SEISMIC RETROFITTING OF REINFORCED CONCRETE BRIDGE FRAMES USING EXTERNALLY BONDED FRP SHEETS

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ABSTRACT :
Following the strong earthquakes like Hyogoken Nanbu earthquake in 1995 and Niigataken Tyuetsu Earthquake in 2004, many RC viaducts in Japan were strengthened in the columns. The ductility of such structures, however, may still be limited due to the potential shear failure at the beams. In this research, experimental investigations were conducted in order to study the possible enhancement of seismic behavior of beams by externally bonded fiber reinforced polymer (FRP) sheets. In shear strengthening beams using FRP sheets, full wrapping is not always possible and in U-wrapping, debonding failure of FRP sheet limits the proper utilization of its strength. Therefore, in this research FRP sheets were mechanically anchored to the beams. A total number of six specimens with different wrap configurations and mechanical anchorage schemes were tested. Experimental results showed that a proper selection of mechanical anchorage scheme for FRP sheet in U-wrap portion is necessary for the significant enhancement of shear strength of RC beam close to that of a fully wrapped beam.

KEYWORDS:
FRP, RC beams, shear strengthening, debonding, mechanical anchorage

1. INTRODUCTION

Strong earthquakes such as Hyogoken Nanbu earthquake in 1995 and Niigataken Tyuetsu Earthquake in 2004 demonstrated that RC viaducts constructed prior to the implementation of modern seismic design codes are vulnerable to impending earthquakes as many of them showed shear failure in the columns (Hamada 1995). Following the earthquake many RC viaducts in Japan were strengthened in the column portion (Takahashi et al. 1996, Tobuchi et al. 1999, Kamogawa et al. 1999, Kawashima 2000). It was, however, found that the ductility of such structures may be limited due to the potential shear failure at beams (Zatar & Mutsuyoshi 2004).

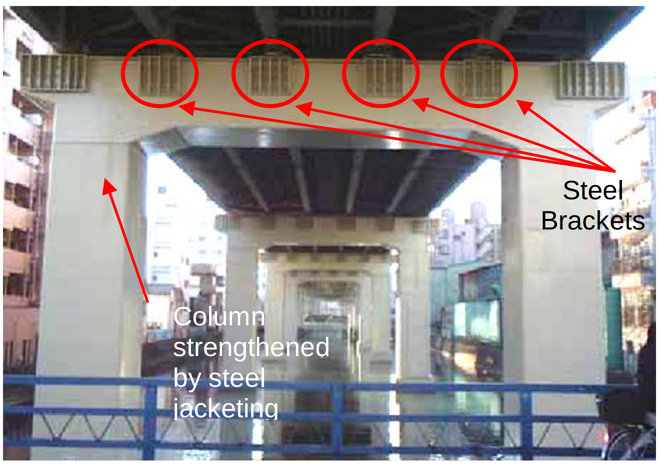


Figure 1 A typical RC frame of a highway bridge in Japan.

For a desirable performance of such structures under strong earthquakes, retrofitting of beams also becomes essential. In this research, experimental investigations were conducted in order to study the possible enhancement of seismic behavior beams by externally bonded aramid fiber reinforced polymer (AFRP) sheets. Previous researches (Uji 1992, Al-Sulaimani et al. 1994, Challal et al. 1998, Khalifa et al. 1998, Triantafillou & Antonopoulos 2000) showed that, enhancing the shear strength of beams can improve the seismic performance of the frames and the degree of enhancement depends on the wrap configuration of the FRP sheets. Especially with U-wrap condition, it is evident that the optimal utilization of FRP material strength could hardly be achieved due to the premature debonding of sheets from the concrete surface (Adhikary & Mutsuyoshi 2004). Especially in the beams strengthened by side plates or U-wrap, the average effectiveness ratio of FRP sheet, which is the ratio of FRP strain at failure to the ultimate tensile strain of FRP sheet, is limited to a value approximately equal to 0.15 to 0.25 (Taljsten 2003).

Figure 1 shows a picture of a typical RC frame of a highway bridge in which the columns have already been strengthened by steel jacketing. Shear strengthening of the beams of such frames is difficult due to the presence of large steel brackets on beams, primarily installed to ease the process of replacing rubber bearings between the beam and girders. Due to this, full-wrapping of the entire beam with FRP sheets is not possible. This paper, therefore, sheds light on the usage of mechanical anchorage system in the beams strengthened by U-wraps to prevent the premature debonding failure and enhance the degree of utilization of FRP material strength.

