AFRP retrofitting of RC structures in Japan

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ABSTRACT: In Japan, many reinforced concrete (RC) bridge structures that were designed and constructed before the introduction of the modern seismic design codes collapsed in the 1995 Hyogoken-Nanbu Earthquake and the 2004 Niigataken-Tyuetsu Earthquake. Following the lessons learnt from these severe earthquakes, proper strengthening schemes were implemented for many existing structures to meet the requirements of the new performance-based earthquake resistant design codes. The application of fiber reinforced polymer (FRP) for strengthening techniques has drawn wide attention due to its advantages such as high strength to weight ratio, corrosion resistance, and ease of execution. This paper introduces current issues related to the deficient RC structural members in Japan and provides an overview of latest innovations in the technology and application of FRP sheets in structural retrofitting. Recent developments on the usage of mechanical anchorage system in strengthening beams of RC bridge frames with externally bonded AFRP sheets is also presented.

1 INTRODUCTION

The 1995 Hyogoken-Nanbu earthquake and the 2004 Niigataken-Tyuetsu earthquake caused widespread damage to RC structures in Japan. It was found that most of the damaged structures during these earthquakes were designed based on the older Japan Society of Civil Engineers (JSCE) standards which existed before the 1980's. The lessons learned from these strong earthquakes have been the main driver for the need of strengthening of RC structures. The various strengthening technologies have been developed including the use of steel jackets/plates, concrete jackets, external post-tensioning and FRP sheets etc.

The application of FRP in civil engineering structures was first introduced in Japan about two decades ago with the development of FRP reinforcement and tendons. Japan has been a pioneer in the research and development of FRP materials for reinforced and prestressed concrete structures especially for bridge engineering. The first JSCE standard specification for the design of FRP reinforcement was published in 1997 and has been adopted in various other countries. Since then, a wide range of applications of FRP materials have been implemented including strengthening of deteriorated structures using FRP sheets and using FRP rods as reinforcement instead of steel. There has been a remarkable increase in the use of FRP sheets, especially carbon and aramid since 1996, as a result of strengthening RC structures (Ueda, 2005).

The high demand of FRP materials in the construction industry has demanded the development of innovative strengthening technologies considering practical applications. This paper introduces some applications of these technologies especially in bridges and highway structures. While various FRP materials have been used for structural rehabilitation, the scope of this paper is limited to the application of FRP sheets. These technologies are discussed through selected case studies using aramid fibre reinforced polymer (AFRP) sheets. The recent developments on the usage of mechanical anchorage system (Pandey et al., 2007) in the RC beams strengthened by U-wraps to prevent the premature debonding failure and enhance the degree of utilization of FRP material strength are also discussed. The results of the experimental investigations conducted in order to study the possible enhancement on the seismic behavior of RC beams by externally bonded AFRP sheets are presented.

2 PROPERTIES OF AFRP SHEETS

2.1 *Stress-strain behavior*

Fig. 1 shows the stress strain behaviour of AFRP sheets compared to other FRP sheets. In retrofitting practice, carbon fibres, aramid fibres and glass fibres are the most commonly used fibres for FRP sheets. Carbon fibre has the highest stiffness and strength, with stiffness comparable with that of steel and a very high strength. Aramid fibres possess lesser strength and stiffness compared to carbon fibres, however, their advantage in handling and execution has made it popular in retrofitting and rehabilitating concrete structures. Glass fibres are also popular in many countries due to its low cost. In Japan, however, glass fibres are not widely used largely due to durability concerns.

