Fracture mechanics testing of the bond between composite overlays and a concrete substrate

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Abstract—This paper presents a methodology for assessing the bond strength of composite overlays to concrete utilizing a fracture toughness test. The principles and practices of existing ASTM standards for determining the fracture toughness of adhesive bonds between double cantilever beam (DCB) metallic and composite specimens (D 3433-93 and D 5528-94a) have been extended to cover the case of an elastic composite layer bonded to a rigid concrete/masonry substrate.

In the theoretical section, the dominant loading conditions, relevant ASTM standards, and the development of energy release rate concepts for analyzing a disbonding composite layer modeled as an elastic cantilever beam are presented. The experimental section covers specimen fabrication and preparation, experimental setup, test procedures, post-test evaluation of the specimens, and data processing. The discussion of test results focuses on explaining the variability in measured strain energy release rate, and identifies trends between the measured strain energy release rate and the fraction of the fracture surface retaining cement paste after disbonding. It was found that good-quality composite-to-concrete bond is associated with high fracture toughness of the adhesive and location of the crack path in the concrete substrate. Strict enforcement of surface preparation and adhesive handling procedures was found to play an important role in promoting good bond strength and high fracture toughness. The fracture toughness test developed in this paper can be used for screening various composite-repair systems, to assess the effect of different environmental attacks, and as a quality control tool.

Keywords: Adhesive bond; composite overlay; composite repair; aging infrastructure; double cantilever beam; fracture toughness; fiber reinforced polymers; energy release rate; DCB.

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1. INTRODUCTION

According to the US Department of Transportation and the Federal Highway Administration, there are about 576,000 bridges in the national bridge inventory, and 23% of these are structurally deficient or in need of repair. Several states have demonstrated that advanced fiber reinforced polymers (FRP) can be used to maintain and to improve the load capacity of concrete bridges. FRP repair technology offers a practical way to rehabilitate aging concrete bridges without severely disrupting traffic flow.

1.1. Composite overlays

Composite overlays are thin sheets of fiber reinforced polymeric material (3–6 mm thick) adhesively bonded to conventional construction engineering materials. Candidate polymeric systems include epoxy, polyester, and vinyl ester. Fibers can be glass, carbon, Kevlar, or combinations thereof. Glass and Kevlar fibers come in a variety of forms including weaves and non-woven fabrics. Carbon fibers can be woven, but common usage relies on unidirectional pre-impregnated sheets (prepregs). The composite may be applied as: (a) wet lay-up; (b) precured panels; or (c) partially-cured prepregs. For wet lay-up and prepreg systems, the adhesive is the polymeric resin itself. For precured rigid panels, a separate adhesive material needs to be used. Structural upgrades with composite overlays offer considerable advantages in terms of weight, volume, labor cost, specific strength, etc. One critical issue raised by the structural engineers is the still unknown in-service durability of these new material systems. Their ability to safely perform after prolonged exposure to service loads and environmental factors must be ascertained before wide acceptance in the construction engineering community is attained.

1.2. Strength and durability of composite overlaid structures

The degradation and loss of performance of composite overlays on concrete or masonry substrate may result from: (a) degradation of the composite overlay; (b) deterioration of the concrete/masonry substrate; and (c) loss of adhesion between the overlay and the substrate. The degradation of composite materials and the fatigue of concrete structures have been extensively researched elsewhere (see, for example [1, 2] for composites; [3, 4], for concrete). However, the durability of the bond between the composite and the substrate remains a critical issue. A sudden loss of bond through wide area delamination — when it happens — can lead to a catastrophic failure of the structure. Hence, the loss of adhesion between the composite overlay and the substrate remains a critical factor. Maintenance of good adhesion between the composite overlay and the substrate structure is of paramount importance for assuring long-term performance and for preventing early failure of such structural upgrades and repairs. To date, this phenomenon has not been extensively studied or is insufficiently documented. The loss of adhesion
and performance degradation can be traced to the interface between the composite overlay and the concrete/masonry substrate. The bond degradation manifests itself in the form of debonding/spalling cracks and delaminations. In certain situations, cracks start at the edges of the composite overlay and propagate towards the center. As cracks propagate, they generate local disbonding of the overlay from the structural substrate. If the disbonding becomes widespread, significant loss of load-transfer capabilities can occur. Crack propagation is promoted by combined hygro-thermal–mechanical cycling. Crack propagation can be delayed and even prevented by increasing the inherent fracture toughness at the composite/substrate interface. The intricate mechanism of crack propagation in an adhesive joint and its relation to adhesive joint durability is extensively researched in academia, industry, and government laboratories [5, 6].

