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Influence of concrete material ductility on the behavior of stud shear connection

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ABSTRACT: This paper presents an experimental study on the influence of concrete material ductility on crucial performance of stud shear connection, including failure mode, slip capacity, and ultimate strength. A series of pushout specimens were tested for this evaluation by using a unique strain-hardening fiber reinforced Engineered Cementitious Composites (ECC). Normal concrete was adopted as the reference material. The experimental results show that the shear connection with ECC exhibits a more ductile failure mode, higher slip capacity and ultimate strength compared to connection with concrete. The superior ductility of ECC was clearly reflected by microcrack development near the shear studs, suppressing the localized fracture mode typically observed in concrete material. This significant enhancement of ductility suggests that the use of ECC material can be effective in redistributing loads among the shear studs and in improving composite action between steel girder and concrete bridge deck.

Keywords: ECC, ductility, shear stud, failure mode, slip capacity, ultimate strength of stud shear connection

1 INTRODUCTION

Currently stud shear connectors are widely used in beam and bridge girder to form composite action between steel and concrete. Composite beams gained popularity in bridges since the 1950's due to the contributions of Viest on the stud shear connectors (1956a, b, 1960). Its primary growth in building construction was a result of the simplified design provisions introduced into the 1961 AISC specification (Driscoll & Slutter, 1961). The work done at Lehigh University (Ollgaard et al. 1971) and later introduced into AASHTO and AISC specifications provided guidelines for the use of lightweight and normal-weight concrete in the composite beams.

Thus far, the research on stud shear connection is on two levels: the pushout subassemblage level and composite beam level. Test results from pushout specimens can be used for design composite beam since it gives conservative value of the ultimate strength (Driscoll & Slutter 1961). Previous research (Ollgaard et al 1971, Oehlers & Foley 1985, Yen et al 1997, Bursi & Gramola 1999) on both levels revealed that concrete fracture contributed to the failure of pushout specimens or composite beams, as can be seen in Figure 1. Illustrated by pushout specimen in Figure 1a, the concrete was fractured on one side due to the stress concentration near the stud head and on the other side, the concrete was crushed due to high bearing stress of the shank of the stud. In Figure 1b, composite beam failed by longitudinal splitting crack between two rows of shear studs.

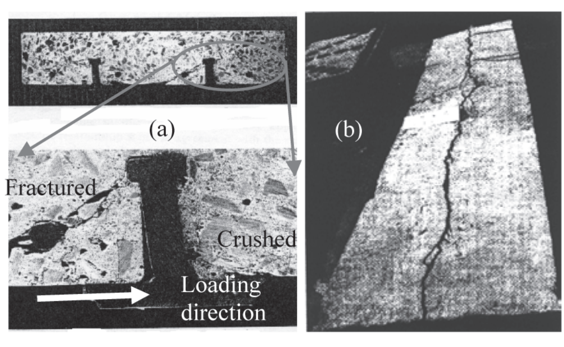

Figure 1. (a) Sawed sections of pushout specimen show fracture of concrete (Ollgaard et al. 1971); (b) Composite beam failed by longitudinal splitting crack between two rows of shear studs (Yen et al. 1997)

Up to now the research on shear connection is only concentrated on systems involving steel studs in concrete and mortar. Since the catastrophic fracture failure may be attributed to high stress concentration induced by steel stud bearing against the brittle concrete materials, it seems that using a more ductile and tough concrete material may result in improved performance for stud shear connection in terms of ductility and strength.

A number of recent studies have indicated that Engineered Cementitious Composites (ECC) (Li 1993), a unique type of high performance fiber reinforced cementitious composites (HPFRCCs), show promise in overcoming the stress concentration problems (Li 1998). Based on micromechanics design approach, ECC shows strain hardening behavior in tension accompanied by saturated multiple cracking, and high toughness as well, while only using a small volume fraction of fibers (typically less than 2%). Particularly, unlike brittle concrete/mortar, ECC reveals a high damage tolerant behavior under stress concentration induced by steel/concrete interaction in a number of experimental studies (Kanda et al 1998, Parra-Montesinos & Wight 2000, Li 2002, Kesner & Billington 2002). This suggests the possibility of adopting ECC to replace concrete in stud shear connection zone to avoid fracture failure.

