

DEVELOPMENT OF ANCHORAGE SYSTEM FOR CFRP SHEET IN STRENGTHENING OF REINFORCED CONCRETE STRUCTURES

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SUMMARY

A strengthening method for reinforced concrete (RC) structures using continuous fiber, such as carbon, glass and aramid have been focused because of its simplicity for construction site and economy. In case of columns, it is easy to wrap them by continuous fiber. The fiber sheets carried shear force directly, and confinement effect is also expected. In case of beams, it is not so easy to wrap, because ordinary beams have floor slabs. Therefore, the development of sheet anchoring method is important to use fiber sheets effectively. The purpose of this research is to develop the anchorage system for carbon fiber (CFRP) sheet using steel angle plates and chemical anchor bolts for post strengthening of RC structures. Newly designed specimens, which represent a corner part of a beam with slab (L-shape specimen), are strengthened by CFRP sheet and tested by uniaxial tensile loading. The test variables are amount of CFRP sheet (weight per unit area), size of angle plate, thickness of ribs (rigidity of angle plate), diameter of anchor bolts. Experimental results show that the rigidity of angle plate and anchor bolt has much influence to the bond strength of CFRP sheet. The bond slip failure occurs within the certain value of deformation of angle plate.

INTRODUCTION

The South Hyogo Earthquake, which occurred at January 17, 1995 in Japan, damaged a quite number of reinforced concrete (RC) structures. In Japan, two major revisions of the standard law for RC buildings were carried out. The first revision was in 1970, and the second revision was carried out in 1981. The last revision is still effective in the present law. These changes of the laws cause the differences of damage levels by constructed years of RC buildings. In addition, it is considered that the present law is most enough for seismic performance. However, a huge number of buildings constructed before 1981 are still exist in all over Japan. If the earthquake with same scale of last earthquake occur in another city, a lot of buildings will be destroyed. It is quite necessary to strengthen or upgrade old buildings constructed before 1981.

Recently, strengthening method using continuous fiber, such as carbon, glass and aramid have been focused because of its simplicity for construction site and economy. In case of columns, it is easy to wrap them by continuous fiber. The fiber sheets carried shear force directly, and confinement effect is also expected. In case of beams, it is not so easy to wrap, because ordinary beams have floor slabs. Therefore, the development of sheet anchoring method is important to use fiber sheets effectively.

This research focuses on the newly developed anchoring method using steel angle plates and anchor bolts. As shown in **Figure 1**, carbon fiber (CFRP) sheet is put on the bottom and side faces of beams with epoxy resin, and then steel angle plates are bonded at the corner part of beams. The holes are made on the bottom surfaces of slabs and the angle plates are fixed to the slabs using steel anchor bolts. In this system, tensile stress of CFRP sheet is transferred to the slabs via an adhesive, angle plate and anchor bolts. In this research, tests on bond between steel plates and sheets was conducted. Also, an experimental investigation on end anchorage near the

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beam-slab or column-wall meeting corner using localized specimen models was done. The main concern of the experiments is to investigate the effects of bond between steel plate and sheet and of the configurations of angles and anchor bolts on the anchorage strength and failure process. Using line models for angles and anchor bolts, a quantitative evaluation of the relation between the applied load and the displacement of steel angle when the failure is on sheet bond was carried out.

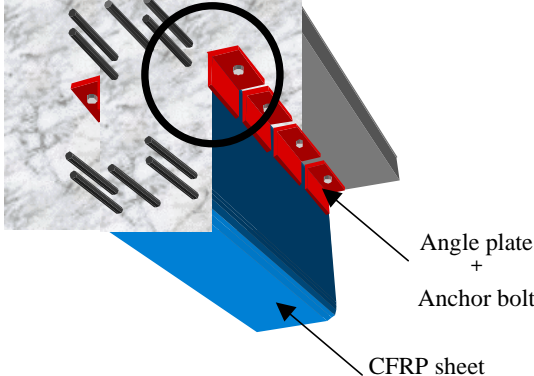


Figure 1: Anchorage system for RC beam.

STEEL AND SHEET BOND TEST

Outline of Experiment

The configurations of specimens are shown in Figure 2. Both faces of a steel plate (SS400) with epoxy resin are attached to sheets with a unit weight of 300g/m², a nominal rupture strength of 3500 MPa, and an elastic modulus of 230 GPa to carry out a bond test. The parameters are sheet layer, which is varied from one to three layers, and bonded length that ranges from 10 mm to 270 mm. There is a total of 36 specimens with twelve variations at three specimens per variation. Pullout forces were applied at the top and bottom ends of the steel plate using a 200 kN universal testing machine. The tensile force and strains on both faces of the sheet were recorded.

