

State-of-the-Art of Advanced FRP Applications in Civil Infrastructure in Japan

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Abstract

This paper addresses advanced applications of fiber reinforced polymer (FRP) materials in civil infrastructure in Japan. The overview of development and applications of FRP materials was described first in aspects of FRP reinforcement for concrete structures and FRP sheet/plate for repairing and strengthening. Secondly, the development of codes was summarized, which included the establishing the corresponding associations and great efforts of plenty of researchers for the publishing of JSCE recommendation of FRP. In this work, we aimed to explore the difficulties confronted by Japanese FRP manufacturers and researchers in recent years, and introduce the innovation and new efforts for developing FRP strengthening techniques, which included new FRP prestressing technique, hybrid FRP technique, underwater strengthening method, and high fracturing strain FRP in retrofitting reinforced concrete piers. Also, we discussed updates on recent works that focus on the JSCE approach against IC debonding in FRP sheet flexural strengthened RC members and the latest effort for long-term behaviors of FRP externally strengthened structures. As a result, a new idea on strengthening design with FRP composites is suggested based on the concept of performance-based design of structures with the performances of durability, damage controllability and recoverability.

1. Introduction

Japan, a pioneering country in manufacturing fiber composite materials and applying FRP in civil infrastructures, has led the world for over twenty years. For example, Japanese manufacturers share about 75% of the global fiber markets^[1], meanwhile many kinds of FRP materials (Carbon FRP, Glass FRP, Aramid FRP etc.) and FRP types (sheets/plates, rods, cables, and grids etc.) are investigated and developed plentifully in structural repairing, strengthening, seismic retrofit and other special civil engineering. However, recently Japanese FRP manufacturers and researchers are faced with difficulties in promoting FRP as a mainstream construction material^[1]. With increasing concerns on actual performances of social infrastructures, FRP needs to highlight not only their excellent high strength to

weight ratio, ease of construction, and free maintenance properties, but also their advantages in cost effectiveness, less impact on the environment, use of linear property, and some irreplaceable innovative functions^[2]. In order to sufficiently use the advantages of FRP and promote FRP applications, a variety of innovative research has been conducted in Japan to meet this requirement, including new prestressing technique with FRP materials^[25-30], hybrid FRP technique^[31-34], underwater strengthening method^[35-39], and high fracturing strain FRP in retrofitting reinforced concrete piers^[40-42] etc.

This paper discusses three main areas, which includes the development and application of FRP materials, introduction of corresponding FRP standards, and some innovation and new effort on FRP strengthening techniques. In the end, JSCE design approach against IC debonding in FRP sheet flexural strengthened RC members adopted from the "Recommendations for Upgrading of Concrete Structures with Use of Continuous Fiber Sheets"(JSCE 2001) are introduced due to its great importance in strengthening structures with FRP sheets and also some updated activities towards the improvement of existing debonding models.

2. Development and application of FRP composites

FRP composite was developed to replace of conventional steel bars and tendons for concrete structures in the early 1980s in Japan due to the stimulation of "Concrete Crisis", which is mainly caused by the problems with steel reinforcement corrosion in concrete structures. Thus, many major Japanese general contractors with material manufacturers began to develop various types of FRP reinforcement including rod/tendons, cables, ground anchors and grids to replace conventional reinforcement in case of corrosion, which are the primary products available in today's market. The annual amount of FRP reinforcement used in construction reached a peak in 1998. After 1998, the annual amount began to decrease, except in 2002. Carbon fiber strands comprised the largest consumption among all kinds of FRP, which was followed by Aramid rods and braids. The amount of Carbon fiber rod and Aramid fiber plate were relatively few.

With respect to its applications, the number of applications increased steadily at the beginning, until 1996. Typically, many FRP reinforcement were applied in coastal and water channel structures, ground anchors, underground structures and non-magnetic structures, where they were often exposed to aggressive environments. Applications in coastal and water channel structures were very common until 2001 and applications in non-magnetic structures occupied only in three years. Its application to ground anchor has increased recently. Although applications began to decrease after 1998, bridges still occupied the largest consumption followed by ground anchor^[1].

