# Trapping mechanism of interface crack at concrete/engineered cementitious composite bimaterial interface

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ABSTRACT: This paper reports on an interfacial crack trapping mechanism experimentally observed in a concrete/Engineered Cementitious Composite system. The mechanism involves cycles of interfacial crack extension, kinking of this interfacial crack into the ECC, and kinked crack arrest. During this process, the macroscopic load capacity continues to increase, allowing for high strength and ductile characteristics of this bi-material system.

## 1 INTRODUCTION

Bimaterial systems can be found in many engineered devices and structures, including thin film/substrate systems for electronic device, coated systems for mechanical devices, and layered composites for many structural applications (Hsueh and Evans 1985; Evans et al. 1990). In these bimaterial systems, the interface between the two different materials is usually the weakest part and fracture failure initiated from an interfacial defect is often observed. Thus extensive research on the mechanics of interfacial failure has been conducted (e.g. Suo and Hutchinson 1989; Cao and Evans 1989; Charalambides et al. 1989; Wang and Suo 1990). Two distinct fracture behavior, interfacial fracture and kink out fracture are typically identified. Analytic tools for evaluation of whether an interfacial defect will advance straight ahead or kink out of the interface have been developed.

In a recent study, intermittent interface crack propagation and kink-out was observed in a cementitious bi-material system in connection with investigations on durability of concrete repair (Lim 1996). In this paper, we report on this *interface crack trapping mechanism*. The concept of the interface crack trapping mechanism is discussed below. This is followed by a presentation of the experimental observations in a bimaterial system containing a normal concrete and an Engineered Cementitious Composite (ECC) (Li, 1996).

## 2 CONCEPT OF TRAPPING MECHANISM

When a bimaterial system is subject to applied load, the relative driving force in terms of energy release rates $\frac{G}{G^t_{\max}}$ for in-plane extension to out-of-plane kinking of an interfacial crack can be analytically determined (Suo and Hutchinson 1989), assuming small scale yielding condition. A crack at the interface between two cementitious materials may satisfy this small scale yielding condition. There is no aggregate interlocking nor fiber bridging across the interface so that a small process zone relative to other body geometry, associated with break down of cement paste material, can be expected. The relative toughness $\frac{\Gamma(\hat{\psi})}{\Gamma_c}$ between the interface and the material into which the kink crack propagates (labeled as material #2 in this paper for convenience) should be evaluated experimentally. The condition for kinking has been expressed in terms of these relative driving force and relative toughness.

$$\frac{G}{G^{t}_{\max}} < \frac{\Gamma(\hat{\psi})}{\Gamma_c} \tag{1}$$

Figure 1 plots these relative quantities schematically. As expected from Eqn. (1), low phase angle (low Mode II to Mode I loading) leads to low values of $\Gamma(\hat{\psi})$, which promotes in-plane interfacial crack extension. Conversely, high phase angle promotes kinking.

Consider a bimaterial system which possesses varying levels of $\Gamma_c$, and therefore $\frac{\Gamma(\hat{\psi})}{\Gamma_c}$. This is possible if, e.g., Material 2 has an R-curve behavior, with low initial toughness which rises with the extension of the kinked crack. This scenario together with the corresponding crack propagation patterns are illustrated in Figure 1, with two levels of $\frac{\Gamma(\hat{\psi})}{\Gamma_c}$ indicated (labeled as Low and High $\Gamma_c$ curves).