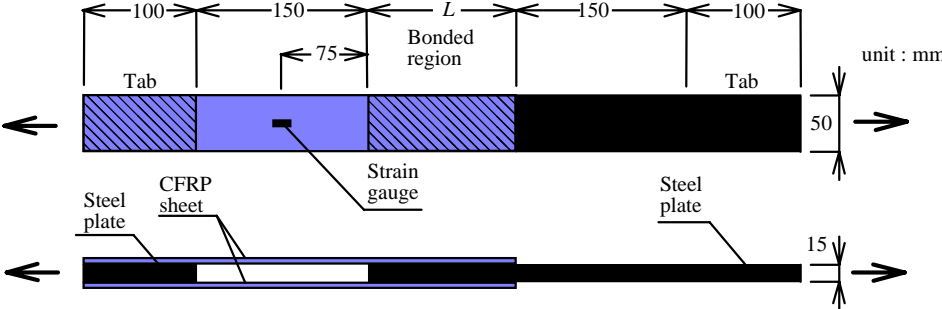


Figure 2: Configurations of bond test specimens

Failure Process

In specimens with one layer of sheet and with 10 mm and 30 mm bonded length, bond failure occurred at the bonded surface of steel and epoxy resin. Those with bonded lengths of 60 mm and 180 mm failed by rupture of sheet. The portion of the sheet at the bonded portion was almost not affected by rupture and the appearance remained almost the same as the original. In the case of specimens with two layers and with bonded length of 30 mm, the epoxy resin was ultimately sheared off. However, both sheet rupture and shearing off failure were observed when bonded length was 60 mm. When the bonded length was 120 mm and 180 mm, sheet remained intact at the bonded region but a phenomenal shearing between sheet layers was seen and the failure ultimately led to rupture of the sheet. Specimens with three layers of sheets and with bonded length of 30 mm, a shearing of epoxy bond occurred. When the bonded length became 90 mm the failure was more on epoxy bond shear-off although one part of a sheet was ruptured.

Maximum Load - Bonded Length Relation

Figure 3 shows the relation between maximum load and bonded length. As the bonded length increases, the maximum load gets bigger but above a certain length the maximum load remains almost the same. A straight line obtained through regression is plotted at the increasing region and another line approximating the constant load region is connected. The bonded length values at the intersections can be obtained as: 58 mm when there is one layer of sheet, 73 mm for two layers and 87 mm for three layers. The effective bond stress region between sheet and steel is not the whole bonded surface but only a portion of the region.

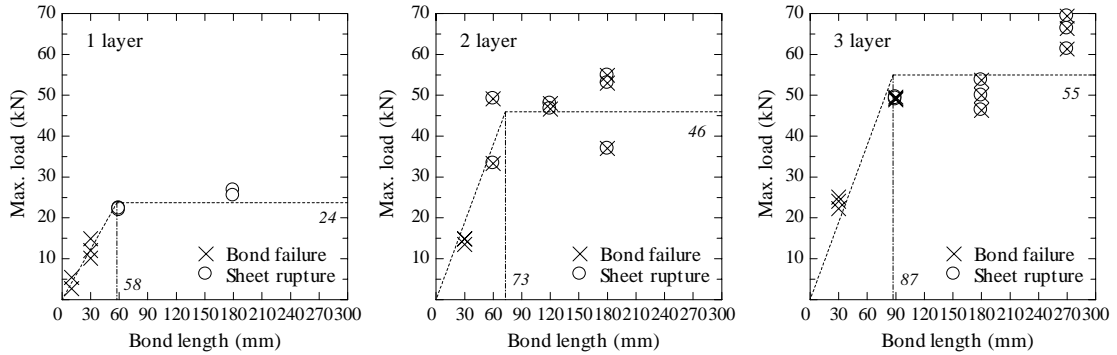


Figure 3: Relation between maximum load and bonded length

SHEET EDGE ANCHORAGE TEST

Outline of Experiment

Figure 4 shows the features of specimens. The specimens are localized models of the meeting corners of a beam with slab. Anchor bolts for slabs of actual buildings were used. The size is M16 and the length is 160 mm (10 times the diameter). If the allowable tensile stress of the anchor bolt is 500 MPa, the capacity becomes approximately 100 KN. Considering the case until two layers of sheets and a unit weight of 300 kg/m², the width of the sheet was made to be 80 mm (rupture strength = 3500 MPa; 94KN). From the results of steel angle bond tests, a size of 100 mm x 100 mm was selected. The anchorage details are illustrated in Figure 5.