2. THEORETICAL BACKGROUND

The durability of the adhesion between the composite overlay and the concrete substrate is related to the initiation and propagation of cracks at the composite–concrete interface. For good durability, the composite–concrete material system should have high resistance to crack propagation, i.e. high fracture toughness. Crack initiation and propagation at the composite/concrete interface can be experimentally studied using the energy release rate method. In this paper, the energy released during crack advancement is determined using a compliance technique [7]. This section briefly reviews the theoretical background involved in this approach, and develops the equations needed for processing and interpreting the test data.

2.1. Dominant loading condition

To develop a test suitable for evaluating the durability of the composite–concrete interface, one needs to consider the type of loading that this interface is likely to undergo during in-service operation. A crack at the interface can experience three loading types: mode I, tension (or tearing) applied to the crack tip; mode II, in-plane shear; and mode III, out-of-plane shear (or torsion). From a strength viewpoint, the two most important loading modes that must be considered are modes I and II, since natural disasters, such as earthquakes, impart both modes at the interface between the composite overlay and the concrete substrate. From a durability viewpoint, processes such as cyclic freeze–thaw and vandalism impart mode I loading. A freeze–thaw cycle, especially in humid conditions, allows moisture to enter the cracks and, upon freezing, the water expands producing crack opening displacement. Likewise, vandalism would also impart a mode I loading if an attempt is made to pull the composite overlay away from the concrete substrate. Therefore, it is important to understand how the composite–concrete interface behaves under mode I loading. Equally important is to develop a fracture-toughness testing procedure that can be easily conducted and applied for in-field testing of the composite overlay/concrete system.
2.2. DCB test method

There are many established test methods for determining the mode I fracture toughness and interfacial fracture energy between adhesives and metallic or composite substrates. For example, ASTM standard D 3433-93 [8] defines the test procedure for determining the mode I fracture toughness and energy release rate of adhesive bonds between symmetric metallic plates using the double cantilever beam (DCB) and the contoured double cantilever beam (CDCB) specimens. ASTM standard D 5528-94a [9] extends the DCB method to composite materials. However, no standardized test methods could be found in the literature that specifically address the testing of the bond fracture toughness for composite overlays applied to concrete or masonry materials. Karbhari and Engineer [10] measured the composite-to-concrete bond toughness with a peel test. Thin composite overlays were pulled off the substrate at a constant rate and fixed angle. Rollers were used to facilitate the peel-off process. However, many of the composite overlays used in the rehabilitation of concrete structures are too stiff to peel off in this manner. Giurgiutiu et al. [6] used the DCB method to study the propagation of cracks in the adhesive layer between two metallic substrates and correlated the results with the development of criteria for predicting the crack propagation path in adhesive layers. In the present work, the principles and practices of ASTM standards D 3433-93 and D 5528-94a have been extended to cover the case of a linearly elastic composite layer bonded to a rigid concrete/masonry substrate.

2.3. Energy release rate

Figure 1 presents a test specimen made up of a substrate block and a composite overlay bonded on its top surface. Since the substrate is much more rigid than the composite overlay, the deformation of the composite overlay is dominant. Hence, the investigation is confined to the study of the deformation and associated strain energy of the composite layer. The composite layer is modeled as a simple beam of width $b$, thickness $h$, and elastic modulus $E_{11}$. Assume that, at a certain moment

![Figure 1. Schematic representation of a composite overlay being delaminated from a concrete/masonry substrate.](image-url)
in time, the composite layer has delaminated, and a crack of length \( a \) is present at the interface between the composite and the substrate. The end of the composite is pulled upwards to induce further delamination. As displacement \( u \) increases, so does the reaction force \( P \). At a certain value of the \( P-u \) pair, the crack starts propagating, promoting further delamination. At this instance, the displacement, \( u \), is kept constant (line AB in Fig. 2). As the crack grows from \( a \) to \( a + da \), the load decreases from \( P \) to \( P - dP \). The strain energy released during this process is represented by the area \( OAB = (1/2)udP \).

