Journal of Southeast University (English Edition) Vol. 28, No. 2, pp. 190 - 194 June 2012 ISSN 1003—7985

Fracture suppression at steel/concrete connection zones by ECC

Qian Shunzhi

(School of Transportation, Southeast University, Nanjing 210096, China)

Abstract: In order to avoid brittle fracture failure, a ductile engineered cementitious composite (ECC) was attempted in steel/concrete connection zones to replace normal concrete. The influence of the ECC material ductility on connection failure modes and structural performance was investigated via the pushout test of stud/ECC connection, the pullout test of two-dimensional anchor bolt/ECC connection and the finite element modeling (FEM). The experimental results suggest that the micromechanically designed ECC with a tensile ductility 300 times that of normal concrete switches the brittle fracture failure mode to a ductile one in steel connection zones. This modification in material behavior leads to higher load carrying capacity and structural ductility, which is also confirmed in FEM investigation. The enhancement in structural response through material ductility engineering is expected to be applicable to a wide range of engineering structures where steel and concrete come into contact.

Key words: engineered cementitious composite (ECC); material ductility; steel/concrete interaction zones; fracture suppression

doi: 10.3969/j. issn. 1003 - 7985. 2012. 02. 011

Fracture of concrete is a dominant failure mechanism when steel and concrete interact mechanically. In a wide variety of structures, such as connections involving steel studs embedded in concrete in composite beam structures, or in hybrid steel/concrete structures involving steel beams which penetrate into concrete columns, steel and concrete must interact with each other when the structure is loaded. Due to the high stiffness of steel and the brittleness of concrete, failure usually occurs in concrete in the form of fractures. A large number of RILEM round robin tests of steel anchor bolt pullout from concrete[1] demonstrate experimentally and numerically that concrete fracture is the governing failure mode and that the anchor capacity is controlled by the material toughness rather than the compressive strength. In the 1995 Kobe earthquake, for instance, it was observed that failure of an exposed column base was due to the fracture of the surrounding concrete near the steel bolts[2]. Other examples involving concrete fracture in steel/concrete interaction zones include severe concrete spalling in RC column-to-steel beam (RCS) connections due to the high bearing stress of the steel beam on concrete[3-4] and concrete cracking in the anchorage zone due to the transfer of prestressing forces through a steel anchorage device[5]. In the aforementioned scenarios, fracture failure of the brittle concrete at the steel/concrete interaction zones clearly compromises the safety of the structures.

A ductilized concrete material, named engineered cementitious composite (ECC)[6], offers a potential material solution to steel/concrete interaction problems. The ECC exhibits a tensile strain capacity in the range of 3% to 6% (300 to 600 times that of normal concrete or FRC)[7-8]. It attains high ductility with relatively low fiber content (2% or less of short randomly oriented fibers) via systematic tailoring of the fiber, matrix and interface properties, guided by micromechanics principles. Associated with its high ductility in tension and shear[9], the ECC reveals a high damage tolerant behavior under severe stress concentration induced by steel/concrete interaction in a number of recent experiments, such as the ECC panel shear-joint test[10], the RCS connection (with the ECC in the joint zone) test[4] and the precast infill panel (made with ECC) test[11]. These tests suggest the feasibility of adopting ECC in the steel/concrete interaction zone to avoid fracture failure, thus leading to significant improvements in the overall structural response.

A number of recent experiments[4, 10, 12] involving the use of ECC in structural elements show significant delay or elimination of fracture localization in ECC in the interaction zones, leading to enhanced structural capacity and ductility as well as post-loading structural integrity. These experiments provide important insights into the behavior of ECC, especially, when compared with that of normal concrete in the high stress concentration regions induced by the interaction between steel and concrete materials. An example of steel/ECC interaction is afforded by a shear-joint test conducted by Kanda et al[10]. In this test, panels made with ECC and jointed together with steel bolts were loaded in shear. While the joints suffer microcrack damage in the ECC panels, connected fractures are revealed in the control test of similarly jointed

Received 2011-12-29.