2. EXPERIMENTAL PROGRAM

A total number of six beam specimens representing the beam portion of RC bridge frames were tested. Steel brackets present in the actual beams were modeled by fixing a 300 × 100 × 3.2 mm steel plate. The beams were strengthened by AFRP sheets with full wrapping in the two third length of shear span while U-wrapping was done in the portion of steel brackets.

2.1. Details of test specimens

The geometric details and reinforcement arrangements of the test specimens are shown in Figure 2. The test specimens had an overall length of 3600 mm and a cross-section of 300 × 300 mm. Loading arrangement was done by keeping a shear span of 1000 mm. Four deformed bars with 32 mm in diameter were used as longitudinal tension reinforcements while four deformed bars with 22 mm in diameter were used as longitudinal compression reinforcements. Table 1 shows the experimental parameters of all the tested specimens.

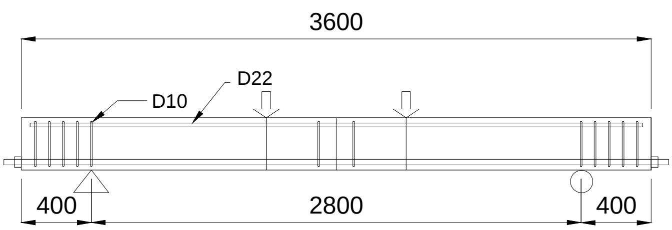


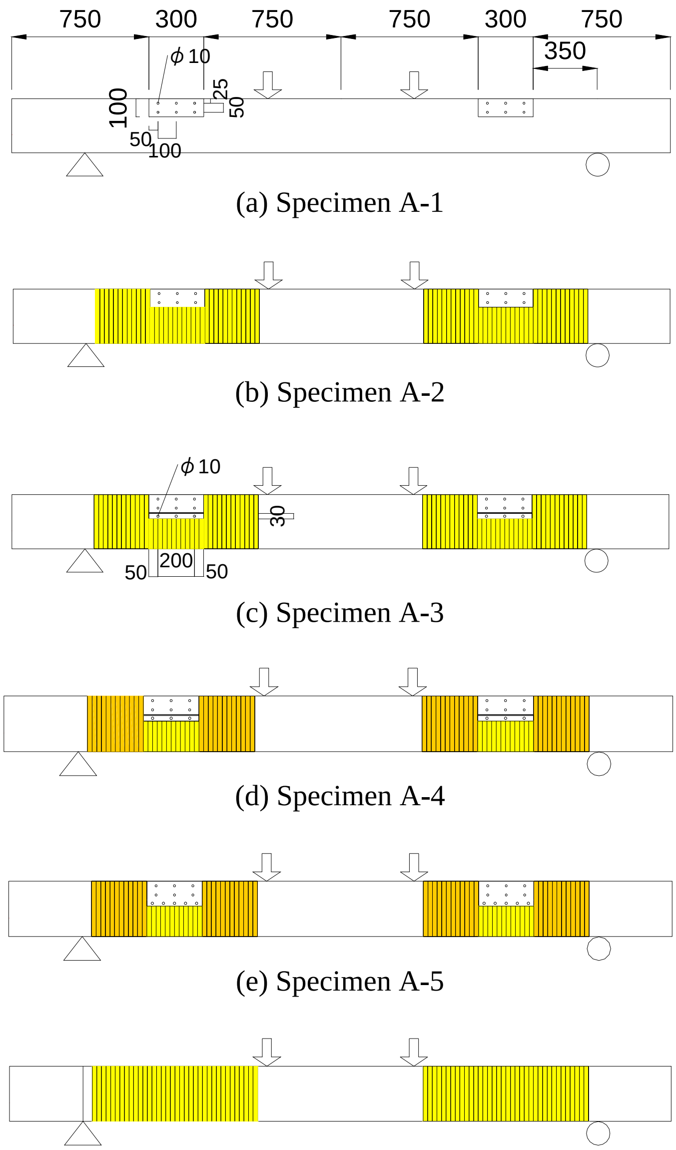
Figure 2 Reinforcement details.