This release of strain energy is used to promote crack advancement (creation of new material surfaces as the crack advances at the interface). The incremental strain energy released during the crack advancement by an increment \( da \) is called strain energy release rate denoted by SERR or \( G \). (In this definition, the specimen of unit width, \( b = 1 \), is assumed.) This quantity is also known as crack-extension force. Under fixed-grips conditions, the relationship between strain energy release rate, \( G \), and the loading variables, \( P \) and \( u \), is given by

\[
G = -\frac{1}{b} \frac{(1/2)u \cdot dP}{da},
\]  

where the negative sign signifies the fact that strain energy is being released.

### 2.4. Compliance-based formulation of strain energy release rate

One way to calculate the strain energy release rate, \( G \), is via the compliance approach [11]. The load-displacement relationship can be written as

\[
u = C(a)P,
\]
where $C(a)$ is the compliance value for a given crack length, $a$. Differentiating $u = C(a) P$ with respect to $a$, and using $u = \text{constant}$, i.e. $du = 0$, yields:

$$du = C(a) \cdot dP + P \cdot dC(a) = 0.$$  \hspace{1cm} (3)

Hence, multiplication by $P$, substitution of $P^2 = u^2/C^2$, and use of equation (1) yields

$$G = \frac{1}{2b} \frac{u^2}{C^2} \frac{dC}{da}.$$  \hspace{1cm} (4)

For convenience, equation (4) can also be expressed in terms of the load, $P$, i.e.

$$G = \frac{P^2}{2b} \frac{dC}{da}.$$  \hspace{1cm} (5)

2.5. Strain energy release rate of a debonding composite layer

The tip deflection of a simple beam of length $a$, width $b$, thickness $h$, modulus $E_{11}$, and cross-sectional moment of inertia $I = bh^3/12$ is

$$u = \frac{Pa^3}{3E_{11}I}.$$  \hspace{1cm} (6)

Using equation (6), we express the compliance as

$$C(a) = \frac{a^3}{3E_{11}I}.$$  \hspace{1cm} (7)

Equation (7) indicates that the cubic root of compliance varies linearly with the crack length, $a$, i.e.

$$C^{1/3} = m \cdot a, \quad m = \left(\frac{1}{3E_{11}I}\right)^{1/3}.$$  \hspace{1cm} (8)

Differentiation of equation (7) with respect to $a$, and use of equation (8) yield the expression for the strain energy release rate:

$$G = \frac{3m^3a^2P^2}{2b}.$$  \hspace{1cm} (9)

2.6. Modified beam theory

The simple beam theory, and the corresponding equation (8), assumes that perfect built-in conditions are present at the crack front. As pointed out in ASTM D 5528-94a, this assumption may not be completely valid in practice, and rotation may occur at the crack front. One way of correcting for this rotation is to apply a modified beam theory (ASTM D 5528-94a) in which the specimen is treated as if it contained a slightly longer debond, $a'$. The value of $a'$ can be determined
experimentally by generating a least squares fit of the cube root compliance plot, \( C^{1/3} \), as a function of the debond length, \( a \). Hence, the compliance is expressed as

\[
C^{1/3} = m \cdot a + n.
\]  

By setting \( a' = a + n/m \), one can use a modification of equation (9) to write:

\[
G = \frac{3m^3(a + n/m)^2 P^2}{2b}.
\]  

3. TEST SPECIMENS

Test specimens consisted of a concrete substrate and a composite overlay applied on its upper surface (Fig. 3a). The concrete substrate consisted of a 51-mm \( \times \) 51-mm \( \times \) 178-mm concrete block. The concrete blocks were fabricated in our

