Mem. Fac. Eng., Osaka City Univ., Vol. 49, pp. 51–58 (2008)

# Shear Strengthening by Ductile Fiber Reinforced Cementitious Composite Jacketing

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(Received September 30, 2008)

**Synopsis**

Present study focuses on verifying shear strengthening effect by DFRCC jacketing around existing members. In this study, a series of experimental tests have been conducted followed by Finite Element nonlinear analyses. It is concluded as following; 1) Horizontal cracks dominate in the DFRCC jacketed section independently with existing member with diagonal shear crack in which no particular bond treatment between existing and jacketing surfaces, 2) FE nonlinear analyses can predict experimental results up to the ultimate, 3) DFRCC shear strengthening effect can be predicted by the JSCE formula with considering the tensile strength of DFRCC.

**KEYWORDS:** Ductile Fiber Reinforced Cementitious Composite, Shear Strengthening Effect, Repair, Retrofit, Finite Element nonlinear analyses

## 1. INTRODUCTION

Ductile Fiber Reinforced Cementitious Composite (DFRCC) is a material with significant tensile ductility due to fiber bridging effect through multiple cracks[1]. This material has been applied to the practice for not only repair but energy dissipation material as well. In the material cost it has disadvantage compared with ordinal reinforced concrete. However, when considering repair and retrofit application, it is potentially competitive to use that material with appropriate quantity by panel adding or winding on the surface of existing structure. Focusing on seismic retrofit application, few studies have been found, especially on shear strengthening [2].

In these back grounds, present study focuses on verifying shear strengthening effect by DFRCC jacketing around existing members. In this study, a series of experimental tests have been conducted followed by Finite Element (FE) nonlinear analyses; 1) selection of DFRCC mix proportion, 2) uni-axial tensile test on composite action between reinforced concrete (RC) and DFRCC panel, and 3) loading tests of DFRCC jacketed member up to shear failure, and 4) FE nonlinear analyses for test result prediction and also for additional numerical experiment.

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## 2. UNI-AXIAL TENSILE TEST OF DFRCC

### 2.1 Test Procedure

Uni-axial tensile test is carried out for three types of mix proportions focused on selection of DFRCC mix proportions. Test parameters are three types of mix proportions as listed in **Tab.1**. Uni-axial tensile test is carried out with these mix proportions. These mix proportions are evaluated from tensile toughness aspect. The utilized chopped fiber is PVA (Pry Vinyl Alcohol) with 0.04mm of diameter, 12mm of length, 1.6MPa of tensile strength and 40GPa of elastic modulus. Test specimen dimension is dumbbell model as shown in **Fig.1**, i.e. 100×100mm of edge section, R350 curve section and 60×100mm of center section. Measurements are load and four displacement gauges.

### 2.2 Test Result

**Fig.2** represents stress strain relationship obtained in uni-axial tensile test, where stress is defined as load divided by cross section area and strain is as averaged displacement divided by measured length. Tensile toughness is evaluated by the strain at which descending stress reaches initial crack strength. In these mix proportions, more tensile toughness obtained is Type-3 of mix proportions, which is used in the following tests.

**Tab.1 Mix Proportion**

| | W/(C+FA) (%) | S/C (%) | $V_f$ (vol.%) | Unit Quantity (kg/m$^3$) W | C | FA | S | PVA | VA | SP |
|---|---|---|---|---|---|---|---|---|---|---|
| Type-1 | | | 1.5 | 413 | 918 | 0 | 459 | 19.5 | 1.4 | 1 |
| Type-2 | 45 | 50 | 2.0 | 440 | 781 | 195 | 391 | 26 | 0 | 1 |
| Type-3 | | | | 458 | 815 | 204 | 407 | 26 | 0.4 | 10 |

(NOTE) W/(C+FA): Water by Binder Ratio, S/C: Sand by Cement Ratio, $V_f$: Fiber Volume Fraction
W: Water , C: Cement , FA: Fly Ash, S: Fine Aggregate, PVA: Pry Vinyl Alcohol Fiber
VA: Viscorsity Imprement, SP: Superplasticizer