The properties of concrete at loading day is shown in Table 1. Unstrengthened specimen A-1 was purposely designed to fail in shear. Therefore, stirrups were not provided at shear span. A large number of stirrups were provided outside the support to prevent the undesirable anchorage failure.   Full-Wrap specimen was designed to fail in flexure mode.

Specimen A-2 was conventionally strengthened by AFRP sheets without proving any mechanical anchorage. Specimen A-3 and A-4 were provided with Type I mechanical anchorage. The difference in these two specimens was in the number of layers of AFRP sheets applied in the portion of full wrap. Specimen A-4 had an additional layer of AFRP sheet. Specimen A-5 had two layers of AFRP sheet in the full wrap portion and was provided with Type II mechanical anchorage.

Table 1 Compressive strength of concrete, FRP wrapping and anchorage details.

Sp. ID	Compressive strength of concrete (MPa)	No. of FRP layers in full wrap	Type of Anchorage
A-1	36.9	-	-
A-2	33.8	One	-
A-3	36.4	One	Type I
A-4	37.7	Two	Type I
A-5	36.3	Two	Type II
Full-Wrap	40.4	One	-



(a) Specimen A-1

(b) Specimen A-2

(c) Specimen A-3

(d) Specimen A-4

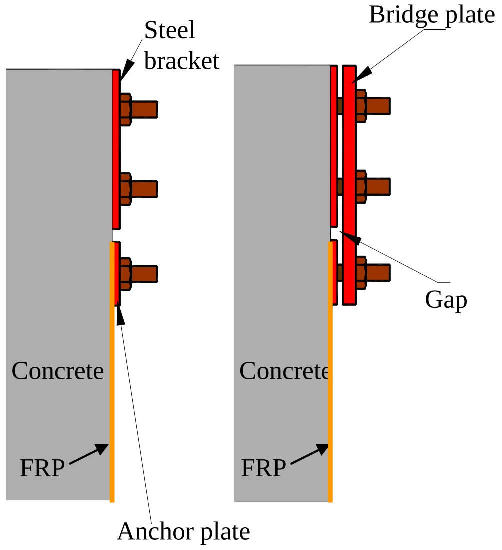
(e) Specimen A-5

(f) Specimen Full-wrap

Figure 3. Details of test specimens.

2.2. Mechanical anchorage

Mechanical anchorage was used to prevent the lack of optimal utilization of the material strength of FRP sheet due to premature debonding failure. Figure 4 schematically shows the two types of mechanical anchorage studied in this research. Type I mechanical anchorage is a rather simple one. The upper ends of U-wraps anchored to the concrete using an anchor plate and a number of anchor bolts. Type II mechanical anchorage is a comprehensive one with the anchorage connected to the steel bracket using a bridge plate.



(a) Type I Anchorage (b) Type II Anchorage

Figure 4 Mechanical anchorage.

2.3. Test setup

The test setup of the specimen was as shown in Figure 5. All beams were tested under four-point monotonic loading. A load cell was used to measure the load applied on the specimen through a hydraulic jack. Displacement of the specimen at mid span was measured using a linear variable differential transformer (LVDT).

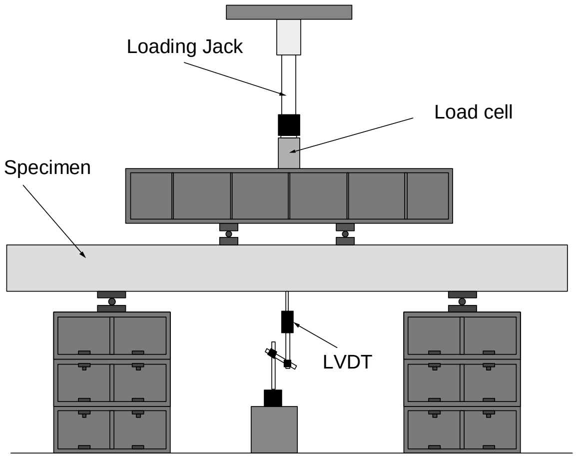


Figure 5 Test setup.

Initiation and propagation of cracks were monitored by visual inspection during testing. Debonding of FRP sheets and its progress was observed by using a pearl hammer.

