Experimental Study on the Damage Evolution of Re-bar Concrete Interface

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Abstract

- A new type of bond-slip test is developed in this study
- Constitutive relationship of bond is obtained for the test
- FEA using this constitutive relationship
- Result analysis and comparing
General Overview

1. Introduction and Literature Review
2. Experiment Procedure
3. Experimental Data Analysis
4. Numerical Computation Study
5. Conclusion and Discussion
1.1 Introduction

- Liu Yu’s Concrete Model

\[
\tilde{D}_i = \begin{cases} 
D_i & \text{when } \sigma_{ii} \geq 0 \text{ or } \varepsilon_{ii} \geq 0 \\
0 & \text{when } \sigma_{ii} < 0 \text{ and } \varepsilon_{ii} < 0
\end{cases}
\]

\[
\tilde{D} = \begin{cases} 
\tilde{D}_1 \\
\tilde{D}_2 \\
\tilde{D}_3
\end{cases}
\]
RCED Model  (RC Element Damage Model)

- Damage in the reinforced concrete
  1. Effective damage in concrete
  2. Slip between concrete and re-bar
  3. Local damage in concrete due to slip
RCED Model (RC Element Damage Model)

Local damage zone in RCED Model
RCED Model  (RC Element Damage Model)

Element in RCED Model
1.2 Literature Review

4 Bond Test Method
   1. Pull-out Test
   2. Beam-type Test
   3. Uniaxial-tension Test
Pull-out Test

No-transverse bar pull-out test

With transverse bar pull-out test
Pull-out Test

Specimen with Hoop Rebar

- hoop rebar
- Plastic Pipe
- Eccentric Rebar
- Central Rebar
Pull-out Test

Figure 1.8 Specimen With Web Rebar

Specimen with Web Rebar
Pull-out Test

Figure 1.9 Rebar In Different Place

Rebar in Different places
Feature of Pull-out Test

Strongpoint

1. Can determine the anchoring strength of bond
2. Easy to procedure

Shortage

Complex stress state around the surface
Beam-type Test

Half-beam Test to Simulate the Inclined Crack

Half-beam Test to Simulate the Vertical Crack
Beam-type Test

Half-beam Test to Simulate the Inclined Crack

Half-beam Test to Simulate the Vertical Crack
Beam-type Test

Simply Supported Beam Test

1: Lever-type Strain Gauge 2: Strain Gauge On the Bottom
3: Strain Gauge on the Side
Feature of Beam-type Test

Strongpoint
1. Very close to the real state
2. Can determine bond strength of both anchoring zone and between cracks

Shortage
Complex and Expensive
Uniaxial-tension Test

Figure 1.15 Uniaxial-draw Test

Uniaxial-tension Test
Feature of Uniaxial-tension Test

Strongpoint
1. Can determine the bond stress between cracks
2. Easy to Procedure

Shortage
Complex distribution of bond stress
2. Procedure of Test

1. Assumption in RCED Model
   a. Pure shear deformation in the bond zone
   b. Linear slip field

2. Test purpose
   a. Determine the evolution of $D_s$
   b. Determine the rational size of RCED element
   c. Determine the parameter of $a_1, a_2$
Test Device and Method

Figure 2.2 Specimen

RC Specimen
Test Device and Method

Loading Device

Clamping Device

LVDT 5
LVDT 4
Steel Plate
LVDT 6,7
LVDT 8
LVDT 9
LVDT 2,3
LVDT 10
Test Device and Method

Stress State of the Specimen

Figure 2.4 The Stress State of Specimen
Test Device and Method

Assumption in RCED Model
1. Shear deformation in bond zone
2. Linear slip field

Feature of the Test
1. Constraint force is applied through PVC pipe and glue. Concrete is under pure shear stress condition
2. Specimen is as thin as possible

Conclusion: This test can satisfy RCED model
Test Device and Method

(a) Concrete Specimen before Test

(b) PVC Pipe before Test
(c, d) During the Test
Test Device and Method

Test Device Setup
Test Procedure

- Design the Mold
- Test of Steel Bar
- Casting of Concrete
- Design of Loading Device
- Specimen Analysis before Test
- Trial Loading and Analysis of Failure
- Improving Method
- Formal Loading
- Standard Specimen Test
1. Design the Mold