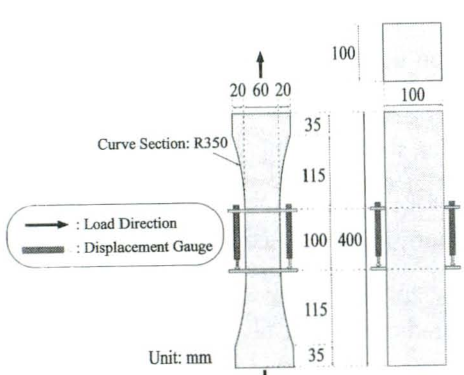



**Fig.1 Test Specimen of Uni-axial Tensile Test**

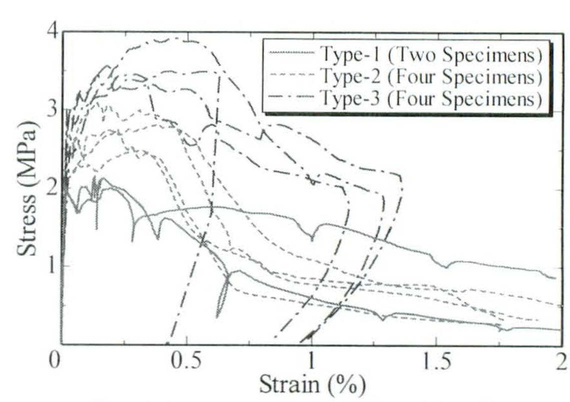



**Fig.2 Stress Strain Relationship of Uni-axial Tensile Test**

## 3. UNI-AXIAL TENSILE TEST ON COMPOSITE ACTION

### 3.1 Test Procedure

Uni-axial tensile test of composite element with RC and DFRCC is carried out focusing on composite action. In this test, composite action is evaluated from tensile stress of DFRCC and crack distribution. **Fig.3** and

**Tab.2** shows dimension of test specimen and summary of composite action respectively. DFRCC panel is bonded to RC section with epoxy. At the end of specimen, steel plate is placed with welded 10mm diameter rebar distributed to specimen. Test parameter is type of bond (Overall Bond: type A, Partial Bond: type B) and the thickness of DFRCC panel ($t$=10, 20 and 30mm). Measurements are load, four displacement gauges and four stain gauges of rebar surface.

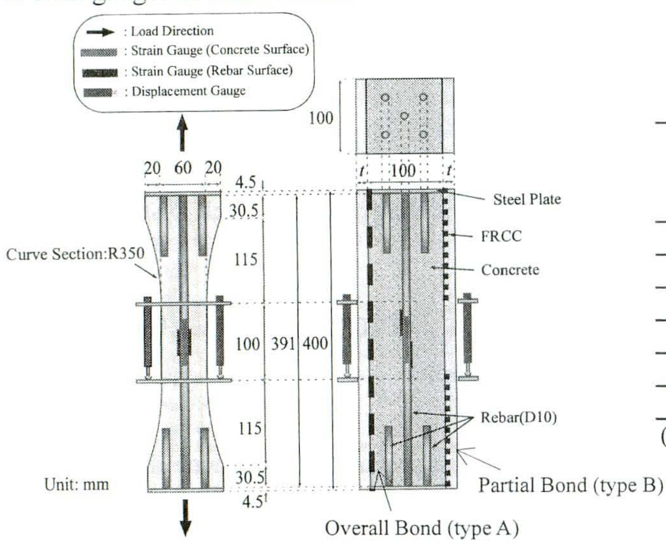



**Fig.3 Test Specimen on Composite Action**

**Tab.2 Summary of Composite Action**

| Specimen | Type of Bond (Bond Area*) | Thickness of DFRCC Panel $t$ (mm) |
|---|---|---|
| A-10 | Overall Bond (type A: ▬ ▬ ) | 10 |
| A-20 | | 20 |
| A-30 | | 30 |
| B-10 | Partial Bond (type B: ••••••) | 10 |
| B-20 | | 20 |
| B-30 | | 30 |

