Advancements in Retrofitting Reinforced Concrete Structures in Japan using FRP Sheets

H. Shinozaki
Senior Researcher
Mitsui Sumitomo Corp.
Japan

T. Aravinthan
Associate Professor
Uni. of Southern Qld.
Toowoomba

G. R. Pandey
Lecturer
James Cook Uni.
Townsville

H. Mutsuyoshi
Professor
Saitama University
Japan

Synopsis: In Japan, many reinforced concrete bridge structures collapsed in the recent severe earthquakes such as the 1995 Hyogoken Nanbu Earthquake and the 2004 Niigataken Tyuetsu Earthquake were designed and constructed before the introduction of the new seismic resistant design codes in 1980. Following the lessons learnt from these severe earthquakes and the continuous advancements of the state of the art and practice, further stringent performance based earthquake resistant design codes for both highway and railway bridge structures are recently enforced in Japan. For many existing structures, to meet the requirements of these new codes, proper strengthening schemes must be implemented. Among various strengthening techniques, the application of fiber reinforced polymer (FRP) has recently drawn a wide attention due to its advantages such as high strength to weight ratio, corrosion resistance, and ease of execution. This paper introduces the current issues related to the deficient reinforced concrete structural members in Japan and provides an overview of latest innovations and advancements in the technology and application of FRP sheets in structural retrofitting. The focus of this paper is mainly on the retrofitting of bridge superstructures and substructures including decks, girders, frames, and columns.

Keywords: structural rehabilitation, retrofitting, concrete structures, FRP materials,

Introduction

Japan lies in an active seismic zone. The 1995 Hyogoken-Nanbu earthquake showed a widespread damage of reinforced concrete structures. Most structures that were damaged during this earthquake were designed based on the older JSCE (Japan Society of Civil Engineers) standards existed before 1980. The 1995 Hyogoken-Nanubu earthquake has been the main driver for the need of strengthening of RC structures. Various technologies have been developed since including use of steel jackets/plates, concrete jackets, external post-tensioning and fiber reinforced polymer (FRP) sheets etc.

The application of Fiber Reinforced Polymer (FRP) in civil engineering structures was first introduced in Japan about two decades ago with the development of FRP reinforcement and tendons. Japan had been a pioneer in the research and development of FRP materials for reinforced and prestressed concrete structures especially in the bridge engineering. The first JSCE standard specification for the design of FRP reinforcement was published in 1997, which has been adopted in various other countries (JSCE, 1997). 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 rods. There has been a remarkable increase in the use of FRP sheets, especially carbon and aramid sheets 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 of these technologies used 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. The relative merits of using different types of FRP sheets are discussed. These technologies are discussed through selected case studies using aramid sheets.

Properties of FRP sheets

Fig. 1 shows the stress strain behaviour of different kinds of FRP sheets and are compared with steel. In retrofitting practice, carbon fibres, aramid fibres and glass fibres are the most commonly used ones. Carbon fibre has the highest stiffness and strength. Its stiffness is comparable with elastic stiffness of steel but has 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 its durability concerns.