On the other hand, like other developed countries, Japan also faces a critical need to repair or strengthen deteriorated and functionally deficient civil infrastructures due to environmental attacks and increase in traffic loads. In Japan, the majority of concrete structures that were built in 1950s cannot satisfy new seismic standards. Others built during the economic boom period from 1960s to early 1980s had deficiencies in design and materials due to limitations in resources and rapid construction. This situation stimulated Japanese industry to develop FRP sheet as a rapid external strengthening material in the late 1980s. In comparison to traditional overlay and steel plate bonding systems, the external bonding FRP system is very attractive with respect to its ease and flexibility of applications, leading to rapid installation with less impact on society and the environment. At the initial stage, applications of FRP sheets in strengthening fields were limited until the Great Hanshin Earthquake in 1995, which was a big driving force for the use of FRP sheets in seismic retrofit. Currently, continuous FRP sheet is the most popular form for various strengthening purposes in Japan due to its convenience in strengthening construction and easily obtaining reliable bonding, as compared to FRP plates and strips. Similar to FRP reinforcement, annual amount of CFRP sheet has been decreasing after 2002. It should be mentioned here that the development and amount of FRP depend greatly on the efforts of manufacturers, constructors and researchers, as shown in Fig-1. Without continuous innovation on FRP technology, a sustaining development cannot be realized. And this may be the reason that Japanese FRP amount keep decreasing in recent five years.

The commonly used FRP includes CFRP and AFRP, while some new FRP with special properties like energy absorption and large fracturing strain have been gradually applied in recent years such as PBO, Dyneema, PET, PEN, and PAF, which are listed in Table 1^[3] and also plotted in Fig.2. Among them, CFRP is the most commonly used due to its high strength and elastic modulus. Recently high strength and high modulus CFRP are developed in Japan to meet the requirement of fully utilizing potential behaviors of FRP, which makes it possible to hybrid difficult kinds of FRP and obtain integrated advanced performances. For this sake, PBO fiber has been explored to have similar advantages with high strength CFRP, but also have greater impact-tolerance and energy absorption ability than any other fibers, as shown in Fig.3. In addition, PBO fiber demonstrates high creep resistance and fire/fuel resistance. Dyneema may have wide applications in strengthening structures due to its special energy absorption ability and water resistance, aside from high strength and high ductility, which is suitable for underwater structures strengthening. For the others, like PET, PEN and PAF, although they do not have similar high tensile strength relative to carbon fiber, they do have great high fracturing strain that seldom exists in other FRP. This specialty is the most important for strengthening or retrofitting seismic behaviors of

columns or piers, where the ductility is of utmost concern, in stead of strength. In Japan, GFRP is seldom used in civil infrastructures due to its sensitiveness to ultraviolet radiation and humidity, despite its economic advantage.

Table 1 Mechanical properties of FRP sheets^[3]

Type of sheet		Tensile strength (N/mm ²)	Elastic modulus (kN/mm ²)	Fracturing strain (%)
Carbon	High strength	3400	230	1.5
	High modulus	1900	540	0.35
Aramid		200-2500	73-120	1.8-3.0
E-Glass		1500	80	1.9
PBO ^[29]		3500	240	1.5
Dyneema ^[39]		1832	60	3.08
PET		923	6.7	13.8
PEN		1028	22.6	4.5
PAF		1730	40	6

Note: PBO (Polypara-phenylene-Benzo-bis-Oxazole), PET (Polyethylene Terephthalate / Polyester), PEN (Polyethylene Naphthalate), PAF (Polyacetal), PBO and Dyneema are referenced from [29] and [39] respectively

The application fields of FRP include bridges, buildings, tunnels, chimneys, and others like electric poles, box culverts etc. Among them, applications in bridges and buildings occupy the majority of the whole market. The bridge piers, girder, plates and building beams, columns and plates are the most common to be strengthened. Recently, more applications could be found in repairing tunnel lining. It should be mentioned here that CFRP sheets are applied widely for tunnel lining in Japan. The early study was performed by Asakara et al. (1996)^[4], which confirmed the effects and countermeasure of FRP sheet and back-fill grouting in strengthening the tunnel lining, as shown in Fig. 4. In addition to FRP structural shape, the number of applications in Japan is much less than USA and Europe. Only two cases for bridges, a GFRP pedestrian bridge in severely corrosive area and a highway bridge upgraded by GFRP supplementary beams, could be found^[5].

3. Development of codes

Since 1980s, FRP has been widely investigated and applied in Japan. To develop the increasing market and standardize market competition, many associations organized by suppliers and large construction companies were established in this period such as Association for Advanced Composite Technology on Construction Field (ACC, formerly Advanced Composite Cable (ACC) Club), Association for Seismic Reinforcement with Carbon Fiber Sheets (ASRCFS), Fiber Repair and Strengthening Association (FiRST), the Carbon Fiber Repair and Reinforcement Research Association (CFRRRA), Aramid Retrofitting System Association (ARSA), and other small associations^[1]. Additionally, important organizations in civil engineering also put significant effort in promoting the development of FRP, like the Japan Highway Public Corporation Bridge