(*) reffer to Fig.3

### 3.2 Test Result

**Fig.4** shows stress strain relationship of DFRCC. Strain is average four displacement gauges. Here, stress of DFRCC is defined as follows;

$$\sigma_{DFRCC} = (P - E_s \varepsilon_s A_s) / A_{DFRCC} \tag{1}$$

where $\sigma_{DFRCC}$= stress of DFRCC (N/mm$^2$), $P$= measured load (N), $E_s$= elastic modulus of rebar (N/mm$^2$), $\varepsilon_s$= measured strain of rebar, $A_s$= section area of rebar (mm$^2$), $A_{DFRCC}$ = section area of DFRCC panel(mm$^2$). No significant difference is observed between specimens with toughness in 10mm thickness specimens. In 20mm thickness specimens, A-20 specimen exceeds maximum stress more than B-20 specimen. However, no difference is almost strain in maximum stress. Additionally, B-20 specimen of softening branch after maximum stress is more gradual than A-20 specimen. In 30mm thickness specimens, B-30 specimen exceeds maximum stress and strain in maximum stress more than A-30 specimen. Therefore, in case of partial bond, it is assumed that tensile toughness of DFRCC can be brought out more effective in comparison with overall bond.

**Fig.5** illustrates pattern diagrams of crack distribution in test termination of type A and B specimens. In type A specimens, a crack from RC section distributes into DFRCC section without another crack distribution as shown in **Fig.5(a)**, that means localized crack opening. On the other hands, in type B specimens, some crack distributions are observed as shown in **Fig.5(b)**.

From the composite element test, in case of DFRCC jacketing to RC, tensile toughness can be demonstrated more effective if type of bond is partial bond. Additionally, the thickness of DFRCC is demonstrated more than 20mm.

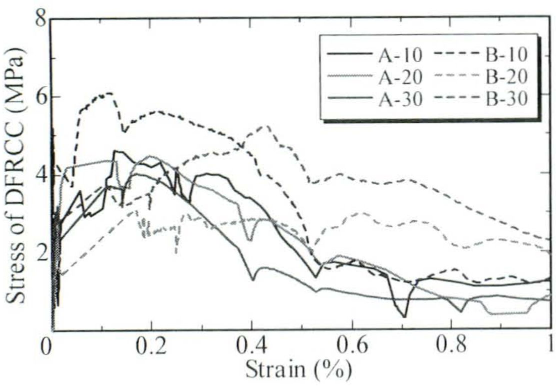



**Fig.4 Stress Strain relationship of DFRCC**

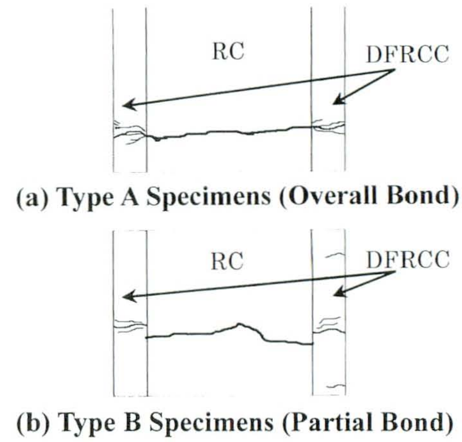



**Fig.5 Pattern Diagrams of Crack Distribution**

## 4. TEST AND FE-NONLINEAR ANALYSES ON DFRCC JACKETING MEMBER

### 4.1 Test on DFRCC Jacketing Member

#### 4.1.1 Test Procedure

**Fig.6** illustrates test specimens and measurements. Core RC of the specimen is the same all dimension. Test specimens are made to precede shear failure by using four main rebar of D22(SD295). Jacketing is reinforced with DFRCC or RC. In the case, no special bond treatment is interface between core RC and jacketing based on test result in section 3. Additionally, thickness of DFRCC jacketing is 20 and 30mm. For comparison, specimen of RC jacketing is designed as shear capacity rises more than the specimen of DFRCC 30mm jacketing. Design shear capacity is calculated by equation (2)[1),3)];

$$\left.\begin{aligned} V_{cu} &= V_{cc} + V_{cs} + V_{cf} \\ V_{cc} &= 0.20\sqrt[3]{f'_c} \cdot \sqrt[4]{1000/d} \cdot \sqrt[3]{p_w} \cdot b_w d \\ V_{cs} &= (A_w f_{wy} / s_s) \cdot d / 1.15 \\ V_{cf} &= (f_{tyd} / \tan \beta_u) \cdot 2td / 1.15 \end{aligned}\right\} \quad (2)$$