**Figure 3.** Test specimen developed in our laboratory for testing adhesion strength and fracture toughness between composite overlay and structural substrate: (a) side view showing support fixture, concrete brick and composite overlay; (b) bottom view showing retention bolts.
laboratory from commercially-available components, as detailed in the following sections. The composite overlay was 3.2 mm thick and 50 mm wide, and consisted of glass fiber reinforced polyester fabricated in our laboratory from commercially available components. During the block casting process, two anchorage bolts (12.5 mm diameter) are inserted and set in place (Fig. 3b). These bolts attach the specimen to the test fixture and take up the reaction forces. Two sets of specimens were fabricated and tested, the D-series (ten specimens) and the S-series (five specimens). The second set of specimens was fabricated after the results from the testing of the first set of specimens were analyzed. Thus, the second set of specimens benefited from the knowledge gained in the fabrication and testing of the first set. The difference between the D-series and the S-series also lies in the operator expertise. Though same fabrication instructions were used in both cases, the S-series specimens were fabricated by an operator with more experience in composite fabrication than the one that fabricated the D-series specimens. This difference in operators' expertise was allowed to simulate the influence of human factor variability while using identical fabrication specifications.

3.1. Fabrication of test specimens

The test specimens were fabricated in stages. First, the concrete blocks were cast and left to cure. After the concrete was cured, the blocks were taken out of the mold and the top surface was prepared for adhesive bonding by wire brushing and vacuuming. Then, surface primer was applied. Finally, the composite overlay was applied through a manual wet lay-up process to simulate the conditions encountered in composite overlay repairs practice. Succinct details follow.

3.1.1. Concrete blocks fabrication. The concrete blocks were fabricated ab initio in our laboratory from commercially available components: cement type I (14.5%), silica fume (1.0%), fly ash (3.4%), gravel #1 (11.2%), gravel #4 (12.9%), gravel #8 (7.0%), sand (38.2), and water (11.8%). The concrete mixture was poured in high-density polyethylene molds in which the anchorage bolts had previously been placed. A vibrator was used to consolidate the concrete mixture. The specimens were placed under a piece of wet burlap for 24 h. After this first day, the bricks were removed from the molds and placed in water where they remained to cure for a total of 7 days. The intended compressive strength of the concrete was 31 MPa. This value was verified through compressive tests.

3.1.2. Surface preparation. After complete cure of the concrete, the surface of the blocks was prepared for optimal adhesion. A steel brush was used to scrape off the loose dust particles, and cement paste from the upper portion of the blocks. A vacuum was used to remove loose particles from the surface. The cleaned surface was primed with Atprime 2A + 2B supplied by Reichhold Chemicals, Inc. Atprime is a reactive polyester polyol that cures in the presence of moisture. The primer was
prepared by mixing Atprime 2B with Atprime 2A in the weight ratio of 4 : 1. The primer was applied to the cleaned surface of the brick with a brush, and allowed to cure overnight.

3.1.3. Fiberglass preparation. Quad axial glass mat type QM-3408 from BTI Corporation, supplied by Reichhold Chemicals Inc., was used as fiberglass reinforcement. The description of this material is given in Table 1. The material is manufactured from E-glass and stitched together with 135D polyester yarn. Three strips of QM-3408 (cut along the 0° direction) were prepared for each brick prior to mixing the resin with the initiator. The dimensions of these strips matched the dimensions of the brick top surface (51 mm × 178 mm).

3.1.4. Priming of the piano hinges. The load was introduced into the specimen through a piano hinge attached at the tip of the composite layer. The hinge was 51 mm long and had two 6.3-mm holes on each side. A piece of sandpaper was used to roughen up the metal hinge surface and to remove any protective coating. Then, the hinges were degreased with ethyl alcohol and subjected to surface conditioning using Micro Measurements, Inc. M-prep products. M-prep Conditioner A (water-based phosphoric acid solution) was applied repeatedly using a fine grit wet-and-dry abrasive paper. During this process, the hinge was cleaned with paper towels until no discoloration was observed on the paper towel. This step was followed by rinsing the hinge with distilled water. Then, the clean surface was dried by a single slow stroke with the paper towel. M-prep Neutralizer 5A (ammonium hydroxide) was applied to the clean surface to neutralize the last traces of acid. This way, the bonding surface of the hinge was prepared for good adhesion with the resin. In order to prevent lockup of the hinge due to the resin absorption, the pin of the hinge was locally greased. Care was taken not to contaminate the rest of the conditioned hinge.