Research Lab. (JHPCBRL), and the Railway Technical Research Institute (RTRI). Many early period guidelines were published by these societies, such as Summary for Design/Construction of CFRP-strengthened Reinforced Concrete Bridge Pier (1995 by JHPCBRL), Manual for Design/Construction on Repair/Reinforcement of Concrete Structures with Carbon Fiber sheets (1996 by ASRCFS), and Guideline for Design/Construction of Seismic Reinforcement of Elevated Railway Bridges with Carbon Fiber Sheets (1996 by RTRI)^[6]. Development of these associations and corresponding guidelines insulated FRP market from cut-throat competition; on the other hand development tightened the cooperation between material suppliers and the construction industry. Thanks to the efforts of these associations and the guidelines mentioned above, JSCE published the first unified recommendation for FRP reinforcement for Design and Construction of Concrete Structure Using Continuous Fiber Reinforcing Materials (JSCE 1997) in 1997, which was also the first code in the world. Additionally this recommendation includes quality specification and test methods, namely Quality Specifications for Continuous Fiber Reinforcing Material, which is used as a standard for specifying FRP reinforcement properties and test methods related to tensile properties, flexural tensile properties, creep failure, long-term relaxation, tensile fatigue, coefficient of thermal expansion, performance of anchorages and couplers in prestressed concrete, alkali resistance, bond strength, and shear properties^[7].

Subsequently, to satisfy the requirement of FRP repairing, strengthening and retrofit, Recommendations for Upgrading of Concrete Structures with Use of Continuous Fiber Sheet (JSCE 2001) was released in 2001 by JSCE also including test method, namely Test Methods for Continuous Fiber Sheets, which were developed to specify their tensile properties, overlap splice strength, bond properties to concrete, bond properties to steel plate, direct pull-out strength to concrete, tensile fatigue strength, accelerated artificial exposure, freeze-thaw resistance, and water, acid, and alkali resistance^[8].

While establishing these codes, many researchers spent significant time on studying material properties, bonding behaviors and strengthening effectiveness with the theoretical method, test and numerical analysis. Among them, the primary achievements were referenced as the foundation of codes. The following is the main work referenced by JSCE 2001. The behaviors of confined concrete structures were investigated by Ohno, T and et al (1992)^[9], Hosoya, M and et al (1998)^[10]. The approaches against IC debonding in FRP sheet flexural strengthened RC members are based on the model of Wu, Z and Niu, H. (2000)^[11]. Shear strengthening methods of columns and beams are based on the researches by Okano, M. and et al. (1997)^[12], Oda, M. and et al. (1993)^[13], Umezu, K. and et al. (1997)^[14], Nakajima, N. and et al. (1997)^[15], and Kamiharako, A. and et al. (2000)^[16]. The studies on retrofitting RC

slab with Carbon fiber sheets were performed by Mori, S. and et al. (1995)^[17]. The seismic retrofit of RC piers were investigated by many researchers such as Masukawa, J. and et al. (1996)^[18], Ohno, S. and et al. (1996)^[19], Osada, K. and et al. (1997)^[20], Hakamada, F. and et al. (1997)^[21], and Machida, A. and et al. (1998)^[22].

After publishing JSCE 1997 and JSCE 2001, AIJ and TSCRS (Tunnel Safety Countermeasure Research Society) also published "Design and Construction Guideline of Continuous Fiber Reinforced Concrete" and "Manual for Tunnel Linings Spalling & Falling Countermeasures with FRP" in 2002 and 2003, respectively, to meet the requirements of FRP markets. With respect to the process of standards establishment, Japan has also pioneered introducing guidelines and standards in design, materials and construction of FRP.

4. Some innovations and new effort on FRP strengthening techniques

As aforementioned in section 1, in recent years Japan has met many difficulties in promoting FRP as a mainstream construction material. The typical advantages of FRP should be used sufficiently, but also their special and potential functions to structures should be investigated and developed to conquer these problems. The latest innovations and new effort for FRP strengthening techniques focusing on developing new behaviors of FRP will be introduced in subsequent sections, which are mainly based on researches by Ibaraki Univ. and Hokkaido Univ., due to their contributions to these aspects in Japan.

4.1 Prestressing technique with FRP materials

Although FRP has many excellent properties such as high strength, light weight, etc., its potential capacity cannot be fully utilized, due to its similar modulus to steel and deficient bond interface to transfer stresses. This condition is even worse when strengthening existing structures. Hence, to solve this problem, it is convenient to relate prestressing techniques with FRP applications. Since early 1990s, effort and studies were conducted by some researchers to investigate the effectiveness of this new technique^[23-25]. By means of prestressing capacity and stiffness of strengthened structures can be improved greatly for the sake of delaying the onset of cracking, reducing the deflection, relieving the strain in internal reinforcement, etc^[26]. But in practice there are still many difficulties need to be conquered.