where $V_{cc}$= core RC contribution of shear capacity, $V_{cs}$= stirrup contribution of shear capacity, $V_{cf}$= DFRCC contribution of shear capacity, $f'_c$= compression strength of concrete(MPa), $p_w$= tensile main rebar ratio, $b_w$= web width(mm), $d$= effective depth(mm), $A_w$= section area of stirrup (mm$^2$), $f_{wy}$= yield strength of stirrup (MPa), $s_s$= spacing of stirrup (mm), $f_{tyd}$= tensile yield strength of DFRCC (MPa), $\beta_u$= crack angle to member axis (this study:$\beta_u$=45 degree), $t$= thickness of DFRCC (mm). **Tab.3** shows summary of test specimen and design shear capacity. **Tab.4** shows material properties. Measurements are load, six displacement gauges, eight strain gauges of main rebar, twelve PI displacement gauges (except C00 specimen), two strain gauges of concrete and eight strain gauges (only RC50 specimen). PI displacement gauge sets up 45 degree to member axis. Crack is observed to every 0.2 times design shear capacity.

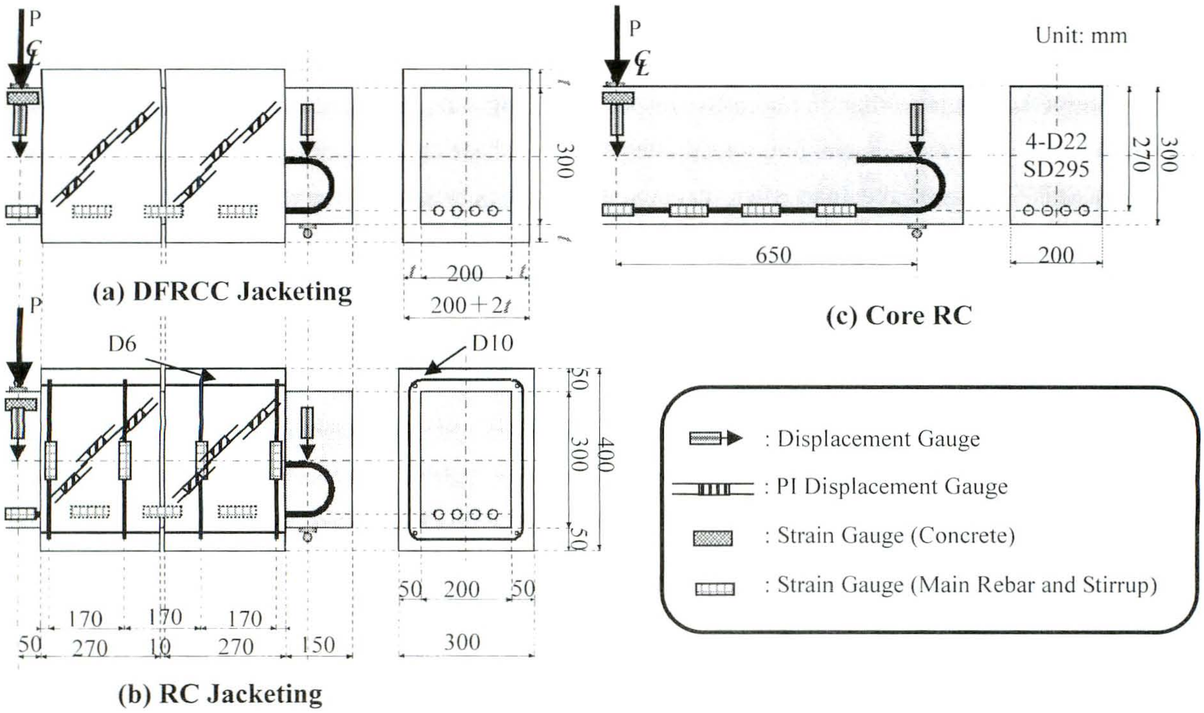



**Fig.6 Test Specimen and Measurements**

**Tab.3 Summary of Test Specimen and Design Shear Capacity**

| Specimen | Thickness of Jacketing $t$ (mm) | Design Shear Capacity: Core RC $V_{cc}$ (kN) | Jacketing: RC $V_{cs}$ (kN) | Jacketing: DFRCC $V_{cf}$ (kN) | Total $V_{cu}$ (kN) |
|---|---|---|---|---|---|
| C00 | - | 68.5 | - | - | 68.5 |
| DFR20 | 20 | 70.3 | - | 28.3 | 98.5 |
| DFR30 | 30 | 70.6 | - | 42.4 | 113.0 |
| RC50 | 50 | 66.3 | 72.7 | - | 140.8 |

**Tab.4 Material Properties**

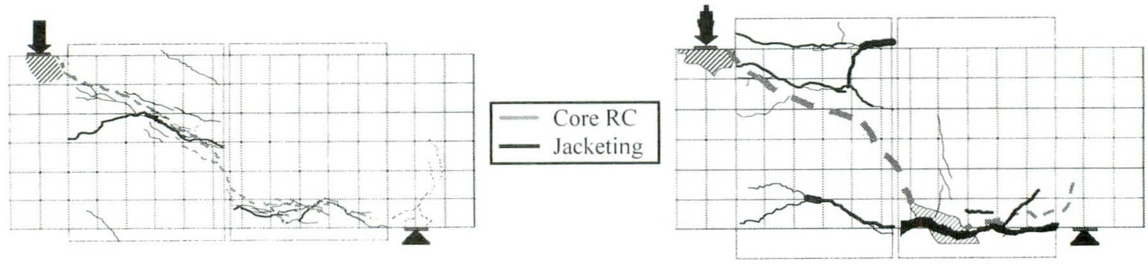