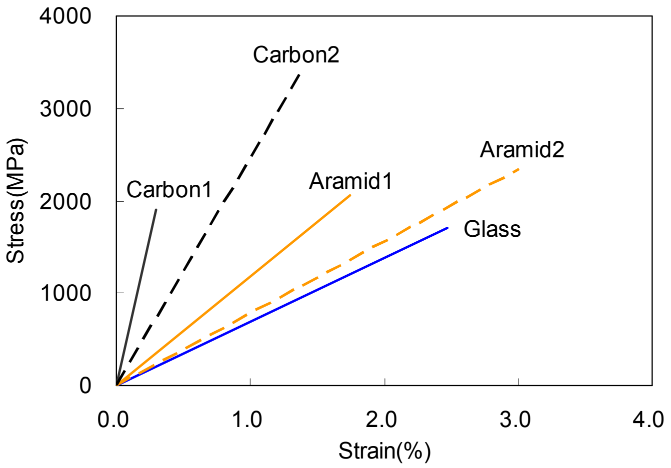


Figure 1. Stress-strain relationship of FRP sheets

2.2 *Comparison of AFRP with CFRP and GFRP*

Table 1 compares the mechanical properties of AFRP sheets with carbon fibre reinforced polymers (CFRP) sheets and glass fibre reinforced polymer (GFRP) sheets. The mechanical properties of CFRP sheet is the best amongst all. However, when it comes to practical application, there are issues related to processing, rounding of corner angles, impregnation of resin, work speed and influence of electrical equipment, where AFRP sheets have distinct advantages. In strengthening RC beams and columns, rounding off corner angles takes a lot of time and effort. Disk sander is sufficient to round off corner angles which save a lot of time and cost using AFRP sheets. GFRP sheets are very economical but due to their inferior mechanical properties and poor resistance to alkali and acid, AFRP sheets are more widely used in Japan.

Table 1. Comparison of FRP sheets.

Properties	AFRP	CFRP	GFRP
Tensile strength (MPa)	2,060-2,350	1,900-3,400	1,400
Young's Modulus (MPa)	245,000-640,000	245,000-640,000	72,000
Tensile capacity (kN/m)	392-1,176	380-570	71
Elongation (%)	1.8	1.5	2.0

2.3 *Comparison with other retrofitting methods*

A number of methods are being used for retrofitting RC structures. The most common ones are the use of concrete lining, steel plates and FRP sheets. Concrete lining has the distinct advantage of being durable but it significantly increases dead weight, requires access for concreting and a long working period during application. Though steel plates used in retrofitting are lighter than the concrete lining, they still require the use of a crane to handle and place into position. Welding is also required to connect plates, which increases the working period. On the other hand, AFRP sheets are non-corrosive, durable and processing is easy and convenient that no crane or access space is required and, hence, the working period is relatively short. The only demerit of using AFRP sheets is the requirement of heating when the temperature goes below 5^{O}C.

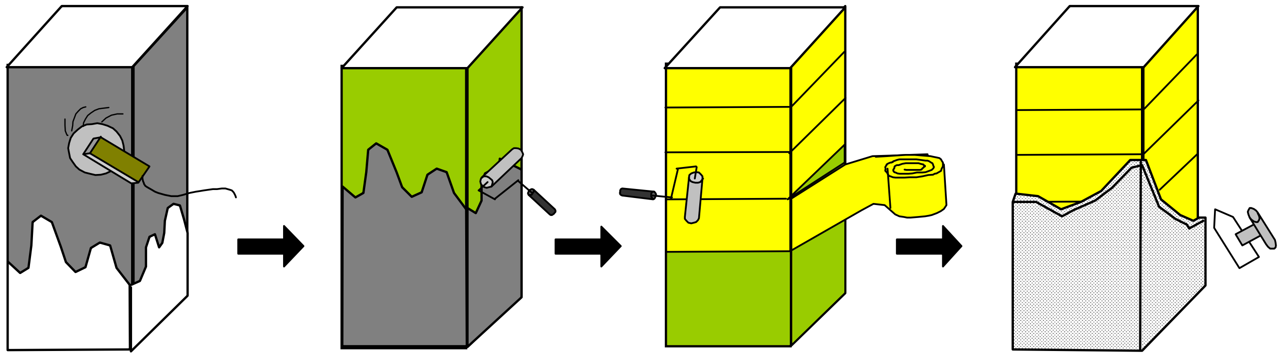
3 APPLICATION OF AFRP SHEETS

3.1 *Steps in applying AFRP sheets*

The application of an AFRP sheet on a concrete surface usually follows the four steps shown in Fig. 2. Surface treatment has to be done on the member where FRP sheet has to be applied to remove surface laitance which are weak. A coat of primer is then applied on the surface followed by a layer of epoxy resin. Fibre sheets are wrapped on the surface by removing trapped air with roller. The final coat of epoxy resin and other protective coats are then applied. This method is called wet lay up which is extensively used in retrofitting existing RC structures.