Biography: Qian Shunzhi (1976—), male, doctor, professor, sqian@seu. edu. cn.

Foundation items: The National Natural Science Foundation of China (No. 51008071), the Natural Science Foundation fo Jiangsu Province (No. BK2010413), Teaching & Research Excellence Grant for Young Faculty Members at Southeast University, the US National Science Foundation (No. CMS-0223971, CMS-0329416).

Citation: Qian Shunzhi. Fracture suppression at steel/concrete connection zones by ECC[J]. Journal of Southeast University (English Edition), 2012, 28(2): 190 - 194. [doi: 10.3969/j. issn. 1003 - 7985. 2012. 02. 011]

concrete panels. The high stress induced by the steel bolts on the ECC is clearly diffused by distributed microcrack damage so that fracture localization is completely suppressed, resulting in a 100% increase in the joint load capacity.

Observations of the influence of concrete material ductility on the structural response of the steel/concrete connections, highlighted above, strongly support the contention that material tensile ductility can be very effective in enhancing the performance of structures governed by critical connections involving steel/concrete interactions. This significant improvement in structural response is achieved by switching the failure mode from brittle fracture in concrete to ductile microcracking damage in ECC. Specifically, in the proposed study ECC will replace the concrete in steel/concrete interaction zones to investigate the feasibility of using material ductility in ECC to suppress concrete fracture failure via two case studies, i. e., the shear behavior of steel stud/ECC connection and the pullout behavior of 2D anchor bolt/ECC connection. This proposed approach exploits the ultra-ductile property of ECC, without relying on external confinement, heavy steel reinforcements and/or other measures. It is expected that this approach is applicable to broad classes of steel/concrete interaction problems, and potentially more reliable and cost effective compared with current approaches.

1 Experimental Program

1.1 Materials

The concrete materials used in this study are shown in Tab. 1, where concrete 1 and ECC 1 are used in the steel stud/ECC connection pushout test and concrete 2 and ECC 2 are used in the 2D anchor bolt/ECC connection pullout test. By the uniaxial tension test, ECC 1 and ECC 2 show a strain capacity around 2.5% and 1% at 28 d, respectively. The moduli of elasticity of Concrete 1 and ECC 1 are measured by the compression test of cylinder specimens. It is worth mentioning that the modulus measured from both the compression test and the uniaxial tension test of ECC specimens agree well. The shear studs used in this test are made from Grade 1018 cold drawn bars, conforming to AASHTO M169 (ASTM A108) Standard Specification for Steel Bars, Carbon, Cold-Finished, Standard Quality. The tensile strength of studs is measured to be 635 MPa. In Tab. 1, f_c' stands for the compressive strength; E_c stands for the modulus of elasticity; ε_u stands for the uniaxial tensile strain capacity; the subcript C stands for type I Portland cement; S stands for silica sand F110 for ECC1 and ECC2, ASTM C778 sand for concrete 1 and concrete 2; CA stands for coarse aggregate with max size 19 mm; FA means type F fly ash; W means water and SP means superplasticizer.

Tab. 1 Mix proportion of different concrete materials kg/m^3

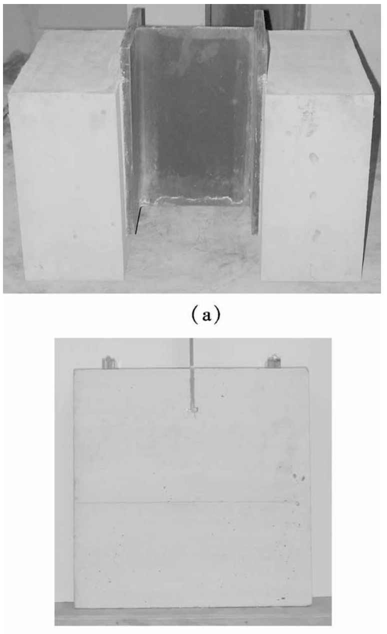
Material	f_c'/MPa	E_c/GPa	ε_u/%	ρ_C	ρ_S	ρ_{CA}	ρ_{FA}	ρ_W	ρ_{SP}	ρ_{Fiber}
Concrete 1	52.3 ±3.6	28.6 ±1.8	0.01	606	788	788	0	218	6	0
ECC 1	60.0 ±2.1	18.1 ±1.4	2.5	560	448	0	672	297	17	26
Concrete 2	45.6 ±1.0		0.01	372	930	930	0	167	3.7	0
ECC 2	41.7 ±0.5		1.0	560	448	0	672	336	17	26