| Specimen | Main Rebar (D22) $E_s$ (GPa) | Main Rebar (D22) $f_y$ (MPa) | Stirrup (D10) $E_s$ (GPa) | Stirrup (D10) $f_y$ (MPa) | Core Concrete $E_c$ (GPa) | Core Concrete $f'_c$ (MPa) | Jacketing (DFRCC or Concrete) $E_c$ (GPa) | Jacketing $f_{ty}$ (MPa) | Jacketing $f'_c$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|
| C00 | 185 | 335 | - | - | 29.9 | 33.3 | - | - | - |
| DFR20 | 185 | 335 | - | - | 30.7 | 36.0 | 15.7 | 3.01 | 48.8 |
| DFR30 | 185 | 335 | - | - | 30.8 | 36.5 | 15.6 | 3.01 | 49.0 |
| RC50 | 185 | 335 | 169 | 369 | 30.3 | 34.4 | 32.0 | - | 37.3 |

(NOTE) $E_s$: Elastic Modulus of main rebar and stirrup, $f_y$: Yield Strength of main rebar and stirrup, $E_c$: Elastic Modulus of concrete and DFRCC, $f_{ty}$: Tensile Yield Strength of DFRCC, $f'_c$: Compressive Strength of concrete and DFRCC

### 4.1.2 Test Result

**Fig.7** illustrates crack distribution of DFR20 and RC50 (crack width represents line thickness). Black and red line shows the crack of jacketing and core RC respectively. **Fig.8** represents mean shear stress drift angle relationship. Specimen C00 reaches maximum load after diagonal shear crack occurs, and brittle failure occurs. Specimen DFR20 is increased the load after diagonal shear crack occurs. Afterward, multiple cracks are observed DFRCC jacketing, and DFR20 gets to failure by 10% descent from maximum load because of the crack is localized. Crack distribution of the jacketing is different from core RC. Specimen DFR30 is more gradual than softening branch of DFR20. On the other hand, DFR30 is similar to DFR20 in terms of crack distribution. In Specimen RC50, maximum load reaches after diagonal shear crack occurs and the stirrup of RC jacketing yield. RC50 occurs brittle failure because of rupturing stirrup of RC jacketing.