In retrofitting columns, wrapping horizontally provides confinement of concrete in the absence of adequate ties or shear reinforcement, while wrapping vertically could be suitable for dissolving lack of flexural strength. FRP sheets can be wrapped by either of the two methods shown in Fig. 3. Columns are wrapped by FRP sheet of certain width and with a certain overlap in sheet method. On the other hand, sheets are applied continuously without the need of any overlap in tape method. The second method is effective because it reduces the cost of construction by saving materials and also it is stronger because it does not have any joints.

In strengthening beams, FRP sheets can be applied using either the abovementioned wrapping methods. However, there are cases that full wrapping is not possible to retrofit RC beams. A typical example is the presence of large steel brackets on beams of a highway bridge RC frame in Japan. The usage of mechanical anchorage for externally bonded AFRP sheets in U-wrapping is studied and discussed in the later section.



(a) Surface treatment
(b) Coating primer and epoxy resin
(c) Wrapping sheet and removing air with roller
(d) Coating epoxy resin and protective coating

Figure 2. Process application of AFRP sheets

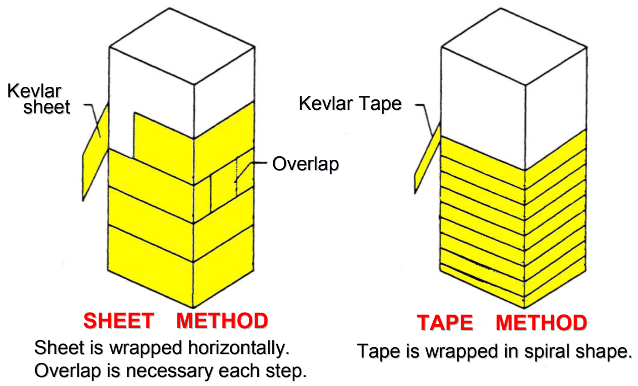


Figure 3. Wrapping methods for AFRP sheets

Figure 4. RC bridge piers retrofitted by AFRP sheets

3.2 *Construction examples*

AFRP has been widely used in Japan in retrofitting RC structures after the strong earthquakes in 1995 and 2004. Design codes were modified and a large number of existing structures have been retrofitted to meet the requirements of the new design codes. Fig. 4 shows the application of externally bonded AFRP sheets for the seismic retrofitting of RC highway piers. A number of buildings have also been retrofitted using AFRP sheets. One of the most important reasons for strengthening is the change in design load due to the alteration of usage such as installation of heavy equipment in a structure. Figures 5a and 5b show some of the applications of AFRP sheets in building structures in Japan.

Applications of AFRP sheets are not limited to building and bridge structures. Other structures have been repaired and retrofitted using FRP sheets. Figures 6 and 7 show the examples of application of AFRP sheets in retrofitting chimney and tunnel respectively. These examples showed the versatility of this method. They also demonstrated that this method does not require heavy machines and does not add additional dead load to the structure.

(a) Retrofitting slab

(b) Retrofitting beam

Figure 5. Application of AFRP sheets in buildings

Figure 6. Retrofitting chimney

Figure 7. Retrofitting tunnel

3.3 *Precast FRP sheets*

Wet lay-up is an excellent method of bonding FRP sheets however it is not always possible due to space limitation and accessibility. The concept of partially precasting FRP sheet has been used in such instances. Figures 8 and 9 schematically illustrate the application of precast FRP sheets in beams and columns respectively. Precast portions are used in inaccessible region while wet lay-up is used in the remaining portions.