2.4 Materials

The concrete used was ready-mixed, normal weight concrete with a 20 mm maximum size coarse aggregate and an average slump of 150 mm. The compressive strength of the concrete on the day of the loading test is shown in Table 1. Deformed bars of 22 mm and 32 mm in diameters were used as longitudinal bars and their yield strengths were determined by tensile test as 397 and 410 MPa, respectively.

AFRP sheet with the thickness of 0.286 mm, tensile strength of 2060 MPa and modulus of elasticity of 118 GPa was used for shear strengthening. Both the anchor bolts and the bolts used for fixing steel brackets had the yield strength of 400 MPa.

3. RESULTS AND DISCUSSIONS

3.1 Load-displacement curve

Figure 6 shows the load displacement curve of all the tested specimens. As expected the unstrengthened Specimen A-1 failed in shear at the load of 213 kN while Full-wrap specimen failed in flexure with the load carrying capacity of 549 kN. With the use of externally bonded FRP sheets in Specimen A-2, a significant improvement in shear strength to 455 kN was observed but the failure was due to the rupture of FRP sheets near steel bracket followed by the debonding of FRP sheets at U-wrap portion just below the steel bracket. In Specimen A-3 with Type I mechanical anchorage, the enhancement of shear capacity was not as impressive and final failure was due to the rupture of FRP sheet near steel bracket similar to the Specimen A-2. In Specimen A-4, Type I mechanical anchorage was used below the steel bracket while two layers of FRP sheets were used in the portion of full wrap. In this specimen due to stronger FRP sheets in full wrap portion some enhancement of shear capacity was observed but the final failure was again due to the rupture of FRP sheets. In order to enhance shear capacity and prevent shear failure a Type II mechanical anchorage was developed and was used in Specimen A-5. The behavior of Specimen A-5 was similar to the Full-Wrap specimen with the maximum load carrying capacity of 544 kN. The specimen failed in flexure mode prior to the yielding of longitudinal reinforcements.