Specimen Mold

- Steel Bar
- Glue
- Round Poly-wood Plate
- PVC Pipe
- Poly-wood Plate
2. Test of Steel Bar

Displacement Determined By LVDT 5

- Slip Between Steel Bar and Concrete
- Elongation of the Free Part of Steel Bar
- Slip Between Steel Bar and Clamping Device
2. Test of Steel Bar

LDVT

Steel Bar

Clamping Device
2. Test of Steel Bar

![Graph showing stress-strain relationship for different steel bars.](image-url)

- Stress (MPa) on the y-axis.
- Strain on the x-axis.
- Three curves represent different steel bars: Bar 1, Bar 2, and Bar 3.
2. Test of Steel Bar

\[ y = 65948x + 18.185 \]
5. Specimen Analysis before Test
6. Trial Loading and Analysis of Failure

Fail Surface of 10-7
6. Trial Loading and Analysis of Failure

Test Result of 10-7
6. Trial Loading and Analysis of Failure

Load Applied directly without PVC Pipe
6. Trial Loading and Analysis of Failure

Load Applied directly without PVC Pipe
6. Trial Loading and Analysis of Failure

Conclusion obtained from trial loading

1. The adhesive isn’t process properly
2. The confinement is still large
7. Improving the Method

- Roughen the adhesive interface deeper
- Split the PVC pipe finely
8. Formal Loading

Test Result of 10-1
8. Formal Loading

Test Result of 15-5
8. Formal Loading

Test Result of 10-5
8. Formal Loading

Test Result of 10-4
8. Formal Loading

Test Result of 15-1
8. Formal Loading

Test Result of 15-6
8. Formal Loading

Test Result of 20-1
8. Formal Loading

Test Result of 20-5
9. Standard Specimen Test

Standard Tube Specimen

- Size: $15 \times 15 \times 15\text{cm}$
- Result:

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Load (KN)</td>
<td>953</td>
<td>1061</td>
<td>959</td>
</tr>
<tr>
<td>Max Strength (MPa)</td>
<td>42.36</td>
<td>47.16</td>
<td>42.62</td>
</tr>
</tbody>
</table>
9. Standard Specimen Test

Six Strain Gauges on Standard Cylinder Specimen
9. Standard Specimen Test

Logitudinal-stress-strain Curve
9. Standard Specimen Test

Side-stress-strain Curve
9. Standard Specimen Test

Stress- Poisson Ratio
3. Experimental Data Analysis

Topical Experiment Original Data
3. Experimental Data Analysis

The following information can be obtained from the experimental data:

1. $\tau-\Delta_1+\Delta_2$ Curve
2. Influence of Height and Radius of Specimen
3. Shear Stress Distribution of Steel Bar and Deformation of Concrete
4. Slip Damage Zone
Original Data
$\tau - \Delta_1 + \Delta_2$ Curve
$\tau - \Delta_1 + \Delta_2$ Curve
\( \tau - \Delta_1 + \Delta_2 \) Curve

![Graph showing \( \tau - \Delta_1 + \Delta_2 \) relationship]
τ-Δ₁+Δ₂ Curve
$\tau - \Delta_1 + \Delta_2$ Curve Fitting
τ-Δ₁+Δ₂ Curve Fitting
Empirical Formula

\[
\tau = \frac{0.7260 \tau_{\text{max}} \left( \frac{\xi}{\xi_0} \right) + 0.061 \left( \frac{\xi}{\xi_0} \right)^{3.2}}{1 - 0.916 \left( \frac{\xi}{\xi_0} \right) + 0.642 \left( \frac{\xi}{\xi_0} \right)^{2.87}}
\]

\( \tau \), Average bond stress

\( \xi \), Value of \( \Delta_1 + \Delta_2 \)

\( \xi_0 \), Value of \( \Delta_1 + \Delta_2 \) at peak point
Influence of Height of Specimen
Influence of Radius of Specimen