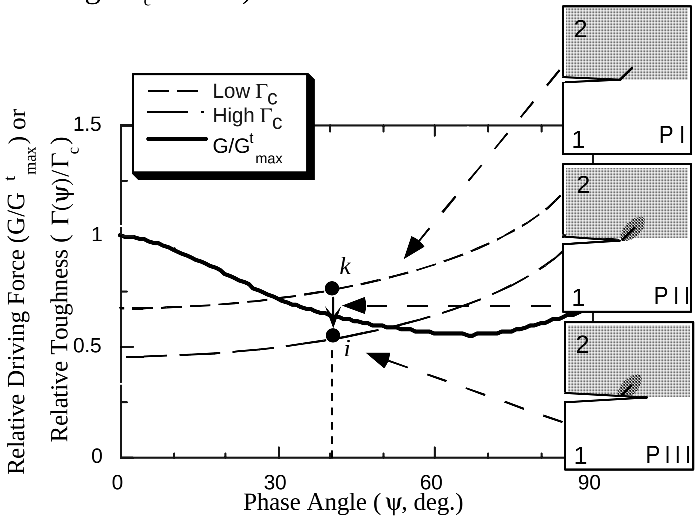


Figure 1: Possible patterns of interface cracking and kinking behavior

The initial low toughness in Material 2 (shaded in Figure 1) attracts the interfacial crack to kink (phase angle around 40 degrees, condition k, Pattern PI). Subsequent rise of the toughness associated with development of a process zone in Material 2 then arrests the kink-out crack (Pattern PII). As the $\frac{\Gamma(\hat{\psi})}{\Gamma_c}$ curve shifts down because of the rising $\Gamma_c$, the kinking condition (Eqn. (1)) is no longer satisfied, and interfacial in-plane crack extension then prevails (condition i, Pattern PIII).

In Figure 2, the conceptual trapping mechanism described above is illustrated together with the load-displacement relation. After the kinked crack is arrested and propagation is forced back into the interface, the relative toughness curve (Figure 1) can move back upward again as the interface crack moves out of the regime of the first damage process zone. Under this new condition, the propagated interface crack can kink out from the interface again. Thus, the sequence of kinking, damaging, trapping, and interface propagation will be repeated under continued increase loading until the full interface is exhausted or other failure modes take over.

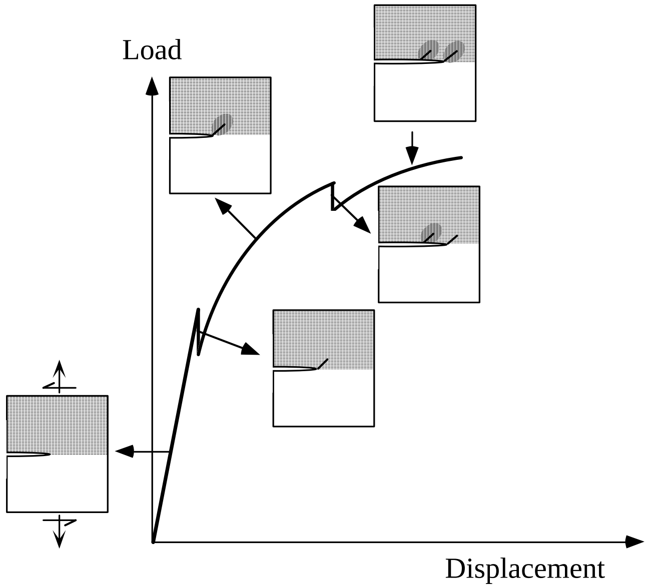


Figure 2: Trapping mechanism in a bimaterial interface system

The conceptual interface crack trapping behavior is motivated by the consideration of interface fracture mechanics. Such a failure process is desirable as it is expected to involve a large amount of energy absorption associated with sub-interface damage in a bimaterial system. The ECC material is a fiber reinforced mortar micromechanically tailored to exhibit high damage tolerance (Li and Hashida, 1993; Li, 1997).

## 3 EXPERIMENTAL PROGRAM

Besides the concrete/ECC bimaterial system, two additional systems were tested as control. All involve concrete as Material 1, while the two control systems have concrete and regular fiber reinforced concrete as Material 2.