As mentioned previously, the primary cause for brittle fracture failure of concrete in shear connection is its brittleness. With a tensile strain capacity of 3-5% and fracture energy of 34 kJ/m^2 (around three orders of magnitude those of normal concrete), the use of ECC is expected to switch the failure mode from brittle concrete failure to ductile ECC "yielding" or even steel stud yielding in shear connection. The corresponding ductility (slip capacity) and strength of ECC/shear connection system may be enhanced since the presence of ECC allow "plastic yielding" of the matrix material, and delaying the on-set of final fracture failure if this happens at all. The enhanced ductility of shear connection may help the desirable load redistribution among shear studs, particularly important for precast bridge deck system where shear connectors are evenly distributed in the shear span while the horizontal shear force is not uniform.

The objective of this study is to investigate the influence of ductility of ECC material on the behavior of stud shear connection and compared to that of concrete on the pushout specimen level, and the feasibility of utilizing superior ductile ECC to replace concrete in stud shear connection to avoid brittle fracture failure. The results presented and discussed herein are preliminary and serve as a beginning of a larger testing series to follow.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

This investigation utilized two ECC mixes, M45 and M45+, both comprised of 2% by volume poly-vinyl-alcohol (PVA) fibers along with standard mortar matrix components, as shown in Table 1. The ECC mix M45+ has a higher water cement ratio compared with M45, so that the compressive strength of M45+ can be roughly comparable to that of the reference concrete. By uniaxial tension test, both M45 and M45+ show a strain capacity around 2.5% at 28 days, as shown in Figure 2. The modulus of elasticity of concrete and ECC were measured by using standard cylinder specimens in compression test. It is worth mentioning that the modulus measured from both compression test and uniaxial tension test of ECC specimens agree well.

Table 1. Mix proportion of ECC and concrete by weight (fiber by volume) and corresponding material properties

Material	C	W	S	CA	FA	SP	V_f %	ε_u %	fc' MPa	E_c GPa
Concrete	1	0.45	2	2	0	0	0	0.01*	38	25.5
M45+	1	0.58	0.8	0	1.2	0.03	2	2.5	46	19.3
M45	1	0.53	0.8	0	1.2	0.03	2	2.5	60	20

(* Assumed value; C: Type I Portland cement; W: Water; S: Silica sands for ECC, regular sand for concrete; CA: Coarse aggregate with max size 19 mm; FA: Type F fly ash; SP: Superplasticizer; V_f: Fiber volume percentage; ε_u: Uniaxial tensile strain capacity; f_c': Compressive strength; E_c: Modulus of elasticity)

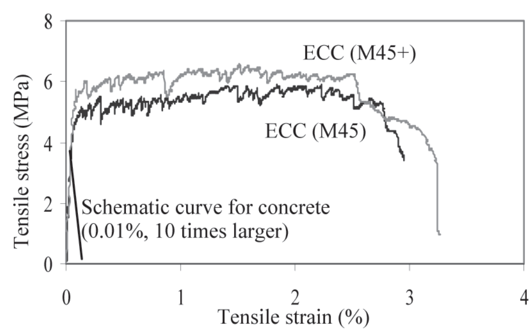

Figure 2. Uniaxial tensile stress-strain curve of ECC material M45 and M45+, tested with plate specimens of 12.7mm x 76.2mm x 304.8mm.

The shear studs used in this test were made from Grade 1018 cold drawn bars, conforming to

AASHTO M169 (ASTM A108) Standard Specification for Steel Bars, Carbon, Cold-Finished, Standard Quality. The studs have a minimum yield and tensile strength of 345 MPa (50 ksi) and 414 MPa (60 ksi), respectively. The geometry of a shear stud is shown in Figure 3.