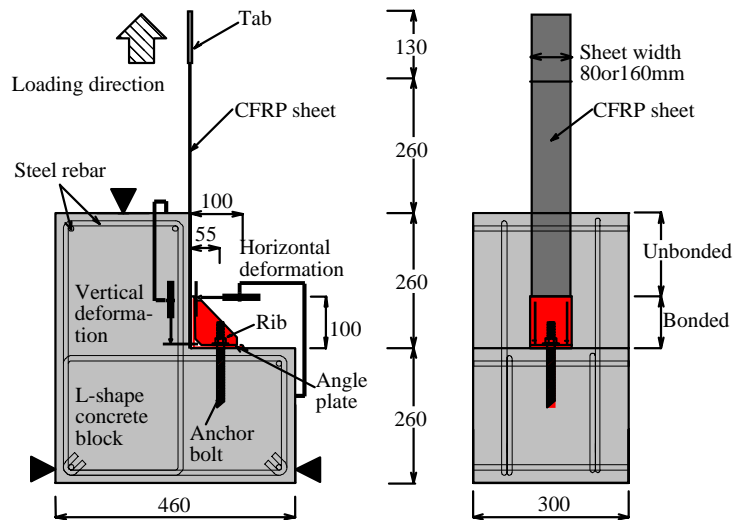


Figure 4: Configurations of anchorage test specimens

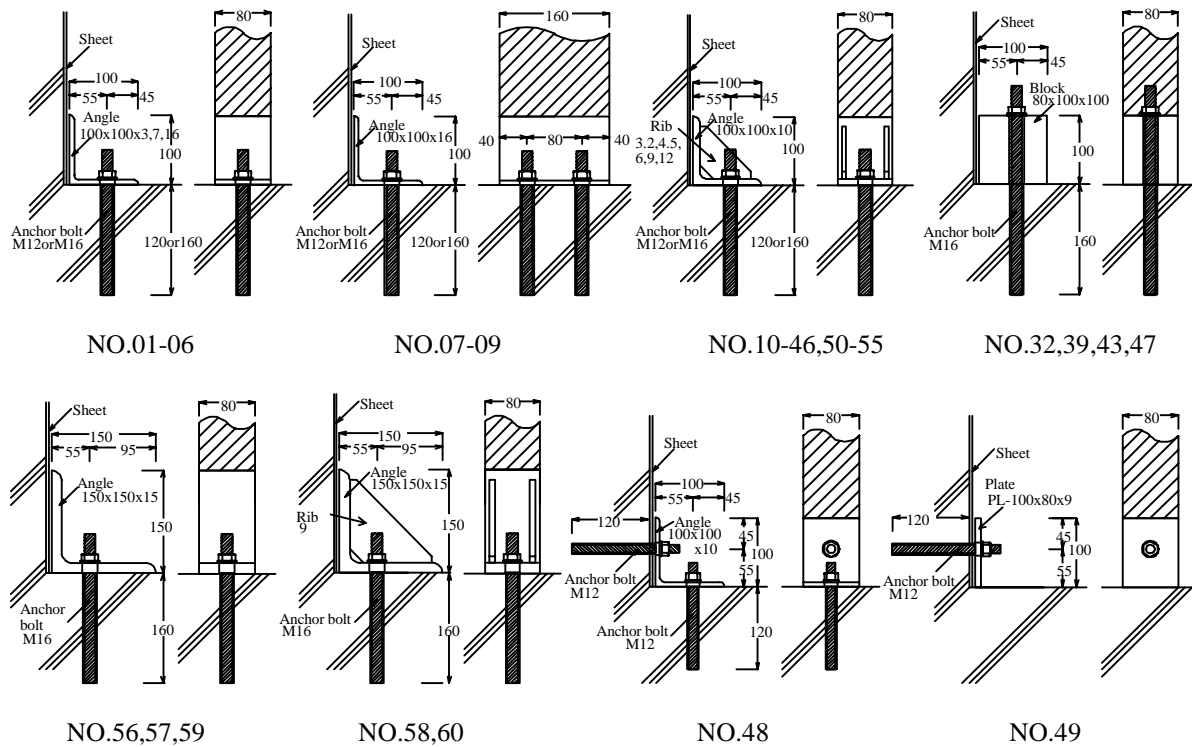


Figure 5: Anchorage details

The bonded region between sheet and concrete is similar to steel angle anchorage. After applying a primer to the concrete surface, sheet is attached to concrete using epoxy resin. Afterwards, putty-like epoxy resin is applied to the angles which are then anchored by bolts. In this experiment, the anchors are chemically bonding and the anchor bolts are screw type with threads and are tightened through the nuts. The test variations are as follows: A, unit weight (100, 200, 300g/m² and 300g/m² with two layers); B, width of sheet (80, 160 mm); C, anchor bolt diameter (M12, M16); D, anchor bolt embedded length (5d, 10d); E, number of anchors (1, 2 pieces); F, angle size (100 x 100 x 3, 7, 10, 16mm and 150 x 150 x 15 mm); G, rib thickness (3.2, 4.5, 6, 9, 12mm); H, sheet manufacturing process (pre-pregnant sheet : previously impregnated resin on the sheet, site construction : resin is applied in the construction site); I, putty-like angle anchorage epoxy (A type : viscosity type, B type). The total number of specimens is 60. Concrete compressive strength varied from 20.2 to 43.7MPa. Mechanical properties of CFRP sheets are shown in

Table 1: Mechanical properties of CFRP sheet

Unit weight (g/m ²)	Nominal Thickness (mm)	Specific gravity	Rupture strength (MPa)	Elastic modulus (GPa)	Elongation (%)
100	0.0555	1.8	3,500*	230*	1.5*
200	0.111	1.8	3,855	244	1.58
300	0.167	1.8	3,970	251	1.58

* nominal value

With regards to the steel angle used in anchoring the sheet, the cross section is L shape steel (SS400), 100 x 100 x 3, 7, 16mm. Specimen 1 to 9 are 100 x 100 x 3, 7, 16mm. Specimen 10 to 55 (excluding specimen 32, 39, 43, 47) are 100 x 100 x 10mm and to increase the rigidity, rib thickness are varied into 3.2, 4.5, 6, 9, 12mm. In specimens 56 to 60, the angle size is 150 x 150 x 15mm and the rib thickness used is 9mm. In specimens 32, 39, 43 and 47, in order to make the rigidity of the angle be infinite, an 80 x 100 x 100mm blocks were made. In

specimen 48 the angle is 100 x 100 x 10mm. Sheets are anchored by bolts on concrete. Specimen 49 has a 100 x 80 x 9mm plate.