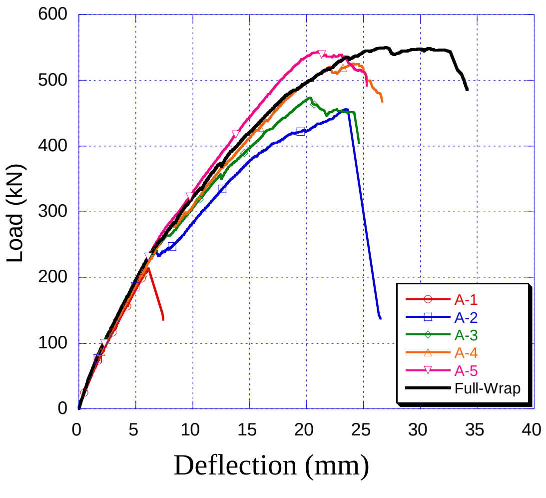


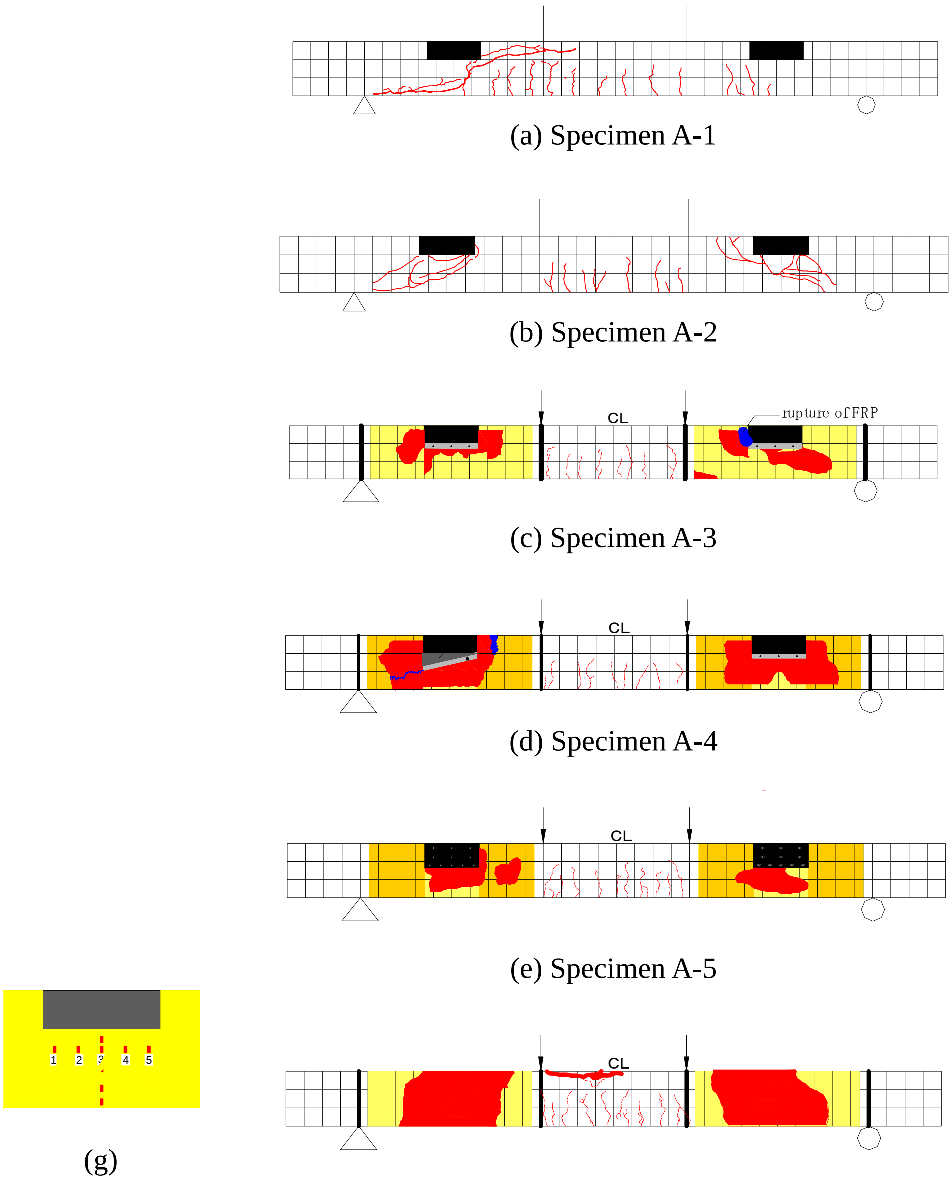
Figure 6 Load-displacement curve.

3.2. Cracking pattern

Figure 7 shows the cracking pattern of all the tested specimens at the ultimate state. Specimen A-1 failed in shear, which is evident from the wide diagonal shear crack at the ultimate state. In specimen Full-Wrap local

debonding of FRP sheets occurred after the applied load exceeded the shear strength of concrete. FRP sheet, however, continued to carry further load due to full wrapping. The specimen finally failed in flexural compression mode.
Specimen A-2 without mechanical anchorage also failed in shear followed by the debonding of FRP sheet below the steel bracket. Specimen A-3 with Type I mechanical anchorage performed in a better way in early stage but once the shear cracks between the steel bracket and anchor plate started widening, the FRP sheet in the U-wrap was no longer capable of carrying further load and finally the specimen failed in shear followed by the rupture of FRP sheet adjacent to the steel brackets. Specimen A-4 also failed in a similar pattern. An additional layer of FRP sheet in the portion of full-wrap only delayed the rupture of FRP sheets adjacent to steel brackets.

Specimen A-5 with Type II mechanical anchorage behaved in a way similar to that of Full-wrap specimen. Due to the presence of bridge plates between anchor plate and steel bracket, widening of crack between them was prevented. Due to this the FRP sheet in the U-wrap portion was fully functional. Similar to the Specimen Full-Wrap, Specimen A-5 failed in flexural compression mode.



(a) Specimen A-1

(b) Specimen A-2

(c) Specimen A-3

(d) Specimen A-4

(e) Specimen A-5

(g)

(f) Full-Wrap

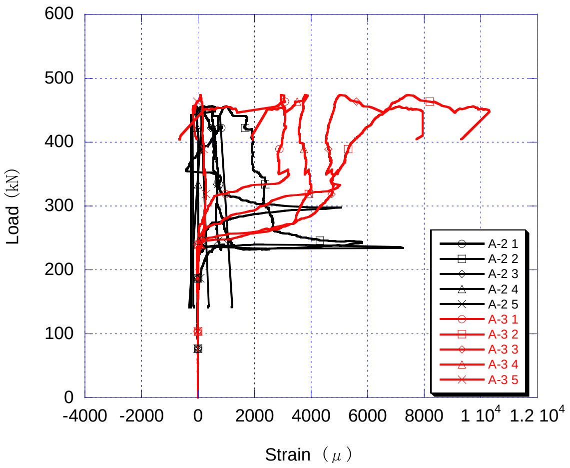
Figure 7 Condition of specimens at the ultimate state (a-f) and location of strain gages in U-wrap.

