FINITE ELEMENT ANALYSIS OF TEST CONFIGURATIONS FOR IDENTIFICATION OF INTERFACE PARAMETERS IN LAYERED FRCC SYSTEMS

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Abstract
Modeling and characterization of material interfaces is necessary for design and verification of layered FRCC systems, such as functionally graded structural members. The main objective of the present study is to analyze, by means of numerical simulations, experimental configurations that could be used to identify the mechanical parameters of interfaces. Namely, the shear beam and shear box tests are studied. The results indicate that while the shear beam tests are suitable for identification of the interface strength parameters, they do not provide data necessary for calibration of the post-failure cohesive relationship. The shear box test is not suitable for evaluation of the interface strength parameters as the failure is initiated by localized stress concentration. The post-failure response is governed by sliding of the interface, however even in this phase non-uniformity of the interfacial tractions should be taken into account.

1. INTRODUCTION
Layered systems represent one of areas in which fiber reinforced cementitious composites (FRCC) are being used. For instance, much research has been done on the use of pseudo-ductile FRCC layers for strengthening or repair of concrete or conventionally reinforced concrete elements with the goal of improving their durability and/or load capacity, e.g. [1]. Another example are functionally graded elements, where different fiber content or even fiber type is used in different layers in order to achieve optimal utilization of the material. The authors’ team has been recently working on development of functionally graded structural elements combining high-strength fiber reinforced concrete (HSFRC) and high-ductility strain hardening fiber reinforced cementitious composite (SHCC), where the former material with steel fibers is used for load capacity, while the latter material with polymeric fibers is employed as a durable and corrosion-free coating [2]. In any of these applications, material interfaces between layers are encountered. These interfaces often represent weak links in the system. In the case, when the fresh material is applied onto a hardened substrate, the interfaces become cold joints, which have different properties than either of the interfacing
materials. Even in functionally graded elements produced by fresh-on-fresh layering, the interfaces lack fiber reinforcement and thus are more brittle than the surrounding FRCC.

Appropriate modeling and characterization of the interfaces is thus a prerequisite for a safe design and verification of the layered systems. In the context of the finite element (FE) analysis, the cohesive interface model is often used, in which the interface is idealized as a zero-thickness line (in 2-D), which transfers normal \( t_n \) and tangential \( t_t \) tractions. These tractions are related to the relative normal \( \delta_n \) and tangential \( \delta_t \) displacements on the opposite sides of the interface and internal variables \( \alpha \), which can be introduced to account for inelastic effects

\[
t_n = t_n (\delta_n, \delta_t, \alpha) ; \quad t_t = t_t (\delta_n, \delta_t, \alpha)
\]

A particular interface constitutive law can be formulated in different ways. Needleman [3], for instance, established a unified framework for describing the process of interfacial decohesion based on potential formulation. Other models, which are often used in FE codes, employ the Mohr-Coulomb failure criterion or its variant, together with a post-failure traction-separation laws for tension and shear (e.g. [4]). Either way, the constitutive model needs to be identified using data from suitable experiments. While testing and calibrating the model parameters for the normal direction (mode I) is relatively well established, e.g. [5], evaluation of the tangential (mode II) characteristics is more tricky. The main difficulty consists in configuring the shear test in such a way that the interface stress distribution can be simply related to the applied load and that stable propagation of the decohesion front is achieved.

Against this background, the main objective of the present study is to analyze, by means of numerical simulations, various experimental configurations that could be used to identify the mechanical parameters of interfaces in layered FRCC systems. The optimal setup will be eventually used for physical testing.

2. MATERIAL MODELS

Test configurations are analyzed by means of the finite element method (FEM). The FRCC materials are modeled using the “individual crack based” approach [6], where, even if the material exhibits multiple cracking, cracks are characterized by the traction-separation relationship (as opposed to the stress-strain relation in the “homogenization based approach”). This way, both pseudo-ductile SHCC and quasi-brittle HSFRC materials can be treated in a unified manner, differing only by the shape and parameters of the traction-separation law. Note that, to properly capture multiple cracking, this approach requires that fine FE meshes, with element size corresponding to the minimum crack to crack spacing, are used.

In this study, we analyze layered systems involving HSFRCs with different fiber volume fractions. Table 1 lists the basic material parameters and Figure 1 (a) shows the traction-separation curves. These characteristics have been adopted from an earlier experimental-numerical study [7].

Material interfaces are modeled by zero-thickness interface elements. The constitutive law is defined by the Mohr-Coulomb failure condition

\[
t = c - \phi t_n
\]

where \( c \) is the pure shear strength (cohesion) and \( \phi \) is the friction coefficient. In addition, elliptic cutoff is used in the tension region [4]. Prior to failure, high penalty stiffness \( (K_n, K_t) \)
is used. The post-failure response is brittle with immediate drop to zero in tension and to the residual dry friction in shear, see Figure 1 (b, c).