1.2 Preparation of specimens and testing

The geometry of the pushout specimen is shown in Fig. 1(a). Two substrate slabs, with a dimension of 305 mm × 305 mm × 152 mm, are connected with a wide flange steel beam W8 ×40 with two shear studs welded on each side of the beam. The geometry is adopted from Ref. [13]. During casting, the material is poured from the top of the specimen. Therefore, the steel beam remains 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 3D state.

The ECC specimens are cured in air, and the concrete specimens are cured in water for 28 d. Totally, 5 pushout specimens are tested, including two specimens for concrete 1 and three specimens for ECC 1. Testing is conducted on a 2 200 kN capacity Instron testing machine. Four LVDTs are mounted on the steel beam at the level of the shear studs to measure the slip between the beam and the concrete/ECC slabs. The loading surface is ground for uniform load distribution before testing, and a ball support is used to maintain the alignment of the specimens.

A 2D anchor bolt/ECC pullout specimen is revealed in Fig. 1(b), which is adopted from the RILEM round robin test[1]. The steel anchor bolt is embedded in a thin ECC slab, with an area of 300 mm × 300 mm and a thickness of 50 mm. The 2D anchor bolt/ECC connection pullout test provides an opportunity for direct observation of damage evolution. In each series (concrete and ECCs) three specimens are tested. The loading is applied by an MTS 810 material testing system. The pullout displacement of the anchor bolt is measured by averaging the results of two LVDTs on both sides of the specimen. The curing conditions for ECC and concrete specimens are the same as stated above in the pushout test.



(a)

(b)

Fig. 1 Geometry of steel/ECC connection specimens. (a) Pushout specimen; (b) Pullout specimen

2 Results and Discussion

2.1 Failure mode

The failure mode of steel/ECC connections is significantly improved when compared with concrete ones due to the high tensile ductility of the ECC. It switches from brittle fracture in the concrete specimen to the steel yielding for the pushout tests and/or multiple microcracking of the ECC (in both cases) in ECC specimens.

ECC pushout specimens show a ductile failure mode due to their extreme tensile ductility. During the initial loading stage, no cracks can be observed from the specimen surfaces. As the load increases, a few microcracks appear, accompanied by the beginning of an inelastic range in the load-slip curve. When the peak load is reached, more microcracks radiate from the shear stud and develop outwards. In some cases, a dominant crack appears, but rapidly diffuses into many microcracks (microcrack width is (42 ± 20) μm). The final failure in the ECC specimens is associated with fracturing of the stud shank near the welds, after the stud shank undergoes large plastic deformation in bending.

Conversely, in concrete pushout tests, as loading approaches the peak value, large cracks (crack width about 2 mm) form in the concrete near the shear studs and develop rapidly throughout the entire specimen as the peak load is reached. Eventually, concrete specimens fracture into several pieces after testing, with fracture clearly initiated from near the head of the shear studs. The high stress concentration induced by the stiff steel stud combined with the brittle nature of the concrete leads to the rapid development of macro cracks, resulting in the catastrophic failure of the concrete pushout specimens.