3.3. Strain in FRP sheets

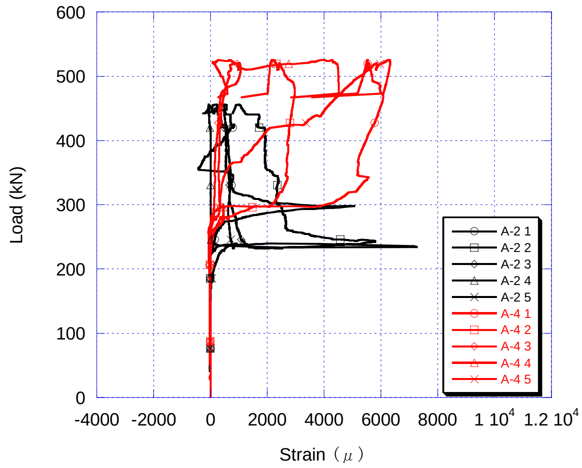
Strains developed in FRP sheets were measured during the experiments by an array of strain gages. Figure 7(g) schematically shows the location of five strain gages in the portion of U-wrap just below the steel brackets and the mechanical anchorage.

Figure 8 shows the comparison of strains developed in FRP sheets of mechanically anchored specimens with those of unanchored specimen. In specimen A-2 without mechanical anchorage, initiation of debonding resulted in an abrupt drop in strain due to the delamination of sheet from concrete surface. Due to debonding, U-wrapping without anchorage was not every effective. In specimen A-3 and A-4 with Type I mechanical anchorage, strain in FRP sheets increased with the increase in applied load but after the cracks started widening between the steel bracket and anchor plate, the strains in the sheet thus remained constant. Since the strains did not drop after debonding, this mechanical anchorage was functional. Due to the growth in the crack width in the gap, however, the FRP sheet in the U-wrap portion was still ineffective.

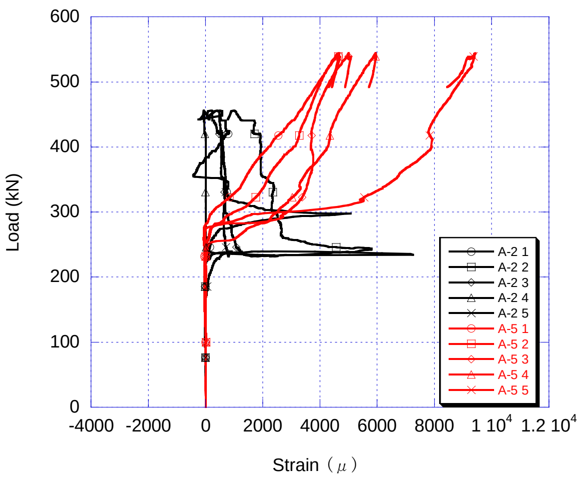
In specimen A-5 with Type II mechanical anchorage, a bridge plate was provided to control the opening of crack in the gap. Due to this the strain in FRP sheets continued to increase with the increase in applied load until the specimen failed in flexure. These results show that the Type II mechanical anchorage is effective in the optimal utilization of FRP strength in the U-wrap portion.



(a) Specimen A-2 and A-3



(b) Specimen A-2 and A-4



(c) Specimen A-2 and A-5

Figure 8 Comparison of FRP strains of anchored and unanchored specimens.

4. CONCLUSIONS

An experimental investigation on shear strengthening of the beam portion of one-story RC frame by externally bonded FRP sheets was carried out. Based on the study the following conclusions are drawn:

- In strengthening RC beams using externally bonded FRP sheets, full wrapping is not always possible and U-wrapping does not ensure a reliable enhancement in shear capacity.
- Improper mechanical anchorage can become totally ineffective in enhancing the performance of shear critical RC beams.

A comprehensive mechanical anchorage system can effectively enhance the shear strength of RC beams to a level close to that of fully wrapped beams.

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