In all specimens, the crack distribution of jacketing is different from that of core RC. Horizontal crack tends to occur in jacketing. **Fig.9** illustrates the mechanism that horizontal crack of jacketing occurs. Core RC expands to vertical direction due to diagonal shear crack. Additionally, there is no particular bond treatment of core RC and jacketing, and jacketing act tensile force of vertical direction with core RC expansion. Therefore, it is assumed that jacketing occur horizontal crack.




**(a) DFR20** **(b) RC50**

**Fig.7 Crack Distribution**

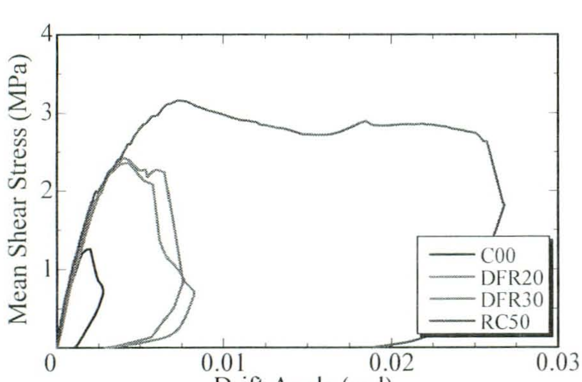



**Fig.8 Mean Shear Stress Drift Angle Relationship**

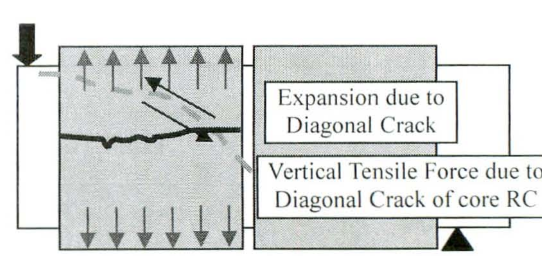



**Fig.9 Mechanism on Crack of Jacketing**

### 4.2 FE-Nonlinear Analyses on DFRCC Jacketing Member

#### 4.2.1 Analytical Procedure

**Fig.10** represents analytical model of DFR20, where concrete and DFRCC are modeled by quadrilateral elements and main rebar are modeled by truss elements. The joint of y direction between core RC and DFRCC jacketing is rigid at the only upper and lower flange, but that of x direction free. Incremental vertical displacement is provided as shown in **Fig.10**. Tri-linear stress strain relationship model is assumed for DFRCC based on uni-axial tensile test result shown in **Fig.11**.

#### 4.2.2 Analytical Result

**Fig.12** represents crack distribution of DFR20 in maximum load. In the test, the center of DFRCC jacketed section is occurred. On the other hand, in the analysis, the crack occurs to an upper and lower flange. But FE nonlinear analysis can predict horizontal crack of jacketing. **Fig.13** shows shear force displacement relationship. Though initial stiffness is slightly different from test result, FE nonlinear analysis can predict test result up to the maximum load.