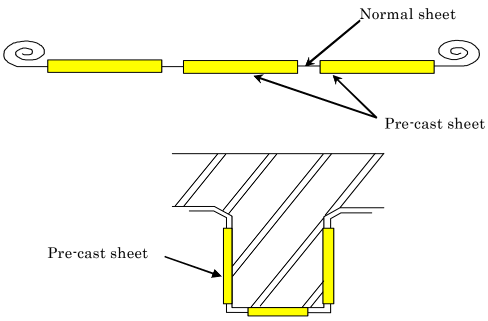


Figure 8. Application of precast FRP sheets in beams

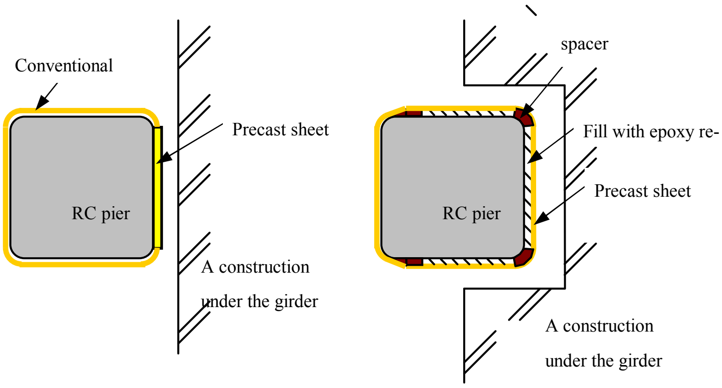


Figure 9. Application of precast FRP sheets in columns

4 MECHANICALLY BONDED AFRP SHEETS

In this section, the result of experimental investigations to study the application of mechanical anchorage on transverse beam of RC bridge frames with externally bonded FRP sheets is discussed.

4.1 *Experimental program*

A total of six beam specimens representing the beam portion of RC frames of a highway bridge in Japan were tested. Steel brackets were modeled by fixing a 300x100x3.2 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 the brackets.

The geometric details and reinforcement arrangements of the test specimens are shown in Figure 10. The test specimens had an overall length of 3600 mm and a cross-section of 300x300 mm. Loading arrangement was done by keeping a shear span of 1000 mm. Four 32 mm diameter deformed bars were used as longitudinal tension reinforcements while another four 22 mm diameter deformed bars were used as longitudinal compression reinforcements. Table 2 shows the experimental parameters of all the tested specimens as well as the properties of concrete at loading. The details of each beam specimens are shown in Figures 11a to 11f. Unstrengthened specimen A-1 was designed to fail in shear, thus stirrups were not provided at shear span. Full-wrap specimen was designed to fail in flexure mode. Specimen A-2 was strengthened by AFRP sheets without any mechanical anchorage. Specimen A-3 and A-4 were provided with Type I anchorage. 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 anchorage.

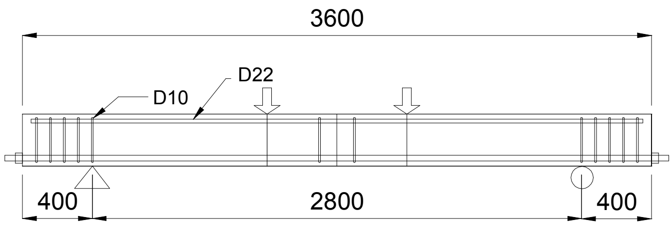
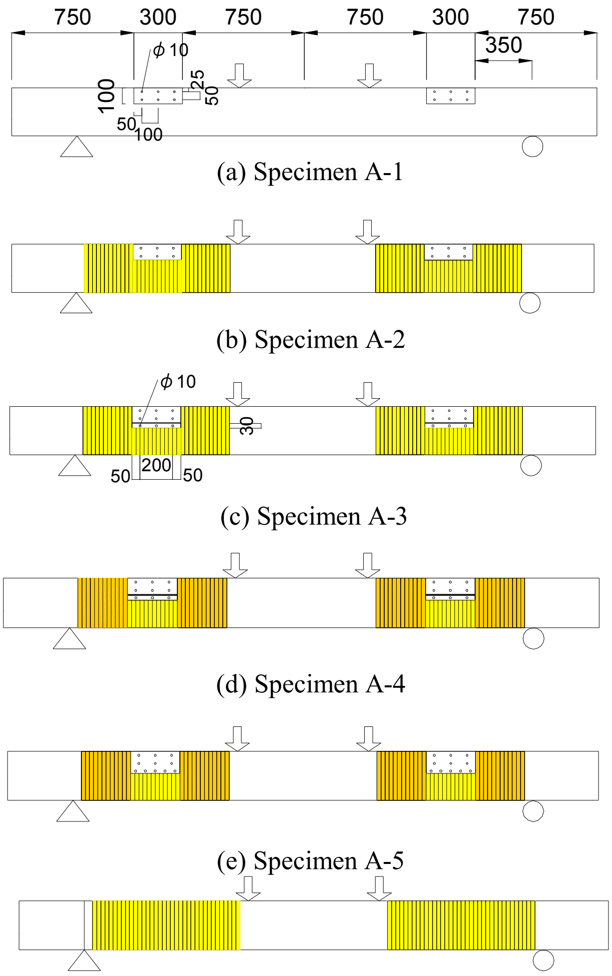