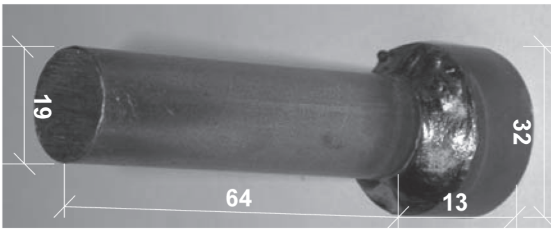

Figure 3. Geometry of a shear stud (unit: mm)

2.2 *Preparation of specimens and testing*

The geometry of the pushout specimen is shown in Figure 4. Two substrate slabs, with a dimension of 305mm x 305mm x 152 mm of matrix material (concrete or ECC), were connected with a wide flange steel beam W8X40 with two shear studs welded on each side of the beam. The geometry is adopted from Ollgaard et al. (1971). During casting, the material was poured from the top of the specimen. Therefore, the steel beam remained vertical to assure a horizontal loading plane. Even though this casting orientation is different from field conditions, the pouring direction is thought to be unimportant since PVA fibers in ECC are likely to be randomly distributed in a 3-dimensional state. To ensure the symmetry of the two slabs, the plywood molds were constructed using two integral side plates and a single bottom plate.

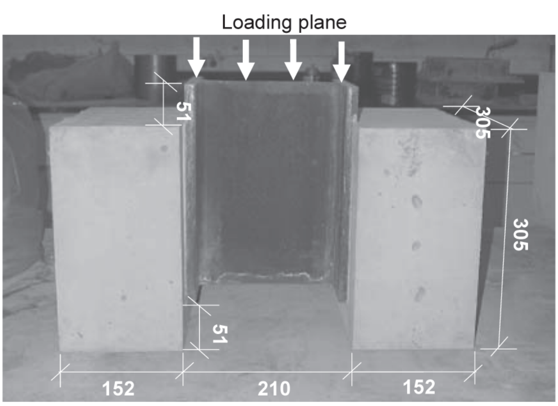

Figure 4. Geometry of the pushout specimen (unit: mm)

The ECC specimens were cured in air, and concrete specimens cured in water for 28 days. Testing was conducted on a 500kip (2224kN) capacity Instron testing machine, as shown in Figure 5. Four LVDTs were mounted on the steel beam at the level of the shear studs to measure the slip between the beam and concrete slabs. An average value was taken from these four measurements. The loading surface was grinded for uniform load distribution before testing, and a ball support was used to maintain the alignment of the specimens.

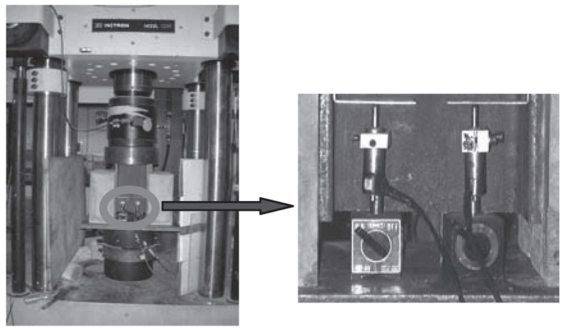

Figure 5. Setup of pushout tests and close view of LVDTs

3 RESULTS AND DISCUSSION

3.1 *Pushout behavior*

Overall, the performance of the ECC/stud connection system is significantly better than the concrete/stud connection system in terms of failure mode, slip capacity (ductility), and load capacity. As shown in Figure 6 and Figure 7, the failure mode of the connection switched from brittle matrix failure in concrete specimens to ductile multiple cracking of ECC and steel yielding in ECC specimens, leading to a higher ductility of ECC/stud connections at higher peak load.

In concrete pushout tests, as loading approached the peak value, large cracks formed in the concrete near the shear studs and developed rapidly throughout the entire specimen as the peak load was reached. Revealed in Figure 6, concrete specimens fractured into several parts after testing, with fracture clearly initiated from near the head of the shear studs. The sudden drop after peak load in Figure 8a demonstrates that after the concrete was fractured, the bearing resistance of concrete was drastically reduced. The concrete under the shear stud was crushed due to the large bearing stress of the stud shank. The high stress concentration induced by the stiff steel stud combined with the brittle nature of concrete led to the rapid development of macro cracks, resulting in the catastrophic failure of concrete pushout specimens.