3.1.5. Application of the composite overlay. The composite overlay was applied using a wet lay-up process. Atlac 580-10 polyester resin and 46747 peroxide initiator (MEKP type) were used to create the composite matrix material. This resin also served as the adhesive between the composite overlay and the concrete
substrate. Both ingredients used in the resin preparation were supplied by Reichhold Chemicals, Inc. The peroxide initiator was thoroughly mixed with the resin (1:80 weight-by-weight ratio) in a hand-mixing vessel. The resin was applied onto the brick surface using a disposable paint roller. The first fiberglass section was placed over the surface and a metal roller was used to impregnate the fibers with the resin. Then, a second layer was applied using the same process. After the second layer was applied, the primed metal hinge was placed at the end of the specimen with the rounded pin-side facing downward (Fig. 4). The third and final layer was positioned on top of the specimen, and the impregnation process was repeated. This way, the metal hinge was incorporated between the second and the third composite layers. A final coating of resin was rolled onto the surface using a disposable paint roller. The composite was allowed to cure under normal room temperature and humidity conditions. The composite seemed fully cured and cool to the touch within 2–3 h. To ensure complete cure, at least 24 h were allowed to pass before the specimen was taken to the next stage.

3.2. Pre-test specimen preparation

The pre-test preparation of the specimen consisted in removing the fiber/resin spill-out, cleaning the sides, initiating the crack, and applying the crack read-out ruler. The specimen was cleaned of fiber/resin spill-out using conventional civil engineering tools. Then, a razor blade was used to initiate the crack at the hinge end of the specimen. The brick was placed in a vise to arrest the crack growth beyond the under-the-hinge perimeter. The razor blade was tapped into the specimen, between the composite and the concrete brick, to induce a pre-crack at the interface. The interface between the composite overlay and the concrete brick substrate was painted with white water-based typewriter correction fluid to facilitate observation.
of crack propagation during testing. A paper ruler was glued to both sides of the brick just below the paint line.

4. EXPERIMENTAL

4.1. Experimental Setup

The experimental setup consisted of an MTS 810 Test System fitted with an 890-N (200-lb) load cell and loading fixture (Fig. 5). The MTS 810 Test System is controlled through a National Instruments Labview interface card and programming language installed on a lab PC. Labview was used to run the test and gather data. Data were collected through the Labview interface and brought into the PC for processing. The loading fixture was first mounted on the ram head of the MTS 810 Test System. The specimen was mounted onto the loading fixture with the bolts protruding downward through the holes. A rubber pad was positioned between the brick and the fixture to prevent damaging the specimen while being tightened to the fixture. A tongue and clevis joint fixture was used to connect the load cell to the specimen. The tongue was bolted to the piano hinge attached at the end of the specimen. The clevis was fixed into the load cell end. The good alignment of the two pieces was verified, and fine adjustments were applied, as necessary.

4.2. Test procedures

The test procedure followed the general rules laid out in the ASTM standards for DCB testing (ASTM D 3433-93 and 5528-94a). The specimen was loaded monotonically under displacement control at a ram rate of 0.13 mm/sec. During loading, the load and displacement values, and the load-displacement curve were displayed in real time. When the load value was observed to drop, or when the crack was observed to grow, the loading was paused, and the crack was allowed to propagate under constant displacement. When the crack propagation was completed and the crack was arrested, the crack length was measured, and the current values of crack length, load, displacement, and time were recorded. Then, the loading restarted, and the process was repeated until complete delamination was achieved. Complete delamination was assessed by load dropping to zero and crack extending along the entire length of the specimen. Photographic documentation was performed during and after the test. Post-test photographs of the fracture surfaces were taken in order to assess the nature of the disbond.