Figure 10. Reinforcement details

Table 2. 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

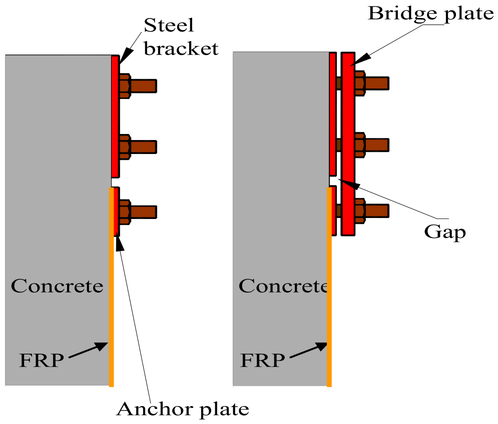
(e) Specimen A-5

(f) Specimen Full-wrap

Figure 11. Details of test specimens

4.2 *Mechanical anchorage*

Mechanical anchorage was used to prevent the premature debonding failure of FRP sheet. Figure 12 schematically shows the two types of mechanical anchorage studied in this research. The upper ends of U-wraps anchored to the concrete using an anchor plate and a number of anchor bolts for Type I anchorage. Type II anchorage is connected to the steel bracket using a bridge plate.



(a) Type I anchorage (b) Type II anchorage

Figure 12. Mechanical anchorage

4.3 *Test setup*

The test setup of the specimen is shown in Figure 13. 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). Progressive debonding of the FRP sheets was monitored by using a pearl hammer.

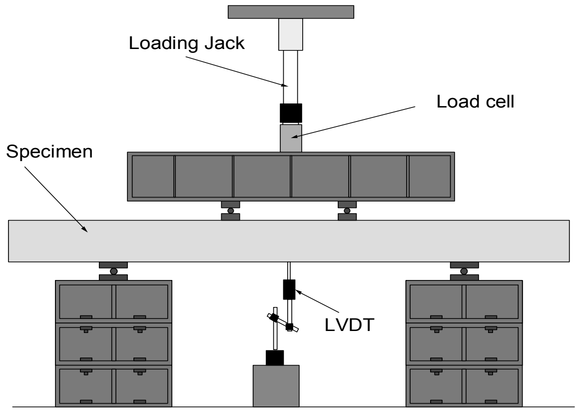


Figure 13. Test setup

4.4 *Load-displacement curve*

Figure 14 shows the load displacement curve of all the tested specimens. As expected, 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. A significant improvement in shear strength to 455 kN was observed in Specimen A-2 but the failure was due to the rupture of FRP sheets near the steel bracket followed by the debonding of FRP sheets at the U-wrap portion. In Specimen A-3, the enhancement of shear capacity was not as impressive and the final failure was similar to the Specimen A-2. In Specimen A-4, some enhancement of shear capacity was observed due to stronger FRP sheets in full wrap portion but the final failure was again due to the rupture of FRP sheets. 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 reinforcement.