Similarly, the failure mode of 2D anchor bolt/ECC pullout specimens is much more ductile than the corresponding concrete ones. As indicated in Fig. 2, the microcracks with a microcrack width of (57 ± 33) μm in ECC initiate from the head of the anchor bolt and then diffuse and grow in both number and length with the increasing pullout load, towards the supporting points. Ultimately, as the tensile strain capacity of ECC material is exhausted, one of the microcracks localizes and eventually leads to the final failure of the ECC pullout specimens. It is interesting to note that the final failure crack is away from the head of the anchor bolt. In contrast, the concrete pullout specimen fails in a very brittle fracture manner (see Fig. 3) with fracture initiated directly from the edge of the anchor bolt head, resulting in a much lower load capacity and structural ductility in comparison with the ECC specimen. This observation demonstrates the ability of the ECC to redistribute the initial highly concentrated stress near the head through a microcrack damage process.

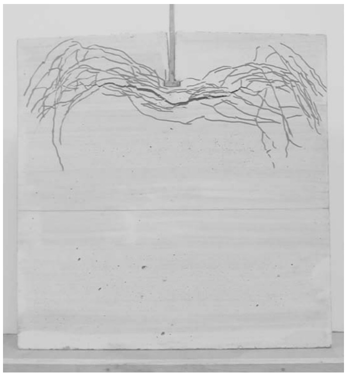


Fig. 2 ECC pullout specimen after test showing ductile multiple cracking behavior

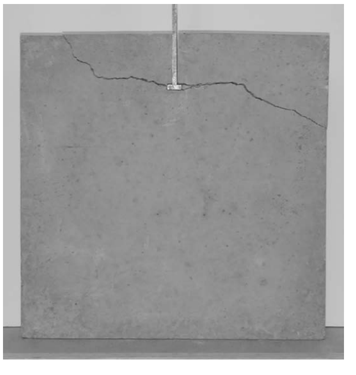


Fig. 3 Concrete pullout specimen after test showing brittle fracture failure mode

2.2 Structural response

Closely related to its superior ductility in tension, the structural performance of the steel/ECC connection specimens is greatly enhanced compared with steel/concrete specimens in terms of load capacity and structural ductility, in addition to its much improved failure mode described above. It should be noted that both materials have about the same compressive strength. This suggests that the material ductility in ECC plays a more significant role than the compressive strength in improving the structural response of the steel/ECC connections.

Tab. 2 shows the measured load per stud as a function of slip for pushout specimens. The measured strength Q_m, the slip capacity S_c and the crack width w_c clearly demonstrate the superior structural response of the stud/ECC connection. The ECC specimens show on average 53% higher strength and a 220% increase in slip capacity, in comparison with the concrete specimens.

Tab. 2 Material properties and structural behavior of concrete and ECC pushout specimens

Material	ε_u/%	f'_c/MPa	E_c/GPa	Q_m/kN	S_c/mm	w_c/μm
Concrete 1	0.01	52.3 ±3.6	28.6 ±1.8	125.5 ±5.4	2.0 ±0.2	~2 000
ECC 1	2.5 ±0.3	60.0 ±2.1	18.1 ±1.4	192.3 ±11.7	6.4 ±1.3	42 ±20

Similarly, the results from the anchor bolt/ECC connection pullout test show greatly enhanced structural response compared with the anchor bolt/concrete connection pullout test (see Fig. 4). The average pullout load capacity and the displacement (structural ductility) of the anchor bolt/ECC connection are 18.5 kN and 1.1 mm, respectively, about twice and 16 times respectively those of the concrete specimens (9.5 kN and 0.07 mm). It should be noted that both ECC and concrete have about the same compressive strength (see Tab. 1). Again, this reveals that compressive strength, as a traditional measurement of concrete material quality, is not necessarily relevant to the structural capacity when it comes to critical steel/concrete connections since it is the fracture failure of concrete that governs the structural capacity.