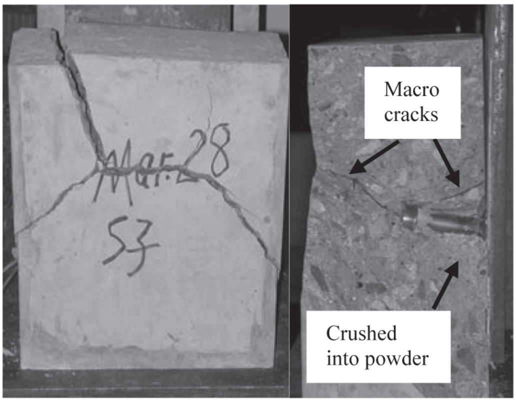

Figure 6. Macro cracks developed in concrete pushout specimen show a brittle failure mode

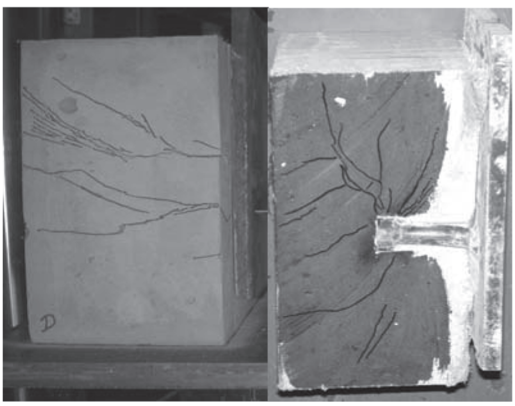

Figure 7. Microcracks developed outside (left) and inside (right, cut section along shear stud) of ECC specimen

Conversely, ECC specimens showed a ductile failure mode due to their unique strain hardening behavior and high toughness. The pushout behavior of M45 and M45+ are similar. During linear elastic stage in Figure 8 b, c, no cracks could be observed from the surfaces of the ECC pushout specimens. As the load increased few cracks were initiated, accompanied by starting of inelastic range in the load-slip curve. When peak load was reached, many microcracks were present, as shown in Figure 7. In some cases, a dominant crack was initiated, but diffused into many microcracks (μ crack width = 42 ± 20 μm) due to the ductile nature of ECC in tension. Since the ECC near the stud head developed a large microcrack zone, and the bearing side resisted the compressive force well, the ECC load-slip curve showed a large inelastic range (Figs 8b, c). The large slip capacity revealed in the ECC specimens indicates the feasibility of engaging adjacent shear studs in carrying the shear load and improving the composite action between steel girder and concrete bridge deck.

Except for one specimen, which prematurely failed with a fracture of the stud welds, ECC specimens failed due to yielding and large deformation of the shear studs. This indicates that the use of ECC allows for "plastic yielding" of the matrix material, resulting in large deformation of the shear stud, and finally a shift of the failure from the matrix to the steel stud.

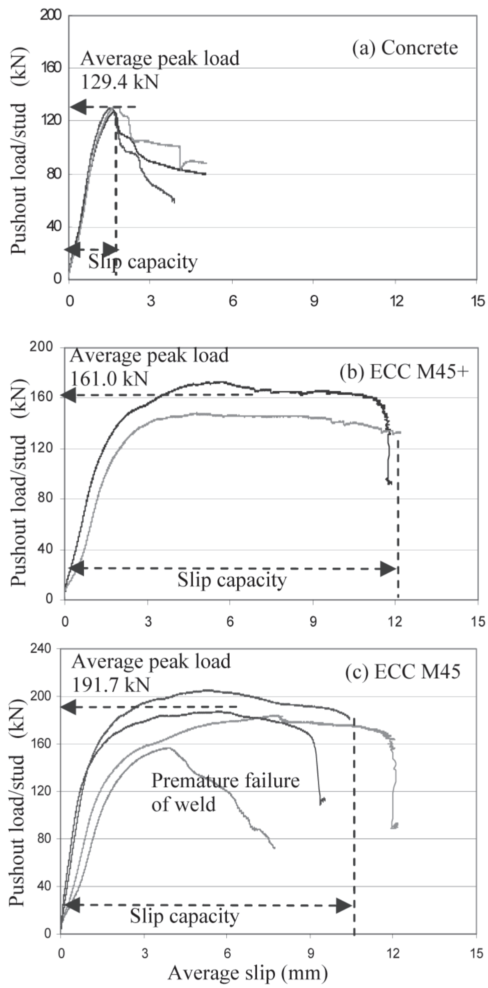

Figure 8. Comparison of pushout load per stud–average slip curves for specimens made of (a) concrete; (b) ECC M45+; and (c) ECC M45