A 2-MN universal testing machine was used in loading the specimens. The concrete material was fixed at the head of the testing machine and the upper end of the sheet is pulled upward. The recorded quantities were: tensile load P , vertical and horizontal displacement of the angle, δ_v and δ_h , anchor bolt strain and the observed failure process.

Failure Process

In the case of Specimen 1 to 9 where angles had no rib stiffeners, sheet and concrete bonded surface was sheared off from the upper portion, after which, while sheet was bonded to the angle, the pullout load increased. Due to inadequate rigidity, angles warped at unanchored portions. Ultimately, the bond between sheet and angle was lost and a pullout failure occurred when the load was about 60 to 70 percent of the rupture strength as can be observed. In specimen 10 to 15 where the unit weight was 100 g/m², angles with rib stiffeners almost remained undeformed and sheet rupture was the ultimate failure.

Specimen 16 to 25 with unit weight of 200 g/m² failed due to progressive disbonding of sheet from concrete and consequently from the angle. There was a vertical movement of the angle by 1.0 - 2.4mm but due to rib stiffeners, the angles were not deformed. The ultimate failure was sheet rupture. When the unit weight was 300g/m² in the case of specimen 26 to 39, the failure was due to progressive disbonding of sheet from concrete and consequently from the angle. A vertical movement of the angle by 1.2 - 3.7mm was observed. Ultimately, epoxy resin between angle and sheet was progressively crushed and that caused cracks. When the remaining bonded region lost its resistance, a pullout failure occurred at a load level approximately 60 - 90% of the sheet rupture strength. Moreover, specimen 32 and 39, that have angles considered to have infinite rigidity, the mode of failure was the same. In the case of specimen 40 to 47 which had a unit weight of 300g/m² and two layers of sheets, the failure was due to progressive disbonding of sheet from concrete and consequently from the angle. A vertical movement of the angle by 1.4 - 3.2mm was observed. Ultimately, epoxy resin between angle and sheet was progressively crushed and that caused cracks. When the remaining bonded region lost its resistance, a pullout failure occurred at a load level approximately 40 - 50% of the sheet rupture strength. Specimen 43 and 47, that have angles considered to have infinite rigidity, the mode of failure was the same. Also, cone-shape crushing due to anchor bolt occurred at the same time.

