit reinforcement ratio, which should be the larger one between $0.20\%$ and $45f_{ct}/f_{yt}$% (0.65%) according to the code [10]. As we all know, for under-reinforced beams, the dowel action of reinforcing bars is not enough, and the performances of concrete and ECC cannot be fully used.

It is an effective way to strengthen the RC beam with ECC layers. But, the thicker ECC layers are not always the better. It should avoid strengthening a beam to an under-reinforced one.
3.2. Shear strains in the side of the specimens
The shear strains in the side of the specimens are shown in figure 3. For the control specimens, the shear strain increases linearly with the increase in load, and then the strain increases greatly after the main cracks initiated. For the specimens strengthened with 20 mm ECC layers, the shear strain increases slowly with the increase in load at the beginning stage. Then, a kind of “yielding stage” arose for the specimen S-20-2. After that, the strain increases greatly, and the final failure happened. No “yielding stage” happened for the specimen S-20-3. For the specimens S-40-2, the shear strains remain at a low level until final failure happened. Compare with the other specimens, the shear strain of specimen S-40-3 is largest at the corresponding loading point.

From the curves, the shear failures for the specimens happened in brittle models, but for S-20-2, “yielding stages” were captured by FBG sensors. It is useful to shear strengthen RC beams with ECC layers and FBG sensors can be used to captured and monitor the development of shear strain of the specimens.

Figure 2. Load and deflection at mid-span of the specimens

Table 3. Four-point bending experimental results

| Specimen ID | Ultimate loading (kN) | Mid-span deflection (mm) | Increase of loading (kN) | Percent of increase (%) |
|-------------|-----------------------|--------------------------|--------------------------|-------------------------|
| CA-2        | 136                   | 8.51                     | ----                     | ----                    |
| CA-3        | 85                    | 6.68                     | ----                     | ----                    |
| S-20-2      | 250                   | 7.44                     | 114                      | 84                      |
| S-20-3      | 117                   | 8.60                     | 32                       | 38                      |
| S-40-2      | 190                   | 9.18                     | 54                       | 40                      |
| S-40-3      | 120                   | 9.86                     | 35                       | 41                      |
3.3. Failure models of the specimens

The failure models of the specimens can be found in figure 4. All control specimens showed typical brittle failure. With increasing loading, hair cracks initiated on the side surfaces in the flexural section and failure happened once the main cracks formed located at the loading points.

All the specimens strengthened with 20 mm ECC layers showed brittle shear failure. Compare with the control specimens, there are more cracks distributed in the strengthened specimens with narrower space. For S-20-2, the ECC layer peeled off from the strengthened beam. For S-20-3, partly debonding...
happened. For the specimens strengthened with 40 mm ECC layers, partly debonding happened through the testing process.

4. Conclusions
A series of four-point bending experiments were conducted on control specimens and specimens strengthened with ECC layers varying the thickness, and shear span-to-depth ratio. Conclusions can be drawn as follows:

1. It is an effective way to shear strengthen RC beams with applying ECC layers on the sides of beams.
2. The ECC thickness should be eluded to override the risk of debonding failure of the concrete interface.
3. It should be avoided to strengthen an RC beam into an under-reinforced one.

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