3.2 *Load carrying capacity of stud shear connection*

According to the AASHTO LRFD code (developed based on the test results of Ollgard et al. 1971), the ultimate strength of a concrete/stud connection is as follows:

$$Q_n = \min \begin{cases} 0.5 A_{sc} \sqrt{f_c' E_c} & \text{(Concrete failure)} \\ A_{sc} F_u & \text{(Steel stud failure)} \end{cases} \qquad (1)$$

where A_{sc} = cross-sectional area of a stud shear connector (283.5mm^2); f'_c = specified 28-day compressive strength of concrete (MPa); E_c = elastic modulus of concrete (MPa); and F_u = manufacturer specified minimum tensile strength of a stud shear connector (414MPa).

Table 2 shows the ultimate strength of a shear stud in the matrix, calculated assuming the validity of AASHTO LRFD code for both concrete and ECC and using the E_c and f'_c values in Table 1. The measured strength and slip capacity of the stud connection are also shown. In these experiments, A_{sc} = 283.5mm^2, which gives $A_{sc}F_u$ = 117.4kN. Both computed values of Q_n from Equation 1 are included in Table 2. The lower value of 117.4kN appears significantly below those of the measured values, probably a result of using over-conservative value of F_u. Therefore, only the higher value of Q_n will be discussed in this study. The measured strength per stud in concrete is 129.4kN, within 8% of the calculated value of 139.7kN. Considering the influence of reinforcements in concrete, which shows a load carrying capacity increase of approximately 6% (An et al. 1996) over plain concrete, the measured strength per stud can then be up to 137.2 kN. This value agrees well with calculated one, which is as expected since the specimen setup used in this study is similar to the pushout tests performed by Ollgard et al. (1971). In both tests, the brittle fracture of concrete was the dominant factor controlling the peak load.

Table 2. Calculated/measured strength per stud and slip capacity in concrete and ECC pushout specimens

Material	Q_n kN	Q_m kN	S_c mm
Concrete	139.7/117.4	129.4	1.8
M45+	134.1/117.4	161.0	12.2
M45	155.2/117.4	191.7	10.4

(* Assumed value; Q_n: Computed strength per stud; Q_m: Measured strength per stud; Sc: Slip capacity)

From the test results of ECC (Figs 8b,c), the measured strength of a stud in M45+ and M45 are about 161.0 kN and 191.7 kN, approximately 20% and 23% higher than the calculated values, respectively. Interestingly, the measured strength of ECC M45+ is around 25% higher than that of concrete while according to Equation 1 both should have about the same ultimate strength. This is mainly due to the fact that the compressive strength, a main contributing factor in AASHTO LRFD code for design of studs in concrete, is not necessarily relevant to the failure of ECC pushout specimens. Instead, the initial high stress concentration induced by the stud/ECC interaction caused "yielding" of the ECC and stress redistribution, leading to a higher load capacity of the ECC specimens. Therefore, the direct adoption of AASHTO LRFD code for ECC material is not suitable. Furthermore, the greatly enhanced ductility of ECC/stud shear connection needs to be addressed in the design procedure if ECC were to be used in the shear connection. All of these issues will be discussed in a comprehensive follow-up paper.

4 CONCLUSIONS

The failure mode, ductility (slip capacity) and ultimate strength of stud shear connection in ECC pushout specimens were found significantly enhanced when compared to those of concrete. 600% increase in slip capacity and 25% increase in ultimate strength were achieved. While concrete pushout specimens failed by brittle fracture failure associated with a lower ultimate strength, the ECC pushout specimens were gradually damaged by ductile "yielding" of ECC material and plastic deformation of steel stud, resulting in a higher load carrying capacity. This phenomenon is due to the ductile nature of ECC material which ensure a shift of failure mode from brittle matrix fracture to ductile matrix/steel yielding. This significant enhancement of ductility suggests that the use of ECC material can be effective in redistributing loads among the shear studs and in improving composite action between steel girder and concrete bridge deck.

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