The material compositions are tabulated in Table 1. The concrete (material #1) was five weeks old when the other material (material #2) was cast on it. The bimaterial system had two weeks curing before testing. The material properties and Dundar's elastic mismatch parameters are reported in Table 2. The difference of elastic modulus between base concrete (material 1) and concrete for material #2 is due to differences in their age of curing.

Table 1: Material composition

| Material | Cement | Water | FA | CA | SF | SP | Fiber† |
|---|---|---|---|---|---|---|---|
| Concrete | 1.0 | 0.5 | 2.27 | 1.8 | - | - | - |
| FRC | 1.0 | 0.5 | 2.27 | 1.8 | - | - | 0.01 (steel) |
| ECC | 1.0 | 0.35 | 0.5 | - | 0.1 | 0.01 | 0.02 (poly ethylene) |

(FA: Fine Aggregate, CA: Coarse Aggregate (maximum size < 9.5 mm), SF: Silica Fume, SP: Superplasticizer, †: Volume fraction)

Table 2: Elastic Modulus and Dundar's elastic mismatch parameter $\alpha$

| Material | Elastic Modulus (GPa) | $\alpha$ |
|---|---|---|
| Base Concrete | 25.8 | - |
| Concrete | 24.9 | 0.018 |
| FRC | 26.1 | -0.005 |
| ECC | 18.0 | 0.178 |

Figure 3 shows the loading configuration and the dimensions of the designed specimen. This specimen include an initial defect in the form of an interfacial crack between the base material and the material #2 as well as a joint in the base material. These specimens can provide stable interface crack propagation condition under this loading configuration (Charalambides et al. 1989). The phase angle of this specimens is about 41˚~45˚.

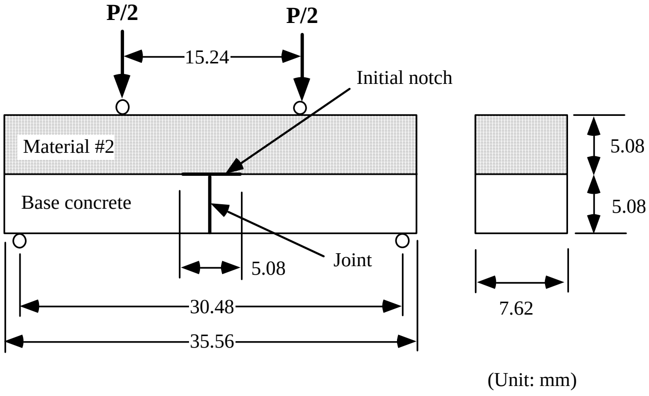
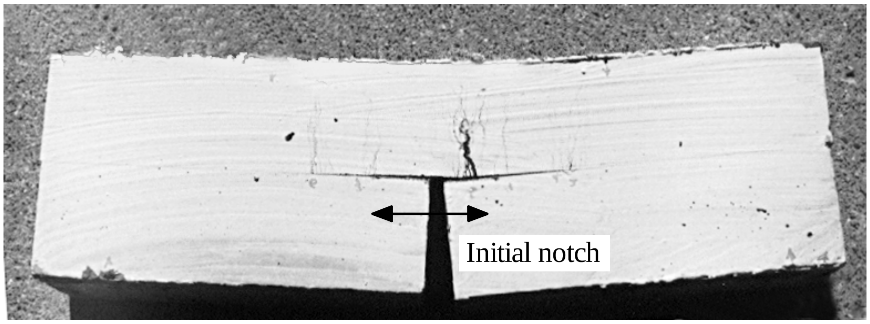


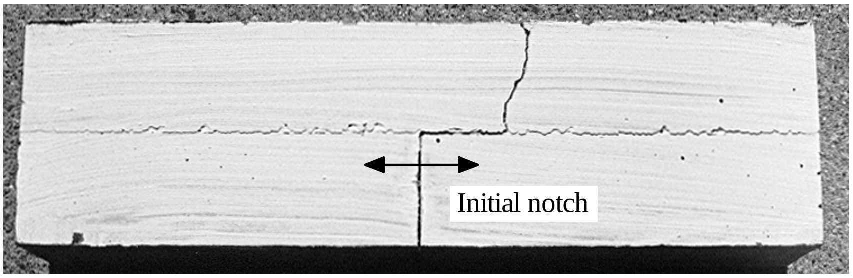
Figure 3: Loading configuration and dimensions of designed specimen