In the case of specimen 48 where sheets were anchored at both surfaces of concrete by bolts, there was almost no deformation of angle and the final failure was sheet rupture. In specimen 49 that used plate as anchor, the plate moved by about 1.4mm vertically and the ultimate failure was sheet rupture.

In the case of specimen 50 to 55 that used M12 anchor bolts, had embedded lengths of 5d and 10d, and had a unit weight of 100g/m², there was no effect due to embedded length variation and the failure was sheet rupture. When the unit weight were 200 and 300g/m² and the embedded length was 10d progressive disbonding of sheet from concrete happened until it reached the angle. A vertical movement of the angle by about 3.5mm was noticed. A pullout failure occurred at a load level approximately 30 - 60% of the sheet rupture strength. When the embedded length was 5d progressive disbonding of sheet from concrete happened until it reached the angle and the final collapse was due to bond failure between sheet and angle together with cone-shape crushing of concrete by the anchor bolt.

In the case of Specimen 56 to 60 with angle size of 150 x 150 x 15mm and had no rib stiffeners, sheet and concrete bonded surface was sheared off from the upper portion until it reached the angle. The maximum vertical movement of the angle was approximately 2.0mm. Ultimately, epoxy resin between angle and sheet was progressively crushed and that caused cracks. When the remaining bonded region lost its resistance, sheet rupture occurred when the unit weight was 200g/m² but when the unit weight was 300g/m² and there were one and two layers of sheets, pullout failure occurred at a load level approximately 50 - 70% of the sheet rupture strength. Specimens with 9mm rib stiffeners, unit weight of 300g/m², one and two layers of sheet, pullout failure occurred at a load level approximately 50% of the sheet rupture strength (see (k))

Effects of Varied Factors

Effect of rib

The relation between the maximum loads of specimens without ribs and angle thickness is shown in Figure 6. In specimen 1 to 9, as the angle thickness increases, the load increases. All failures are by direct pullout. In order to

reach the sheet rupture, the angle thickness should be increased. Specimens with greater rigidity due to rib stiffeners reached sheet rupture such as specimen 16 with a unit weight of 200g/m^2 and angle thickness of 3.2mm . When the sheet width is 160 such as in specimen 7 to 9, the failure mode was direct pullout. This implies that angles should be stiffened with ribs.

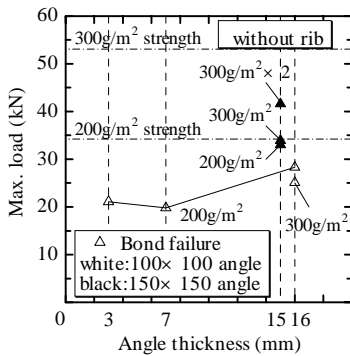


Figure 6: Specimens without ribs

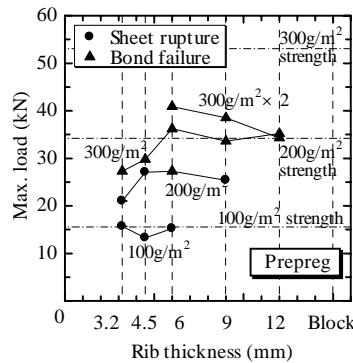
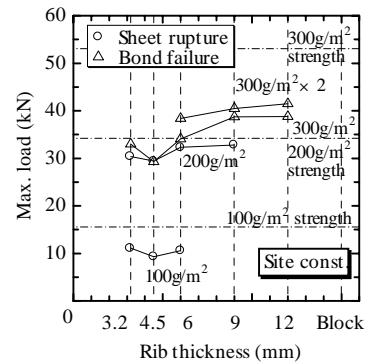


Figure 7: Maximum load and rib thickness



Effect of rib thickness

Figure 7 shows the relation between maximum load and rib thickness. Specimens with prepreg sheet and site construction sheet are plotted for M16 anchor bolts and angle size of $100 \times 100 \times 10\text{mm}$. The maximum loads are almost the same in both cases. In the case of direct pullout failure, as the rib thickness increases, the pullout load increases but when the rib thickness becomes 6mm , the load remains almost constant. When the unit weight is 300g/m^2 and has two layers of sheets, even if the rib thickness is increased, there is no remarkable increase in the load due to yielding of anchor bolts.