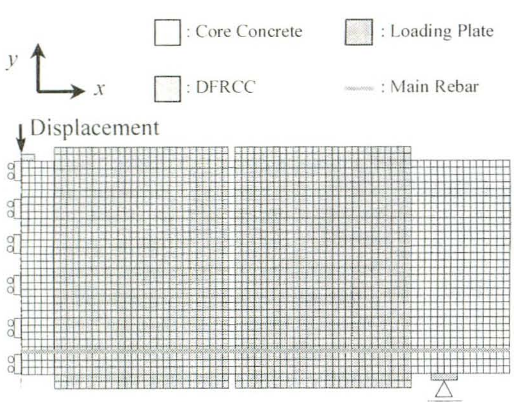



**Fig.10 Analytical Model of DFR20**

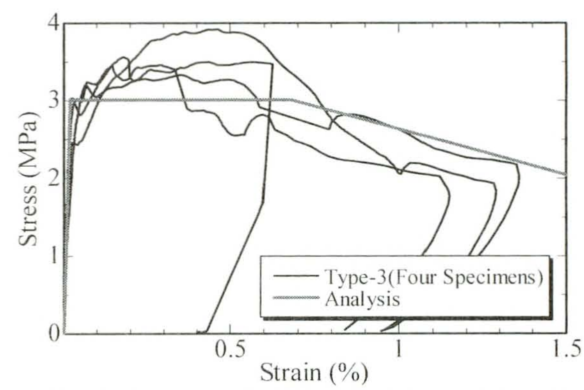



**Fig.11 Stress Strain Relationship of DFRCC**

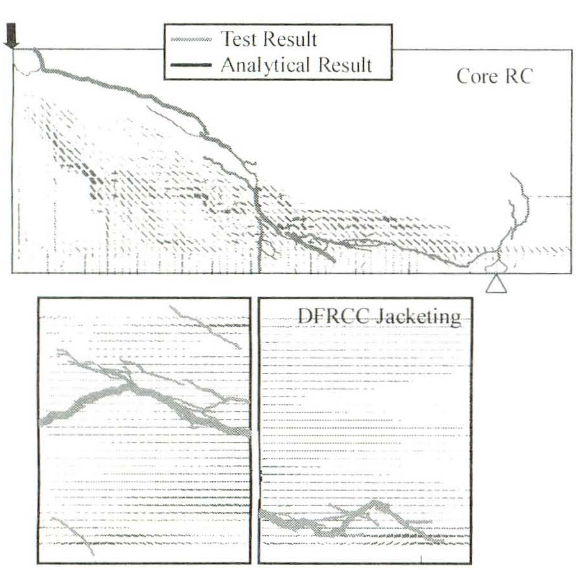



**Fig.12 Crack Distribution**

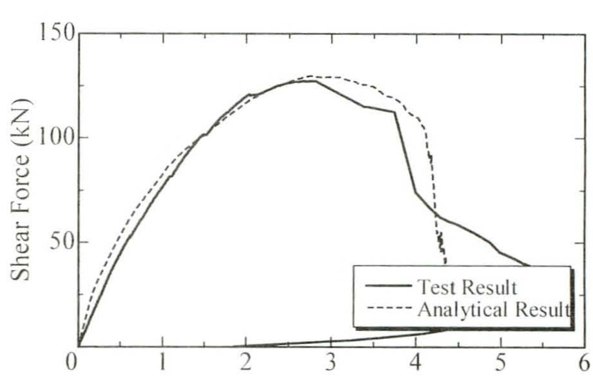



**Fig.13 Shear Force Displacement Relationship**

### 4.3 Shear Strengthening Effect by DFRCC Jacketing

**Fig.14** shows shear strengthening effect obtained by tests and experimental analyses. Here, the result of additional numerical experiment is also shown besides test results on DFRCC jacketing member. Additional numeric experiment assumes 10 and 40mm thickness of DFRCC jacketing. The strengthening component is calculated by equation (2). In C00 and DFR30 specimens, shear capacity by experimental analyses are larger than the test results by 10%. However, in DFR20 and RC50 specimens, shear capacity by experimental analyses correspond to the test results. Good agreement is obtained between test and analytical results. As a result, DFRCC shear strengthening effect can be evaluated by the JSCE formula (dotted line of **Fig.14**).

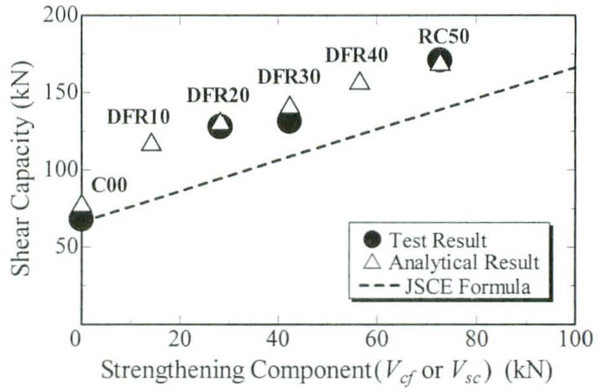



**Fig.14 Shear Strengthening Effect**

## 5. CONCLUDING REMARK

Present study is concluded as followings.

(1) Horizontal cracks dominate in the DFRCC jacketing section independently with existing member with diagonal shear crack in which no particular bond treatment between existing and jacketing surfaces.

(2) FE nonlinear analyses can predict experimental results up to maximum load.

(3) DFRCC shear strengthening effect can be predicted by the JSCE formula with considering the tensile strength of DFRCC.

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