Strength vs. Radius

- Strength vs. Radius
- Strength
- Average Strength

Radius (mm)

Strength (MPa)

0 5 10 15 20 25 30 35

0 2 4 6 8 10 12
Shear Stress Distribution along Steel Bar

Obtain the Shear Stress Distribution from the following conditions

1. Elongation of the steel bar
2. Relationship between $\tau$ and $\Delta$
3. Linear assumption in RCED model
Shear Stress Distribution along the Steel Bar

Stress Ratio

Average
Slip Damage Zone

In this test, there is no obvious slip damage zone founded with UPV. So we consider that the slip damage zone is very small, which appears just around the interface of concrete and re-bar.
Numerical Study

Objectives

1. Whether the empirical relationship of bond-slip obtained from the test can be used directly in finite element analysis
2. To verify the assumption in RCED model
Numerical Study

- Finite Element Analysis Software
  1. Linear analysis: MARC k 7.3.2
  2. Non-linear analysis: Sap 91
- Element Type and Mesh
  Concrete, Steel bar, Glue and PVC pipe: 20 nodes 3D element.
  Bond: Spring element
Mesh of Specimen Series 10
Mesh of Specimen Series 15
Numerical Result
Comparison with Test Results

Result of Test and FEA (Stress: Δ 1 + Δ 2), Specimen Series 10

![Graph showing comparison between test results and FEA predictions for shear stress and displacement.](image)
Comparison with Test Result

Result of Test and FEA (Stress $\Delta 1+\Delta 2$), Specimen Series 15

- Shear Stress (MPa)
- $\Delta 1+\Delta 2$ (nm)

Test Point, Linear FEA, Non-Linear FEA, Fitting for Test Point
Comparison with Test Result
Comparison with Test Result
Comparison with Test Result

The errors between the test results and numerical results are smaller than 10%. Hence, the bond-slip relationship obtained from the test can be directly used in finite element analysis.
Slip Field in the Specimen

![Graph showing slip field in the specimen with data points for Specimen 10 and Specimen 15, and a linear slip field assumption line.](image)
Slip Field in the Specimen

- The linear degree of slip field is 0.925. The assumption of linear slip field in RCED model is rational.
- The size of the specimen influences the slip field lightly.
Bond Stress along Steel Bar

Stress Distribution (10)

Shear Stress (MPa)

Distance to Top (cm)

Linear Assumption Result  FEA Non-Linear Result
Bond Stress along Steel Bar

Stress Distribution

Shear Stress (MPa)

Distance to Top (cm)
Change of Bond Stress

Bonding Stress Distribution (Group 10)

Shear Stress (MPa)

Distance to Top (cm)

Load 1
Load 2
Load 3
Load 4
Conclusions

1. Obtain the full curves of the relationship of $\tau - \Delta_1 + \Delta_2$. The empirical formula of $\tau - \Delta_1 + \Delta_2$ is obtained for the curves. Numerical study proves that this formula can be used in FEA directly.

2. The influence of specimen size to the local damage zone is not obvious.

3. The linear slip field in RCED model is rational.
Appendix

To apply the RCED model in real structure analysis.

Case 1: Using RCED model to analyze our test.

Case 2: Using RCED model to analyze the Doerr’s uniaxial-tension test (ASCE Vol.113, No.10, October, 1987)
Mesh of Case 1

Common Concrete Element

RCED Element
Result \((\tau - \Delta_1 + \Delta_2)\)
Result (Deformation of Concrete)
Mesh of Case 2

4 RCED elements

150

250
Result (Steel bar axial-force)
Element Number to Obtain the Same Precision

<table>
<thead>
<tr>
<th>Traditional element</th>
<th>RCED model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Case 1</td>
</tr>
<tr>
<td>Element used: 656</td>
<td>Element used: 5</td>
</tr>
<tr>
<td>Case 2</td>
<td>Case 2</td>
</tr>
<tr>
<td>Element used: 192</td>
<td>Element used: 4</td>
</tr>
</tbody>
</table>

Conclusion: the element number RCED model needed is much less than the traditional ones.

RCED model is useful in real structure analysis.