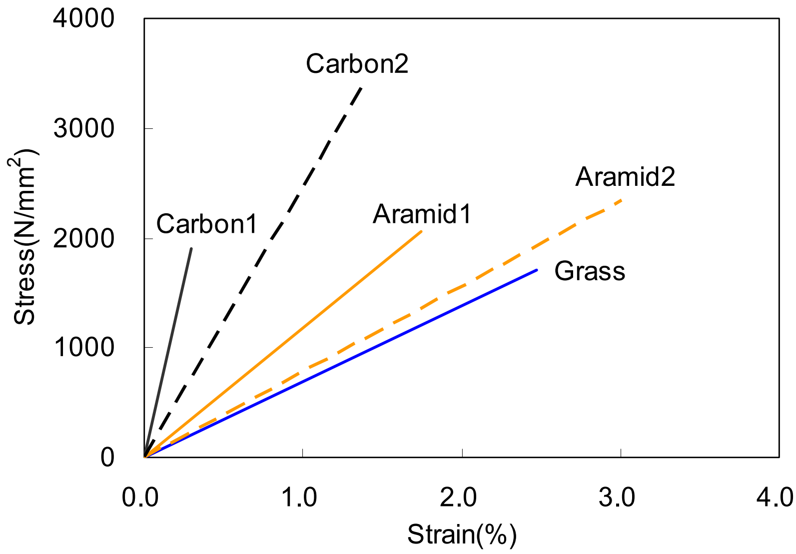


Fig. 1 Stress strain relationship

Comparison of AFRP sheets with CFRP and GFRP

Table 1 and Table 2 compare the properties of Aramid Fibre Reinforced Polymers (AFRP) sheets with Carbon Fibre Reinforced Polymers (CFRP) sheets and Glass Fibre Reinforced Polymers (GFRP) sheets respectively. Mechanical properties of CFRP sheet is the best amongst all. When it comes to practical application, however, there are issues related to processing, rounding of corner angles, impregnation of resin, work speed and influence of electrical equipments, AFRP sheets have distinct advantages. Especially, while strengthening RC beams and columns, rounding off corner angles takes a lot of time and effort. Using AFRP sheets the use of disk sander is sufficient to round off the corner angles and saves a lot of time and cost. GFRP sheets are very economical but due to its inferior mechanical properties and poor resistance to alkali and acid, AFRP sheets are widely used in Japan.

Table 1 Comparison of CFRP sheet and AFRP sheet

	Carbon Sheet	Aramid Sheet
PROPERTIES		
TENSILE STRENGTH (N/mm^2)	1900～3,400	2,060～2350
YOUNG'S MODULUS (kN/mm^2)	245～640	78～118
TENSILE CAPACITY (kN/m)	380～570	392～1,176
ELONGATION (%)	1.5	1.8
PROCESSING	Moderate	Easy
Rounding of corner angles	R>40mm	R>10mm (only disk sander)
Impregnation of resin	Moderate	Easy
Work speed	One ply per day	Multi-plies per day
Influence of electrical equipment	Create troubles with chop of fibre	No troubles
Durability	Long term	Long term
Direct Expense (In Japan)	120t/m sheet \$404/m^2	120t/m sheet \$322/m^2

Table 2 Comparison of AFRP sheet and GFRP sheet

ITEM	Aramid Sheet	Glass Fibre Sheet
CHARACTERISTICS OF FIBER		
DENSITY (g/cm^3)	1.45	2.6
TENSILE STRENGTH (N/mm^2)	2,840	2450
YOUNG'S MODULUS (kN/mm^2)	109	73
ELONGATION (%)	2.4	4.0
CHARACTERISTICS OF SHEET		
WEIGHT (g/m^2)	830 (AK-120)	344 (MG300)
TENSILE STRENGTH (N/mm^2)	2,060	1,400
YOUNG'S MODULUS (kN/mm^2)	118	72
TENSILE CAPACITY (kN/m)	1,176 (AK-120)	71 (MG300)
ELONGATION (%)	1.8	2.0
ALKALI - RESISTANCE	EXCELLENT	WEAK
ACID - RESISTANCE	EXCELLENT	WEAK

Table 3 shows the properties of various AFRP sheets available for application. The properties basically depend of the thickness of FRP sheets. AK-120 is the thickest sheet available and it is often used in retrofitting. If one layer of sheet is insufficient, a number of layers can be applied to meet the required strengthening performance.

Table 3 Properties of AFRP sheets

CODE	WEIGHT	TENSILE STRENGTH	YOUNG'S MODULUS	TENSILE CAPACITY	DESIGN THICKNESS
	g/m^2	N/mm^2	kN/mm^2	tf/m (kN/m)	mm
AK-40	280	2,060	118	40 (392)	0.193
AK-60	415	2,060	118	60 (588)	0.286
AK-90	623	2,060	118	90 (882)	0.430
AK-120	830	2,060	118	120(1,176)	0.572

Comparison with other retrofitting methods

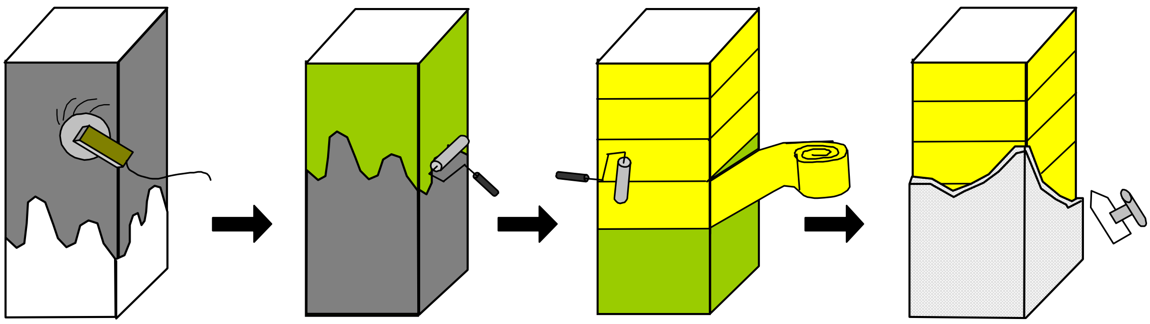
A number of methods are being used for retrofitting RC structures. The most common ones are the use of concrete lining, steel plates and FRP sheets. Table 4 compares the merits, demerits, working period and cost of all these methods. Concrete lining has distinct advantage of being durable but it significantly increases dead weight, it requires access for concreting and it requires a long period. Though steel plates used in retrofitting are lighter than the concrete lining, it still requires the use of crane to handle it. It also requires the use of welding to connect plates which increases the working period. On the other hand AFRP sheets are noncorrosive, durable and processing is so easy and convenient that no crane and access space is required and hence the working period is very short. The only demerit is that in cold climate when temperature is under 5^{O}C, it requires heating.