5. POST-TEST PROCESSING AND EVALUATION

5.1. Evaluation of specimens

The specimens were evaluated visually in terms of: (a) appearance of the composite; (b) appearance of fracture surfaces; and (c) type of crack propagation, i.e. at the
Figure 5. Experimental setup for determining the fracture toughness of the bond between the composite overlay and the concrete substrate: (a) test machine and specimen indicating the loading direction; (b) close-up view of specimen D-2.
Table 2.
Summary of test results

<table>
<thead>
<tr>
<th>Specimen number</th>
<th>SERR Rate ($J/mm^2$)</th>
<th>Percentage of fracture surface retaining cement paste</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average value</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>D-1</td>
<td>0.265</td>
<td>0.151</td>
</tr>
<tr>
<td>D-2</td>
<td>0.094</td>
<td>0.035</td>
</tr>
<tr>
<td>D-3</td>
<td>0.075</td>
<td>0.005</td>
</tr>
<tr>
<td>D-4</td>
<td>0.099</td>
<td>0.024</td>
</tr>
<tr>
<td>D-5</td>
<td>0.171</td>
<td>0.017</td>
</tr>
<tr>
<td>D-6</td>
<td>0.059</td>
<td>0.013</td>
</tr>
<tr>
<td>D-7</td>
<td>0.111</td>
<td>0.019</td>
</tr>
<tr>
<td>D-8</td>
<td>0.151</td>
<td>0.065</td>
</tr>
<tr>
<td>D-9</td>
<td>0.098</td>
<td>0.017</td>
</tr>
<tr>
<td>D-10</td>
<td>0.077</td>
<td>0.007</td>
</tr>
<tr>
<td>S-1</td>
<td>0.232</td>
<td>0.017</td>
</tr>
<tr>
<td>S-2</td>
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<td>0.021</td>
</tr>
<tr>
<td>S-3</td>
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<td>S-4</td>
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<td>0.058</td>
</tr>
<tr>
<td>S-5</td>
<td>0.229</td>
<td>0.029</td>
</tr>
</tbody>
</table>

interface or in one of the constituents. In general, it was observed that the crack propagated in a mixed fashion, partially through the upper layer of the concrete substrate, and partially at the interface between the concrete and the composite. When the crack propagated through the upper layer of the concrete substrate, cement paste residue was observed on the matching surface of the composite overlay. When the crack propagated along the interface, both fracture surfaces had no cement-paste residue and had a glossy appearance. The percentage of the fracture surface that was retaining cement paste residue was measured and recorded (Table 2).

5.2. Data processing

Load-displacement graphs were drawn and examined. These graphs clearly indicated the loading cycles and the crack propagation regions. Next, plots of the cubic root of compliance vs crack length were generated and a least-squares straight line fit was applied. These graphs correspond to equation (10) and generate the $m$ and $n$ values necessary for the calculation of strain energy release rate, $G$, with equation (11). In producing these fits, attention was paid to eliminate outliers that would distort the results. Outliers were defined as any point lying outside the interval defined by the lower and upper quartiles $±1.5 \times$ interquartile range [12]. Finally, the fitted $m$ and $n$ values were used in equation (11) to generate graphs of strain energy release rate, $G$, vs crack length, $a$. Typical results of data processing are presented in Fig. 6. Three graphs are presented for each specimen: (a) the as-recorded load-
displacement plot; (b) the linear fit between the cubic root of compliance, \( C^{1/3} \), and the crack length, \( a \); and (c) the plot of strain energy release rate, \( G \), as function of crack length, \( a \). The \( C^{1/3} - a \) plots show very little scatter and indicate a good linear fit of the data and confirm the soundness of the experimental method. The \( G - a \) plots show some data scatter.

6. DISCUSSION OF TEST RESULTS

Table 2 gives a summary of the main results obtained in this study. The percentage of fracture surface retaining cement paste, and the mean SERR values are given. Plots of these results are given in Figs 7 and 8. An examination of these values reveals that the percent of fracture surface retaining cement paste and the SERR values for the two specimen sets (series D and S) are substantially different. The first set of specimens (D-series) presents extensive scatter, and have a lower SERR value (\( G_{\text{average}} = 0.120 \, \text{J/mm}^2 \)). The second set of specimens (S-series) present much less scatter and has a much higher SERR value (\( G_{\text{average}} = 0.252 \, \text{J/mm}^2 \)).
Figure 7. Summary of D-series test results: (a) mean SERR values; (b) percentage of fracture surface retaining cement paste.