Effect of unit weight of sheets

Figure 8 shows the relation between maximum load and the unit weight of sheet. Specimens with prepreg sheet and site construction sheet are also plotted for M16 anchor bolts and angle size of $100 \times 100 \times 10\text{mm}$. The maximum loads are almost the same in both cases. Specimens with unit weight of 100g/m^2 and 200g/m^2 the failure is sheet rupture and the maximum load increases. When the unit weight is 300g/m^2 with one or two layers of sheets, the maximum load gets bigger and the failure is direct pullout of sheet.

Effect of size of anchor bolts

As shown in Figure 9, the effect of anchor bolt diameter is shown on the graph showing the relation between maximum load and the unit weight of sheet. In specimens with 6mm rib, angle size of $100 \times 100 \times 10\text{mm}$, and embedded length of $10d$, the maximum load when the diameter is M16 is bigger than that of M12. No much difference in the strain of anchor bolts can be noticed. Rib thickness and anchor bolt rigidity affect the maximum load.

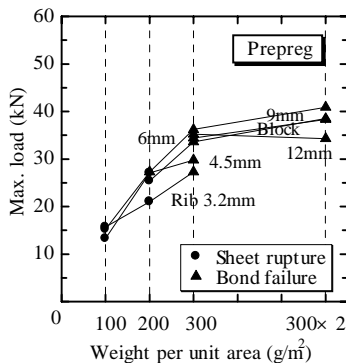


Figure 8: Maximum load and unit weight of sheet

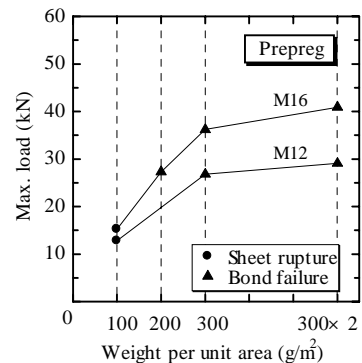
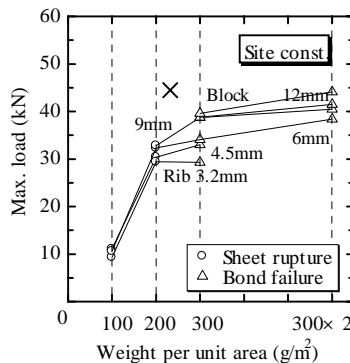


Figure 9: Effect of anchor bolts

Effect of type of resin

Figure 10 shows the effect of type of epoxy resin. The difference in A type and B type does not affect the maximum load.

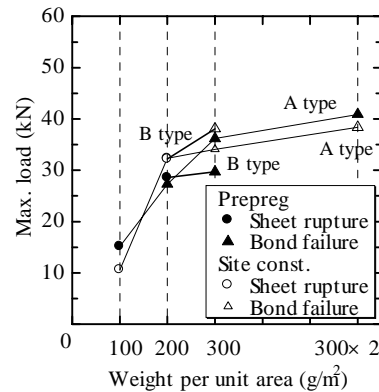


Figure 10: Effect of resin type

Sheet Pullout Failure Mode and Deformation of Angles

The process of failure can be visualized in Figure 11. First, the sheet separates from concrete for the upper portion and progressed until cracks occur. Those cracks penetrate the lower portion of the angle. Until the maximum load that can be resisted by the sheet - angle bond is reached, the bond on angle is slowly sheared off. Finally, when there is a lateral displacement at the upper portion of the angle, the sheet is pulled out.

The details of how the failure progresses between sheet and concrete are shown in Figure 12. Bond between sheet paste and fine aggregates in concrete deteriorates slowly. Frictional resistance also occurs. There is resistance until the frictional capacity is overcome. Figure 13 shows the horizontal deformation of angles at the maximum load in case of pullout failure mode. The horizontal deformations are almost the same value in spite of several rib thickness, i.e. rigidity of angles.