Table 4 Comparison of retrofitting techniques

Method	Concrete Jacketing	Steel Jacketing	AFRP sheets
Outline	After installing re-bar & form, concrete is placed to surface of existing concrete.	After setting steel plate with anchor bolt, epoxy resin is injected the space.	AFRP sheet is bonded to concrete with epoxy resin.
Merit	・Concrete is durable. ・Has been used widely.	・Has been used widely ・Steel plate is lighter than concrete	・AFRP sheet is non-corrosive and durable. ・Processing is easy, requires no crane & access space.
Demerit	・Deadweight increase (minimum thickness of concrete is 25cm) ・Requires access for concreting.	・Steel plate is heavy and requires crane (minimum thickness of concrete is 6mm for welding procedure) ・Require welding machine	・When temperature is under $5^{O}C$ requires heating.
Working period	LONG	MODERATE	SHORT
Direct expense (in Japan)	at 25cm concrete thickness and re-bar (D22, pitch 17cm) used ¥30,000/ m^2	at 6mm steel plate ¥70,000～90,000/ m^2	at AK-120,1ply ¥35,000/m2

Application of AFRP sheets

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



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

Fig. 2 Process of application of AFRP sheets

While retrofitting columns, FRP sheets can be wrapped by either of the two methods shown in Fig. 3. In sheet method columns are wrapped by FRP sheet of certain width and with a certain overlap. In tape method sheets are applied continuously without the need of any overlap. 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 joint.

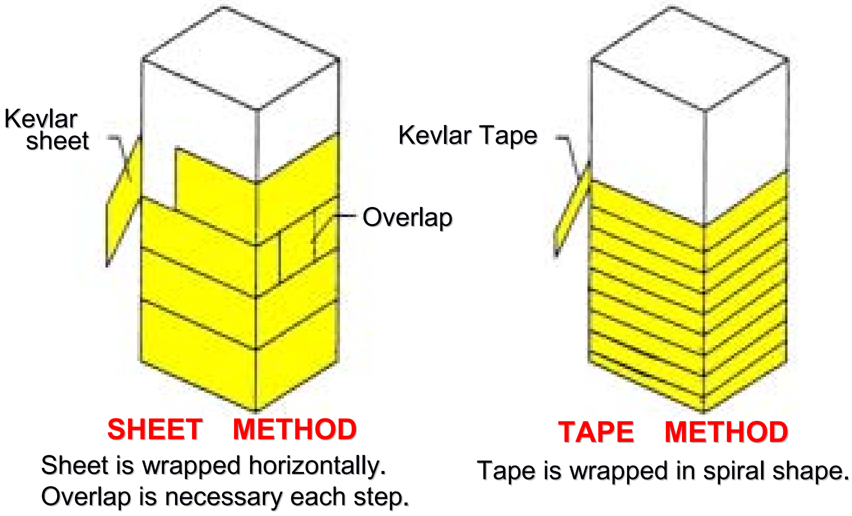


Fig. 3 Wrapping methods for AFRP sheets

Construction Examples

AFPR has been widely used in Japan in retrofitting RC structures. Especially after the 1995 Hyogoken Nanbu earthquake, design codes in Japan were modified. To meet the requirements of new design codes, a large number of existing structures have been retrofitted. Fig. 4 shows the application of externally bonded AFRP sheets for the seismic retrofitting of highway piers in Saitama city. Fig. 5 and Fig. 6 shows the application of AFRP sheets in flexural strengthening of slab and beam, respectively

Fig. 4 RC bridge piers retrofitted by AFRP sheets.