6.1. Discussion of specimens

6.1.1. D-series specimens with higher-than-average SERR. Specimens D-1 and D-5 showed a higher-than-average SERR. This means that the adhesion fracture toughness of these specimens was higher than of the rest. This indicates an overall stronger adhesion. The percentage of fracture surface retaining cement paste after fracture is also the highest in this specimen (Fig. 7b). This indicates that a good bond was created between the composite and the substrate during the wet lay-up process. Thus, when cracking took place during the test, the crack was forced to propagate in the concrete substrate. Since the cement paste present in the upper layer of the concrete substrate is weaker than the rest of the concrete, the crack propagation took
place in the cement paste layer. As shown in Fig. 7a, this type of crack propagation yields the highest fracture toughness. An examination of specimen D-5 also shows a significant percentage of the fracture surface retaining concrete paste (Fig. 7b). However, the ranking of specimen D-5 in terms of the percentage of fracture surface retaining cement paste is lower than its ranking in terms of fracture toughness. This indicates that the percentage of the fracture surface retaining cement paste is not the only indicator of a strong bond, and that other factors may be involved.

6.1.2. D-series specimens with lower-than-average SERR. Specimens D-3, D-6, and D-10 had lower-than-average strain energy release rate values (Fig. 7a). Of

![Graph](image)

Figure 8. Summary of S-series test results: (a) mean SERR values; (b) percentage of fracture surface retaining cement paste.
these, specimens D-3 and D-6 are also the specimens with the lowest percentage of the fracture surface retaining cement paste. From this point of view, these specimens indicate that a trend exists between the fracture toughness and the percentage of the fracture surface retaining cement paste. On the other hand, specimen D-10 shows a different behavior. Its ranking in terms of the percentage of the fracture surface retaining cement paste is higher than its ranking in terms of fracture toughness. This observation indicates that, though a trend exists between bond fracture toughness and percentage of the fracture surface retaining cement paste, other factors may also be involved.

6.1.3. S-series specimens. The results for the S-series specimens present significantly less scatter than for the D-series specimens. Visual examination the S-series specimens reveals that the character of fracture is significantly more consistent than for the D-series specimens. Figure 8a shows the SERR values for the S-series specimens. In addition, most S-series specimens show a good fraction of the fracture surface retaining cement paste (Fig. 8b). This indicates that the composite-to-concrete adhesion was quite good, and that the failure propagated cohesively through the top of the concrete block. A typical image of the fracture surface for the S-series specimens is given in Fig. 9.

Figure 9. Fracture surfaces of specimen S-5 are typical for S-series specimens. The cement paste retained on the composite overlay (top) indicates adequate adhesion between the composite overlay and the concrete substrate.
6.2. Relation between the measured SERR and the percentage of the fracture surfaces retaining cement paste

A sample-to-sample variation of approximately one order of magnitude was observed in the SERR values. This variation is related to differences in the fracture paths in the samples. The fracture surfaces of all samples had areas where cement paste retained on the composite overlay after it was peeled off, indicative of good adhesion between the composite and the substrate in these areas. However, there were also regions where the cement was not retained on the composite overlay, indicating poor adhesion and/or pre-existing voids at the composite/concrete interface. The relative fraction of the fracture surface retaining cement paste varied significantly among the samples.

Though, arguably, the number of specimens was relatively small for a full statistical study, the trend between the fraction of fracture surface retaining cement paste and the quality of adhesion was studied. The fraction of the fracture surface retaining cement paste was quantified by measuring its area percentage using a statistical point-counting method. When the SERR was plotted against the fraction of fracture surface retaining cement paste, as in Fig. 10, it is clear that a trend exists. In this figure, the data and the regression line show that SERR increased with an increased fraction of fracture surface retaining cement paste. The 0% mark represents failure at FRP/concrete interface, and the 100% mark represents cohesive failure in concrete. The situations in between these marks represent mixed-mode fracture. In general, a trend exists between observed fraction of fracture surface retaining cement paste and SERR. However, there seems to be also other factors involved. For example, three samples, having the fraction of fracture surface retaining cement paste between 40 and 60%, fell below 1 standard deviation of the regression line. A closer examination of the fracture surfaces of these samples

Figure 10. Correlation of SERR with percentage of fracture surface retaining cement paste.
indicated that they had large debond areas, whereas the debond areas on the other samples tended to be smaller and more equally distributed on the surface. On one of these samples, one part of the fracture surface was almost bare of cement paste while the other part was almost completely retaining it. While the trend of increasing SERR with increased fraction of the fracture surface retaining cement paste exists, these observations indicate that the distribution of the debonds also plays an important role in determining the effective toughness of the composite-to-concrete bond.