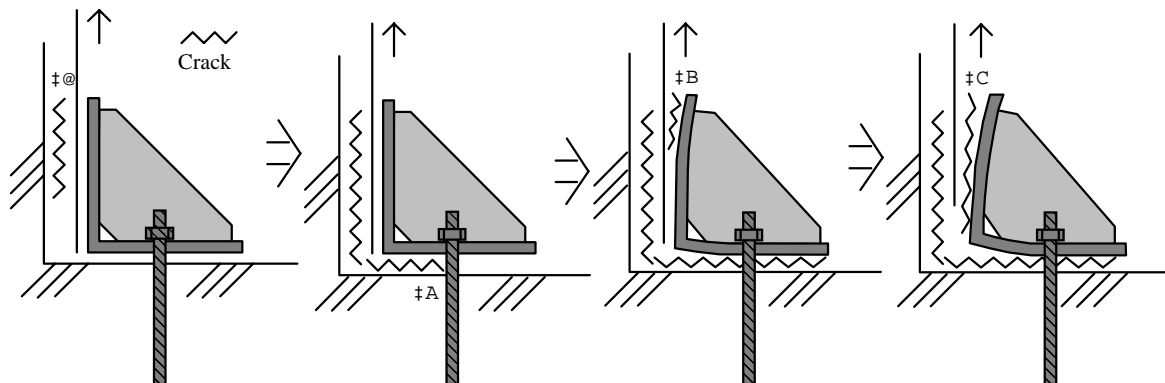


Figure 11: The process of sheet pullout failure

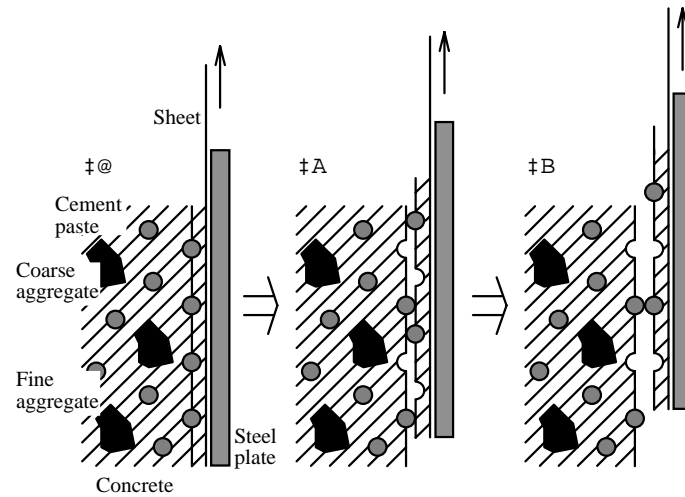


Figure 12: Details of pullout failure

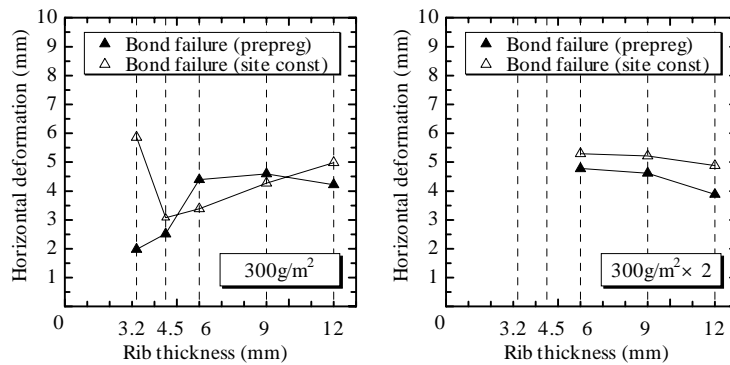


Figure 13: Horizontal deformation of angle at the maximum load

CONCLUSIONS

1. The effective bond stress region between sheet and steel is not the whole bonded surface but only a portion of the region. In case of under 3 layers of 300g/m² CFRP sheet, bond length of 100mm is enough for anchor.
2. In case of pullout failure mode in the anchorage test, the lateral displacement of steel angle has a great influence on the resistance. As the rib thickness increases, the pullout load increases but when the rib thickness becomes 6mm, the load remains almost constant.
3. The horizontal deformations of angles are almost the same value in spite of several rib thickness, i.e. rigidity of angles.

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