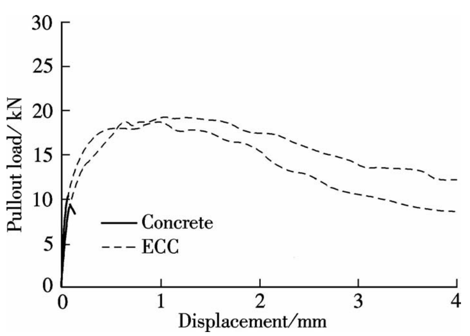


Fig. 4 Relationship of pullout load and displacement for ECC and concrete

2.3 Comparison with simulation results

As mentioned earlier, the 2D anchor pullout experimental results are employed for benchmark verification of the anchor pullout FEM model before parametric studies are executed for a broader material properties variation. For all materials, the compressive strength is 40 MPa. For ECCs, the first cracking strength is 4 MPa; the ultimate tensile strength is 4.8 MP; the modulus of elasticity is 16 GPa; the crack opening displacement (COD) is 6 mm. For concrete, the modulus of elasticity is 25 GPa and the COD is 0.062 5 mm. The detailed verification and parametric studies for the 2D anchor pullout test can be seen in Ref. [14]. A brief summary of these parametric studies[14] is presented here for comparison purposes.

The influence of material tensile ductility on the anchor pullout behavior is shown in Fig. 5. Both the ECCs with 2% and 4% strain capacity show that the load capacity is more than twice that of concrete. Accordingly, the ultimate pullout displacement (also displacement capacity: the displacement corresponding to the peak load) for ECCs is about an order of magnitude higher compared with that of concrete. From strain capacity 2% to 4%, the displacement capacity of ECC also increases significantly. Comparison between Figs. 4 and 5 suggest that the FEM simulation can capture the trends observed in experiments. Furthermore, the simulation results confirm that the material tensile ductility is the governing factor to switching the structural failure mode and greatly enhancing the structural performance.

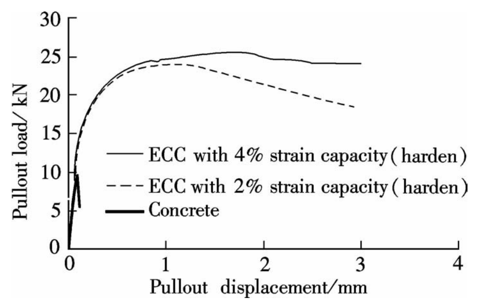


Fig. 5 Influence of material ductility on the anchor pullout response[14]

It is interesting to note that the load capacities for these ECCs are not significantly different even though their strain capacities differ by a factor of two. It is, therefore, expected that the influence of tensile strain capacity on the anchor pullout load is a highly nonlinear relationship. The relationship of pullout load with material tensile ductility is shown in Fig. 6, where the x-axis is shown in logarithmic scale. Therefore, the linear line in Fig. 6 reveals a logarithmic relationship between the anchor pullout load and the tensile strain capacity. When the ECC tensile ductility ranges from 2% to 4%, the anchor pullout load can be practically regarded as unchanged.

3 Conclusion

A new approach and material solution, i. e., exploiting

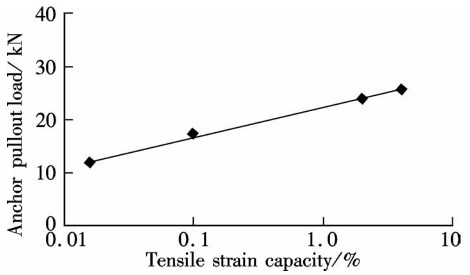


Fig. 6 Relationship of anchor pullout load capacity and tensile strain capacity [14]

ECC tensile ductility to suppress concrete material fracture failure in steel/concrete interaction zones, is proposed and experimentally demonstrated through two sets of representative steel/ECC connection tests. Significant delay or elimination of fracture localization due to high stress concentration can be achieved via extensive inelastic straining offered by the ECC, resulting in much improved structural performance in terms of load capacity and structural ductility. This material-based solution to concrete fracture problems is expected to be applicable to broad classes of structural applications involving critical steel/concrete connections. Material ductility needs to be considered in the design procedure for better prediction of structural performance of such critical connections made with ECC.