## 4 EXPERIMENTAL RESULTS

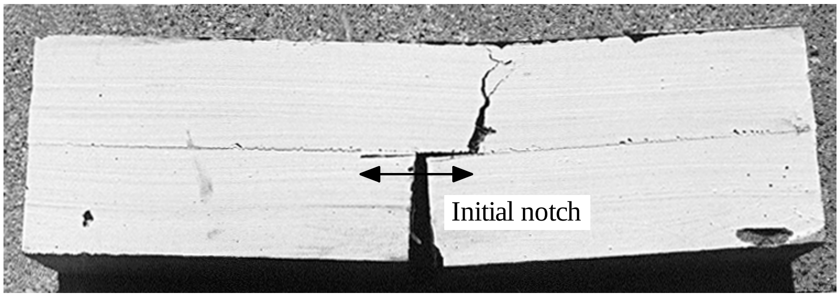
As expected, the concrete/ECC bimaterial system shows the distinctive trapping mechanism under this experimental condition. The failure process with trapping mechanism shows tremendous differences compared with those of the control specimens (Figure 4). In the concrete/ECC system, the initial interface crack propagated along the interface about 5 mm, followed by kinking out from the interface. Subsequently, the kinked crack appeared trapped inside the ECC and the mother crack (interface crack) propagated along the interface again (about 27 mm). Then, the interface crack kinked and was trapped again. After several cracking and kinking, the final failure occurred due to the large opening of a flexural crack in the middle of the specimen.



(a) Concrete/ECC system



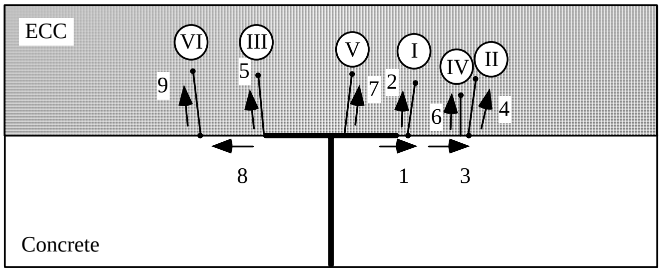
(b) Concrete/Concrete system (reassembled after test)



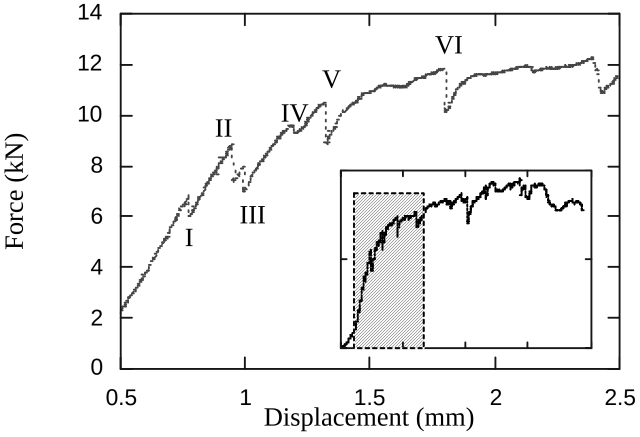
(c) Concrete/FRC system

Figure 4: Cracking in specimens

The sequence of cracking behavior for one of the two tested concrete/ECC bimaterial system is illustrated in Figure 5(a). The arrows and the number beside the arrow indicate the direction of crack propagation and the time sequence of cracking. The load drop associated with the kinked cracks (numbered by Roman numerals) are illustrated in Figure 5(b), which shows the load-deflection curve of one of the specimens in the concrete/ECC bimaterial system. The kinked cracks occurred immediately following interface crack propagation. Thus, it is difficult to distinguish between interface cracking and kink cracking in terms of load drops. After the sixth kinked crack (VI) occurred, the bimaterial system failed with flexural crack development in the ECC. All kink cracks emanated from the tip of the current interfacial crack. In contrast, the flexural cracks developed at sites not associated with the interface crack tip.