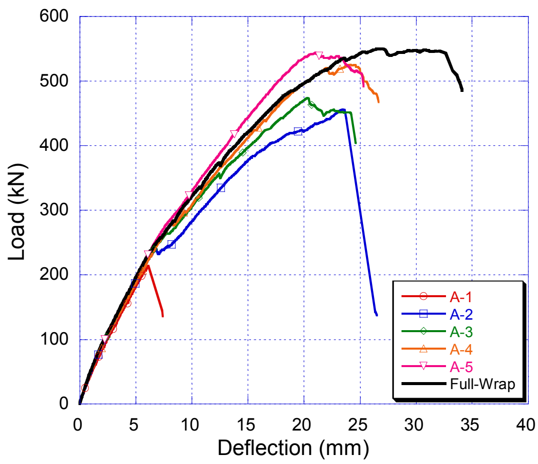


Figure 14. Load-displacement curve

4.5 *Strain in FRP sheets*

The strains developed in FRP sheets were measured during the experiments by an array of strain gauges. Figure 15 schematically shows the location of five strain gauges in the portion of U-wrap just below the steel brackets and the mechanical anchorage.

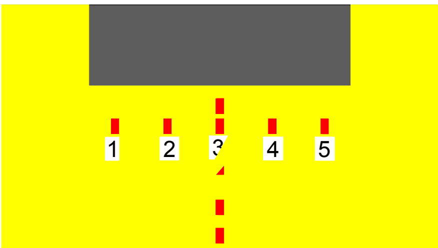
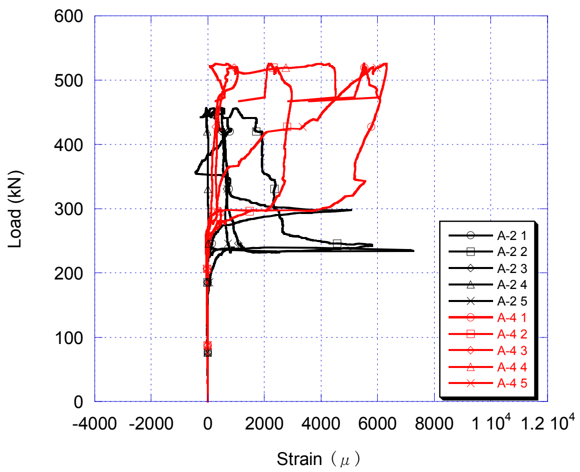


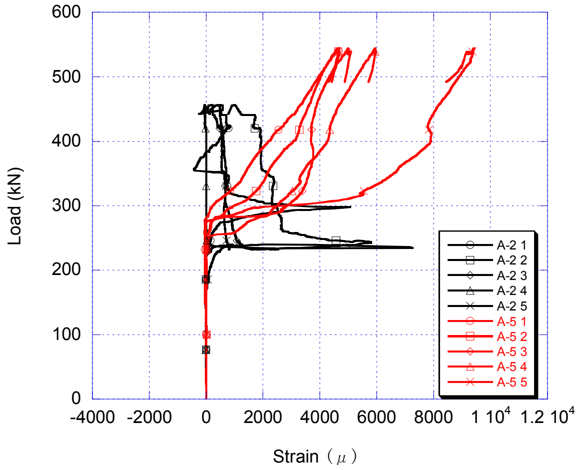
Figure 15. Location of strain gages below steel jacket

Figure 16 shows the comparison of strains developed in FRP sheets of mechanically anchored specimens with those of unanchored specimen. In specimen A-2, initiation of debonding resulted in an abrupt drop in strain due to the delamination of the sheet from the concrete surface. Due to debonding, the U-wrapping without anchorage was not every effective. In specimen A-4 with Type I mechanical anchorage, the strain in FRP sheets increased with the increase in applied load. After the cracks started widening between the steel bracket and anchor plate, the strains in the sheet thus remained constant. The strains did not drop after debonding, which shows that 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-4



(b) Specimen A-2 and A-5

Figure 4. Load-strain curves

5 CONCLUSIONS

The advancements in the retrofitting technologies for reinforced concrete structures using FRP sheets in Japan are discussed in this paper. The main driver behind such application has been the effect of two major earthquakes in recent years. While various materials (aramid, carbon and glass) have been used to produce the FRP sheets, the selection of appropriate material depends on the particular structure, cost and other considerations.

Full wrapping is not always possible and U-wrapping does not ensure a reliable enhancement of a retrofitted RC beams with externally bonded FRP sheets. A comprehensive mechanical anchorage system can effectively enhance the strength capacity of retrofitted RC members to a level close to that of fully wrapped beams.

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