![Figure 1](image)

**Figure 1:** (a) Traction-separation relations for HSFRC with different fiber volume fractions $V_f$ [7]. Interface material model in tension (b) and shear (c) [4]

It is noted that the material parameters of the interfaces are not exactly known at this stage. Thus, two cases are considered in the numerical experiments. First, the interfaces are assigned artificially high strength, such that the interfaces do not fail and the structural collapse results from cracking elsewhere in the body. This analysis allows us to determine the maximum tractions that can potentially develop at the interfaces for the given configuration. From these results we can estimate the maximum value of interfacial strength that can be identified from the test setup. Secondly, the interfaces are assigned assumed realistic strength (Table 2). These simulations then allow us study the specimen response after interfacial failure takes place. In particular, we investigate whether the propagation of the decohesion front along the interface can be controlled or whether it spreads in an unstable manner. We also analyze the pre- and post-failure stress state and stress distribution at the interface, which is necessary to know if the interfacial traction-separation relation is to be identified from the test.

Table 1: Parameters of material model of high strength fiber reinforced concrete

<table>
<thead>
<tr>
<th>Tensile strength [MPa]</th>
<th>Compressive strength [MPa]</th>
<th>Young’s modulus [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.8</td>
<td>106</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 2: Parameters of interface model

<table>
<thead>
<tr>
<th>Tensile strength $f_t$ [MPa]</th>
<th>Cohesion $c$ [MPa]</th>
<th>Friction coefficient $\phi$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High strength interface</td>
<td>11.8</td>
<td>10.8</td>
</tr>
<tr>
<td>Realistic interface</td>
<td>11.8</td>
<td>10.8</td>
</tr>
</tbody>
</table>

### 3. NUMERICAL EXPERIMENTS

In this section, we discuss numerical simulations of three possible experimental configurations, designed so as to induce shear-dominated failure at material interfaces.

#### 3.1 Ohno shear beam with vertical interface

The first test setup is a variant of the configuration, which was originally used by Arakawa and Ohno [8] to investigate the shear failure in reinforced concrete. It involves a beam, which is loaded in antisymmetric four-point bending (Figure 2) in such a way that the central vertical section sustains only shear force but no bending moment. According to the Bernoulli-Euler...
beam theory, the normal stress at this section is zero and the shear stress has a parabolic distribution with maximum value at the mid-height:

$$\tau_{\text{max}} = \frac{3P}{4A}$$

(3)

where $P$ is the acting load and $A$ is the cross-sectional area.

As seen in Figure 2, the specimen is configured so that the material interface coincides with the central section. The beam is strengthened along the top and bottom surfaces by fiber reinforced polymer (FRP) strips to avoid bending failure. The numerical experiment is controlled by displacement prescribed at the load point of the load-distributing beam; reaction evaluated at this point corresponds to the load $P$.

Figure 2: Finite element model of Ohno shear beam with vertical interface

Rigorously, validity of Eq. (3) is limited to the elastic range and homogeneous cross-section. As we consider cracking in the HSFRC material, applicability of Eq. (3) for estimation of the interfacial stress from the applied load is checked by the FE calculation.

The load-deflection curve calculated by the FE model with non-failing high strength interface is shown in Figure 3 (a). Figure 3 (b) compares the maximum shear traction calculated with Eq. (3) from the load $P$ and that evaluated in the interface element at the center of the specimen. It is seen that Eq. (3) provides an acceptable estimate of the maximum shear traction at the interface. Figure 3 (c) shows that compressive traction develops at the interface during loading, but remains at the level of about 17% of the shear traction up to the peak. Occurrence of this traction indicates that the assumptions of the Bernoulli-Euler beam theory are not strictly satisfied due to high depth to span ratio of the beam. Thus, when estimating interface strength parameters using Eq. (2) from this experiment, it should be taken into account that the central part is not exposed to pure shear but to a combination of shear and compression.

Figure 3(a) also shows the load-displacement diagram predicted with the model where realistic strength of the interface (Table 2) was used. Figure 4 shows that the sudden collapse of the beam is associated with the failure of the interface. The interface cracks in an unstable manner along the entire height of the beam during one loading increment and the beam splits in two parts right after the peak load is reached.

It can be concluded from the simulation that the analyzed Ohno beam configuration can be used to identify parameters of the interface failure condition from the peak load. However, it does not provide any information that could be used to calibrate the post-crack cohesive law of the interface.
3.2 Horizontally layered Ohno shear beam

For the next numerical experiment we consider a horizontally layered Ohno shear beam shown in Figure 5. The dimensions, supports and loading are the same as in the previous example. This configuration represents a more realistic loading conditions that a functionally graded beam could experience in a real structure. We also anticipate that even if the interfaces fail, the beam will not immediately disintegrate and the post-failure behavior can be retrieved.