(a) Sequence of kinked crack development



(b) Load-deflection with kinked sequence

Figure 5: Kinked crack development in concrete/ECC bimaterial system

Both control specimens showed only one macro-crack opening due to the kinked crack at the initial interface crack tip (Figures 4b and 4c). In the concrete/concrete bimaterial system, brittle behavior was observed. Quasi-brittle behavior was observed in the concrete/FRC bimaterial system. This quasi-brittle behavior comes from the fiber bridging, but the bridging effect in the FRC is not enough to create the trapping behavior. The concrete/ECC system shows macroscopic strain-hardening response. These behaviors can clearly be found in the load-deflection curves in Figure 6.

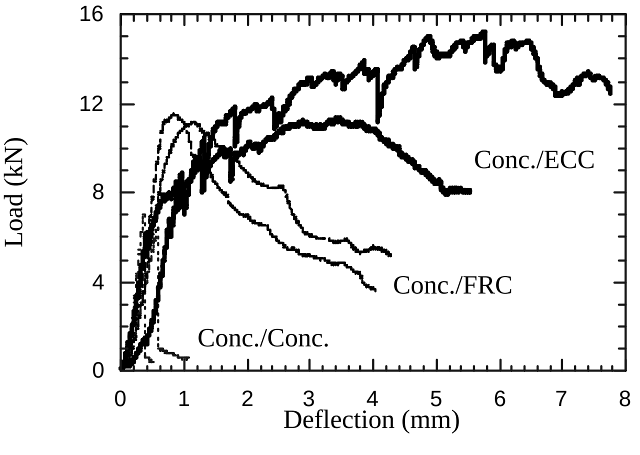


Figure 6: Load-deflection behavior in different bimaterial system

## 5 CONCLUSION

The concept of interface crack trapping mechanism is introduced, and its existence is confirmed in experimental investigations. Among the three bimaterial systems tested, only the concrete/ECC system revealed the trapping behavior. This system shows high ultimate strength and large deflection capacity with large amount of energy absorption. The ultimate failure mode has been shifted from one associated with interface crack extension to one associated with the flexural strength of the ECC. This dramatic improvement in terms of strength, deflection, energy absorption capacity and ultimate failure mode is not feasible without the trapping mechanism.

ECC is characterized by strong fiber bridging property combined with a low cement matrix toughness. The low matrix toughness promotes the satisfaction of the kink condition represented by Eqn. (1), circumventing brittle delamination of the interface. The strong fiber bridging property leads to a rapidly rising R-curve as the kinked crack extends, eventually forcing the cracking behavior back into the interface under continued rising applied load. On a more macroscopic level, the observed crack pattern may also be alternatively interpreted as a result of the strain-hardening characteristics and damage tolerance of the ECC material. The high tensile stress near the interface crack tip causes the ECC to go into strain-hardening, and to accommodate the local strain with microcrack inelastic deformation. In this interpretation, the interface crack never (macroscopically) kinks out, but trapped inside the interface due to an effectively toughened interface. This interpretation implies an interface with R-curve behavior. The damage in the ECC becomes part of the interfacial fracture characteristics. For either interpretation of trapping in interface or in the ECC, improvement in mechanical performance is unequivocally demonstrated to exist in the concrete/ECC bimaterial system. Implications of these findings on the durability of repaired concrete structure using ECC as a repair material are discussed in Lim and Li (1996) and Lim (1996).

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