Fig. 5 Strengthening of slab

Fig. 6 Strengthening of beam

A number of buildings have also been retrofitted using AFRP sheets. Building structures are mainly retrofitted to meet the requirement of new design codes. Another reason for strengthening is the change in design load on structures due to the alteration of usage such as installing a heavy equipment in a structure designed for normal use. Fig. 7 shows the application of AFRP sheets in building structures in various parts of Japan

Fig. 7 Application of AFRP sheets in building structures

Applications of AFRP sheets are not limited to building and bridge structures. Many other structures have been repaired and retrofitted using FRP sheets. Fig. 8, Fig. 9 and Fig. 10 show the examples of application of AFRP sheets in retrofitting chimney, tunnel and reservoir, respectively. These examples show the versatility of this method. They also demonstrate that this method does not require heavy machines and does not add additional dead load to the structure.

Fig. 8 Retrofitting chimney

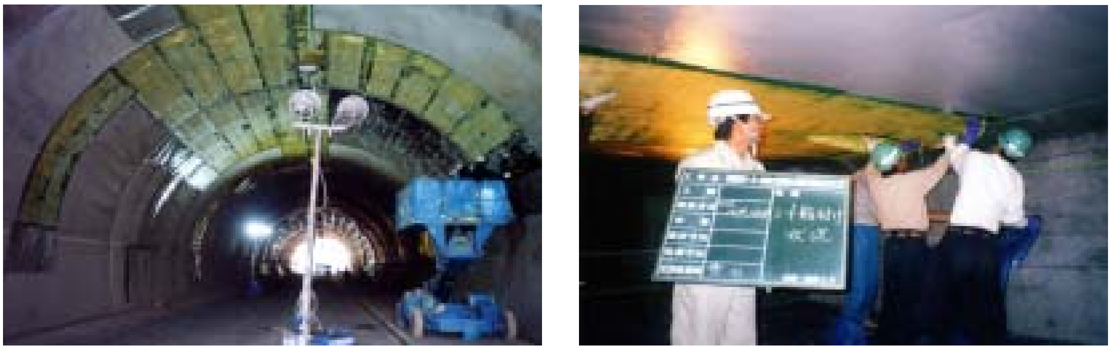


Fig. 9 Retrofitting tunnel

Fig. 10 Retrofitting reservoir

Application of precast FRP sheets

Though wet layup is an excellent method of bonding FRP sheet, due to space limitation and accessibility, it is not always possible. A concept of partially precasting FRP sheet has been used in such instances. Fig. 11 and Fig. 12 schematically illustrate the application of precast FRP sheets in beams and columns respectively. Precast portions are used in inaccessible region while wet layup is used in remaining portions. A gap is provided between precast sheet and concrete surface using spacers which is later filled by epoxy resin.