Figure 5: Finite element model of horizontally layered Ohno shear beam

The load-deflection curve calculated by the FE model with the strong interfaces is shown in Figure 6 (a). Figure 7 shows that the interfaces in the central part sustain a combination of shear and compression. The extreme shear occurs at the center of the specimen on the middle interface, while on the upper and lower interface this location is shifted to the left or right, respectively. Figure 6 (b, c) show the evolution of the maximum shear traction and corresponding normal traction at the interfaces. Up to the load $P$ of about 175 kN, the
Tensions are nearly linearly proportional to the applied load. It is also evident, that all the interfaces sustain almost the same extreme shear, but the middle interface is exposed to lower compression than the other two.

Figure 6: (a) Load-displacement diagram for Ohno shear beam - displacement is measured at the bottom in the middle of the beam. Evolution of the shear (a) and normal (b) traction calculated in the interface elements at points A, B, C marked in Figure 7

Figure 7: Diagram of the shear (a) and normal (b) tractions along interfaces at $P = 154$ kN

Figure 8: Deformed shape and cracks of the beam with realistic interfaces: (a) at the load step before the peak, (b) at the load step after the peak

The load-displacement diagram for the model with realistic strength of the interfaces is also displayed in Figure 6 (a). The sudden drop of the load can be attributed to simultaneous failure of all three interfaces, as seen in Figure 8. However, the interfaces do not fail along the entire length of the beam. The cracks kink into the adjacent layers at the ends of the central part of the beam. After the failure, the beam retains residual load capacity. Further deflection of the interfaces and opening of the kink cracks.

It can be concluded that it is possible to calibrate the interfacial failure condition from the ultimate load for this Ohno beam configuration. However, the post-peak behavior is governed by simultaneous interface sliding and crack growth, and thus the post-failure interface cohesive law cannot be identified from the experimental data.
3.3 Shear box test

Finally, we consider the shear box test shown in Figure 9 (a). The shear box consists of two parts, the lower part is fixed and the upper part is mobile. Constant vertical force $V$ is applied on the top of the box. Horizontal loading is applied by means of increasing horizontal displacement of the upper part – reaction at the load point then corresponds to the horizontal load $H$. A cubic bi-material HSFRC specimen with horizontal interface in the middle is placed in the box. The material interface is weakened by a notch, 10 mm deep, on the loaded (right) side.

The load-displacement curve for the model with realistic interface properties and $V = 50 \text{kN}$ is shown in Figure 10 (a). The response is nearly linear until the peak. The post peak drop corresponds to unstable decohesion of the interface, which instantaneously fails along the entire specimen width, as seen in Figure 9 (b). Subsequent, nearly constant, residual resistance is due to the activation of friction at the interface. Figure 10 (b, c) shows that at the peak load, the tractions exhibit very non-uniform distributions with concentrations near the edges. The interface failure is initiated once the tractions at the right side satisfy the failure condition of Eq. (2). Consequently, at the peak load, the average shear traction ($t_{s, av} = H/A_i = 4.44 \text{MPa}$, where $A_i$ is the interface area) is far lower than the shear strength of 13.02 MPa that would correspond to the average normal traction $t_{n, av} = V/A_i = -5.56 \text{MPa}$ according to the failure condition of Eq. (2). Even in the post-failure regime, the interfacial tractions remain significantly non-uniform.

![Figure 9: (a) Finite element model of the shear box test (b) deformed shape after the peak load](image)

![Figure 10: (a) Load-displacement diagram of the shear box test- displacement is measured at the loading point. Distribution of shear (b) and normal (c) tractions along the interface](image)
Thus we conclude that shear box test should be used for calibration the interface model with caution. In particular, the model should not be calibrated based on the average normal and shear tractions, but it is necessary to take into account the non-uniformity of the interfacial tractions during both the pre- and post-peak phase of the test.

4. CONCLUSIONS

- Suitability of various test configurations for identification of the interfacial failure condition and post-failure traction-separation law was investigated by means of FE simulations.
- The Ohno shear beam configurations (with either vertical or horizontal interfaces) can be used to identify the interface strength parameters from the peak load using the relations between the applied load and interface tractions obtained through the FE analyses. However, the tests do not provide data necessary for calibration of the post-failure cohesive relationship.
- The shear box test is not suitable for evaluation of the interface strength parameters as the failure is initiated by localized stress concentration. The post-failure response is governed by sliding of the interface, however even in this phase the interfacial tractions remain non-uniform. To rigorously calibrate the shear-slip relation, one should not rely on the average tractions but this non-uniformity should be taken into account.

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REFERENCES