The variation in the results is likely associated with the hand lay-up procedures used to fabricate the specimens. Poor adhesion could be related to the time elapsed between applying the primer and the composite, or to the resin being applied too late after mixing, while it started to gel. The differences in the distribution of the poorly retained areas could be attributed to the inexperience of the personnel (student assistants) who fabricated the test specimens. This underscores the importance that training, experience, and quality control will have when composite materials are applied to civil engineering structures in the field.

It must be also realized that the fraction of fracture surface retaining cement paste is actually not just a function of the adhesive, but also a function of the type and quality of the concrete near the adhesion area. In addition, concrete, due to its inhomogeneous microstructure, shows substantial local variation. It should also be pointed out that there is a substantial difference between cement paste and concrete. The latter is likely to be the substrate in the field. In this case, the presence of aggregate and interactions with the aggregate will be an additional point of interest for further studies. Another aspect that may be important, though not researched in this study, is the effect of the resin primer coat used in the process. Under certain situations, this can introduce an additional interface. The evaluation of these aspects could make the object of further studies.

7. SUMMARY

A new fracture toughness test for assessing the bond between a composite material overlay and a concrete substrate has been presented. Methods and procedures for this new test have been developed from existing double cantilever beam (DCB) test methods for evaluating the adhesion of metals (ASTM D3433-93) and composites (ASTM D5528-94a). Utilizing the general concepts outlined in these ASTM standards, we elaborated, ab initio, the specimen geometry, the specimen fabrication technique, the specimen loading and support devices, the test procedure, and the data reduction methodology for measuring the fracture-toughness of the composite/concrete bond. As a measure of the bond fracture toughness, the strain energy release rate, $G$, was selected.

During our development work, two sets of specimens were fabricated and tested: D-series and S-series. The S-series specimens were fabricated after analyzing the D-series results, and therefore reflected an improvement in the specimen fabrication
procedure. Consequently, the S-series specimens gave an average value of the SERR $G_{S-series} = 0.252 \text{ J/mm}^2$ which was twice as much as that showed by the D-series specimens. $G_{D-series} = 0.120 \text{ J/mm}^2$. Besides a higher SERR, the S-series specimens also presented a significantly reduced scatter: While the D-series SERR values varied from a low of 0.059 (specimen D6) to a high of 0.265 J/mm$^2$ (specimen D1), the S-series SERR values only varied from 0.229 (specimen S5) to 0.241 J/mm$^2$ (specimen S4).

The tests also revealed the nature of crack propagation in the bond between fiberglass/polyester composite material overlay and a concrete substrate. The specimens with high fracture toughness had large proportion of crack propagation inside the concrete substrate, while the specimens with low fracture toughness had crack propagation predominantly at the interface. When cracks propagated inside the concrete substrate, the crack path was contained in the concrete-paste layer, which is expected to have lower fracture toughness than the bulk of the concrete. The specimens that had cracks propagating along the interface are believed to be deficient from the point of view of specimen fabrication. However, the results obtained with these specimens are nevertheless valuable, since they may be representative of what could happen in real-life situation when insufficient attention is paid to the details of composite material handling and fabrication.

One of the outcomes of the test method developed in this study is to have a simple testing technique that can assess the strength and fracture toughness of the bond between the composite overlay and the structural substrate during in-field deployment of the composite overlay repair/rehabilitation technology. The fracture toughness test developed in this paper can be used to screen various composite-repair systems, to assess the effect of different environmental attacks, and as a quality control tool. The concept of the method can be used to develop a portable fracture toughness tester for in-field comparison of different concrete-repair systems performance under environmental exposures such as water submersion, temperature–humidity cycles, freeze–thaw, and ultraviolet light exposure. As a quality control tool, this method can be utilized to accept/reject a repair system based on a minimum fracture toughness value that should be base-lined through extensive experimentation. Further extension of the method would be to investigate specimens that have been exposed to environmental attacks.

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