References

[1] Elfgren L. Round robin analysis and tests of anchor bolts in concrete structures. TC 90-FMA [R]. Bagneux: RILEM Publication, 1998.

[2] Architectural Institute of Japan and Japan Society of Civil Engineers. Records of the 1995 great Hanshin-Awaji earthquake disaster [R]. AIJ/JSCE, 1995. (in Japanese)

[3] Sheikh T M, Deierlein G G. Beam-column moment connections for composite frames: Part 1 [J]. *Journal of Structural Engineering*, 1989, **115**(11): 2858 - 2876.

[4] Parra-Montesinos G, Wight J K. Seismic response of exterior RC column-to-steel beam connections [J]. *Journal of Structural Engineering*, 2000, **126**(10): 1113 - 1121.

[5] Breen J E, Burdet O, Roberts C, et al. Anchorage zone reinforcement for post-tensioned concrete girders. NCHRP 356[R]. Washington: National Cooperative Highway Research Program, 1994.

[6] Li V C. From micromechanics to structural engineering—the design of cementitious composites for civil engineering applications[J]. *JSCE Journal of Structural Engineering and Earthquake Engineering*, 1993, **10**(2): 37 - 48.

[7] Li V C, Kanda T. Engineered cementitious composites for structural applications [J]. *Journal of Materials in Civil Engineering,* 1998, **10**(2): 66 - 69.

[8] Li V C, Wang S, Wu C. Tensile strain-hardening behavior of PVA-ECC[J]. *ACI Materials Journal,* 2001, **98**(6): 483 - 492.

[9] Li V C, Mishra D K, Naaman A E, et al. On the shear behavior of engineered cementitious composites[J]. *Journal of Advanced Cement Based Materials,* 1994, **1**(3): 142 - 149.

[10] Kanda T, Watanabe W, Li V C. Application of pseudo strain hardening cementitious composites to shear resistant structural elements [C]//*Proceedings FRAMCOS*-3. Freiburg, Germany: AEDIFICATIO Publishers, 1998: 1477 - 1490.

[11] Kesner K E, Billington S L. Experimental response of precast infill panels made with DFRCC[C]//*Proceedings of JCI Workshop on DFRCC.* Takayama, Japan, 2002: 289 - 298.

[12] Fukuyama H, Matsuzaki Y, Nakano K, et al. Structural performance of beam elements with PVA-ECC[C]//*Proceedings of High Performance Fiber Reinforced Cement Composites* 3 (HPFRCC 3). Ann Arbor, MI, USA, 1999: 531 - 542.

[13] Ollgaard J G, Slutter R G, Fisher J W. Shear strength of stud connectors in lightweight and normal-weight concrete [J]. *AISC Engineering Journal,* 1971, **8**(2): 55 - 64.

[14] Qian S, Li V C. Headed anchor/engineered cementitious composites (ECC) pullout behavior[J]. *Journal of Advanced Concrete Technology,* 2011, **9**(3): 339 - 351.

利用高延性水泥基材料抑制钢/混凝土连接区域的断裂破坏

钱吮智

(东南大学交通学院,南京 210096)

摘要:为了避免混凝土的脆性断裂破坏,在钢/混凝土连接区域中用高延性水泥基材料(ECC)代替了普通混凝土.采用剪力键/ECC 的抗剪试验、二维锚固螺栓/ECC 拔出试验和有限元模拟研究了 ECC 材料的延性对于连接区域破坏模式、结构性能的影响. 实验结果表明:通过微观力学原理设计的 ECC 具有 300 倍于普通混凝土的拉伸延性,从而使钢/混凝土连接区中混凝土断裂破坏模式由脆性转变为延性.混凝土材料的高延性使结构承载能力和变形性能获得改善,这也同时为有限元模拟结果所验证.通过改变混凝土材料延性而提高结构性能的理念也可在其他类似的钢/混凝土组合结构中得到应用.

关键词:高延性水泥基复合材料;材料延性;钢/混凝土相互作用区;断裂抑制

中图分类号:U444