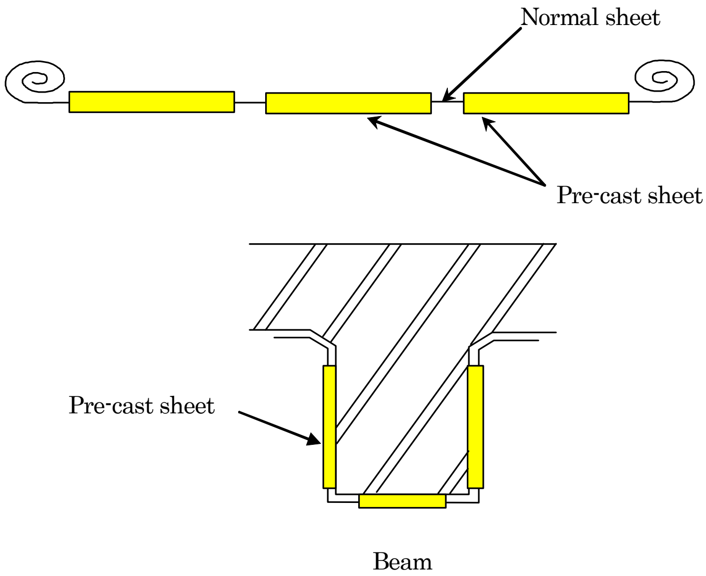


Fig. 11 Application of precast FRP sheet in beams

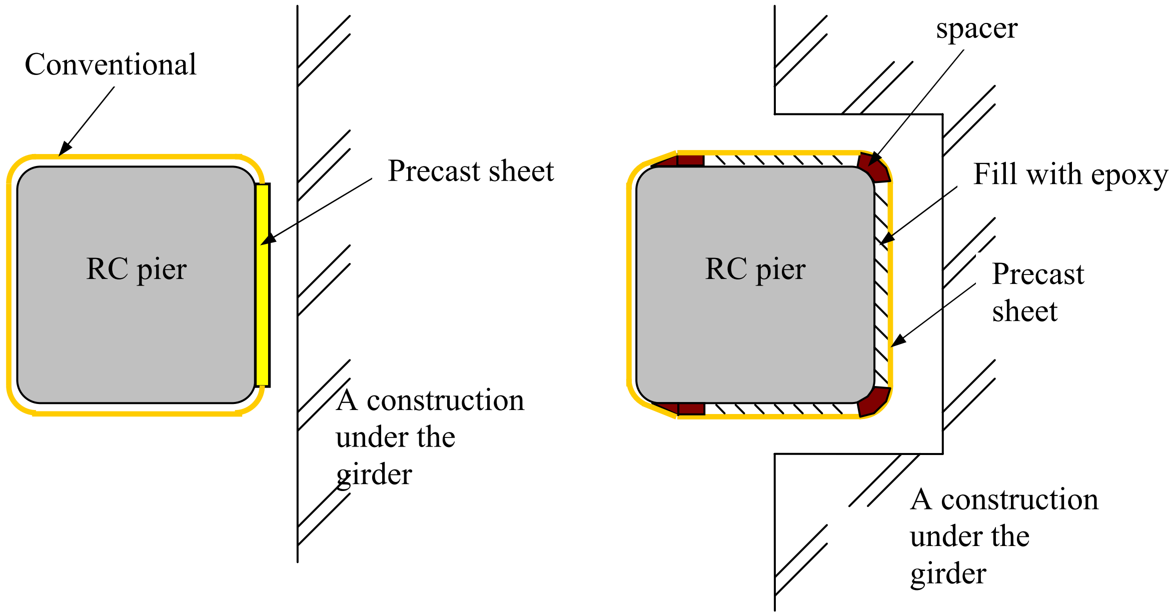


Fig. 12 Application of precast FRP sheet in columns

Future Directions
While the above sections demonstrate the extensive use of FRP in structural rehabilitation of reinforced concrete structures, the trend is shifting towards the construction of FRP structures. In the last decade, the research and development of all FRP structures in civil engineering has progressed substantially in several countries (Keller, 2003, VanErp, 2006). The first all FRP bridge in Japan was constructed in Okinawa prefecture in 2001 (Ueda, 2005). This bridge is a two span continuous girder pedestrian bridge as shown in Figure 13, which is located in the road-park of Ikei-Tairagawa road. All the structural elements have been made with Glass Fiber Reinforcement Plastics (GFRP). The all FRP solution was chosen for this bridge due to its heavily corrosive environment where the bridge is surrounded by the ocean. As we believe that the innovative materials can be competitive to conventional materials in the near future when life cycle cost is taken into account, there is an urgent need for research and development of this cutting edge technology in Japan. Recently, a research project sponsored by the Ministry of Ministry of Land, Infrastructure and Transport in Japan investigates the potential of using hybrid FRP girders in bridge engineering. Initial investigations reveal there is huge potential for such hybrid girders in civil engineering, if some of the issues could be resolved (Mutsuyoshi (2007), Asamoto(2007)). With such research and development, it is anticipated a use of FRP materials in the construction industry will further increase in the near future in Japan.


Figure 13 All FRP Pedestrian Bridge in Okinawa made of GFRP

Concluding Remarks
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 the recent years. While various materials (aramid, carbon and glass) have been used for to produce the FRP sheets, the selection of appropriate material depends on the particular structure, cost and other considerations. Research and development is emerging in Japan in the last five years in the application of all FRP structures in civil engineering. These provide evidence for the increasing demand and potential of FRP materials in the construction industry.

References:

Asamoto, S., Mutsuyoshi, H., Aravinthan, T. and Suzukawa, K. (2007). Experimental investigation of innovative hybrid composite girders with GFRP and CFRP, the fourth international structural engineering & construction conference (ISEC-4), (submitted).

Keller, T. (2003). Use of Fiber Reinforced Polymers in Bridge Construction. *International Association for Bridge and Structural Engineering*. Zurich.

JSCE (1997). Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials, Concrete Engineering Series 23

Van Erp, G. (2006). Future Materials – The Use of fiber Composites in Civil Engineering. *Proc. of Main Roads Technology Forum*, Brisbane.

Ueda, T (2005). FRP for Construction in Japan. *Proc. of JSCE-CICHE Joint Seminar*, Mongolia

Mutsuyoshi, H, Aravinthan, T, Asamoto, S and Suzukawa, K (2007). Development of New Hybrid Composite Girders Consisting of Carbon and Glass Fibers, Proc. of COBRAE CONFERENCE 2007 - Benefits of Composites in Civil Engineering, Stuttgart. (in print).