In the early stage of FRP prestressing technique, CFRP plate is often chosen as prestressing material to strengthen the structures due to its fixed shape, whereas just this fixed shape often affects the bonding quality greatly because of the unevenness of concrete surface^[27]. Not just CFRP plate, CFRP sheet are similar because CFRP sheet must be impregnated by resin before its

regidification and then could be tensioned and bonded to structural surfaces. This complex operation is generated from FRP's poor ability of energy absorption, which means fibers cannot maintain force evenly without resin. Due to this limitation a new idea is needed for prestressing technique. Therefore a new kind of FRP, namely PBO, has been developed by Ibaraki Univ. for strengthening concrete beam [28-29]. PBO fiber, compared with typical CFRP, not only has similar high strength and high modulus, but also great energy absorption ability. This special characteristic makes it possible to be prestressed before being impregnated with resin, and guarantees good bonding between two materials. In the actual construction, the stress concentration at the end of anchor zone often leads to some premature failures. To solve this problem, two types of methods have been employed to relieve stress concentration, namely tapering FRP sheets and multi-step releasing prestressing, as shown in Fig-5. Additionally, the U type CFRP sheets are also bonded at the end of PBO sheets to obtain better anchor effect. In terms of the above concept and ideas, a new set of integrated operation system has been developed namely P-PUT (PBO Prestressing Upgrading Technique) by Ibaraki Univ., which includes the equipment for prestressing, curing and the auxiliary, which warrants the interfacial bonding quality and high efficient goal "completing construction in one day". Test results are shown in Fig-6 and, indicate higher yield loading, greater stiffness after yielding and better bonding effect of the post-impregnation method. It should be mentioned that the failure mode of PFRP (PBO FRP) sheets-strengthened beam is changed from PFRP sheets debonding to PFRP sheet rupture with increasing prestressing magnitude.

At the same time the prestressing technique with CFRP plate is still on developing in spite of some disadvantages mentioned above [30-31], because of well understanding of typical FRP. Many researchers has put great effort to solve the problems limiting the development of prestressing CFRP plate technique, such as bonding quality, anchorage treatment and tension magnitude. New methods of intermediate anchoring have been suggested to prevent premature peeling failure and improve bonding quality [30]. However problems still exist and more investigations should be conducted. For instance, tension magnitude of CFRP plate is still restricted in low level, which is below than 10 tons, due to the limitation of anchoring device.

Applying PFRP in prestressing strengthening technique is feasible and effective. However, in some seriously corrosive areas or for some structural members that are easily physically attacked, the protection of strengthened FRP is primarily important. For this case, combining prestressing technique with near surface mounted (NSM) method is a possible method of strengthening the flexural capacity of concrete beams [32]. With this method, it can not only protect FRP by placing them inside structures, but it also improves the flexural behaviors of concrete beams owing to more reliable

bonding. Nevertheless, in actual structures, the thickness of concrete cover usually dose not reach the design value due to construction problems, measure errors, and etc. This deficiency of concrete cover usually leads to issues with bonding for NSM strengthening. Consequently, an additional covering layer on the surface of the grooves is expected to solve this problem (Fig-7). The test results demonstrate that the best performance could be achieved by applying epoxy resin and polymer cement mortar as bonding layer and covering layer respectively (Fig-8).

This study is only limited to investigate the short-term behavior of strengthened RC beams with prestressed NSM CFRP tendons. Further investigation, however, is required to clarify the long-term behavior in the adhesive such as creep before using this technique.

4.2 Hybrid FRP technique

For a single type of FRP, limitations in their properties often lead to some restriction in their application such as CFRP with high strength elastic, high modulus, but low ductility, and GFRP with relatively high ductility and high strength, but low elastic modulus. Considering these limitations, hybridizing different types of FRP may be an effective way to enhance the strengthening effect in many structures [33-35]. The idealized new hybrid material property is shown in Fig.9, which is hybridized with high strength (HS), high modulus (HD) CFRP sheets, and high ductility (HD) GFRP sheet. The mechanical behavior can be divided into three distinct zones according to the gradual fractures of different types of fiber sheets. During the first zone (Zone I), just prior to the initiation of fractured HM fiber sheets, linear stress-strain behavior is demonstrated, and the slope of the stress-strain curve represents the initial stiffness of the hybrid sheets. Two important strength points are noted at the fractures of HM and HS fibers, corresponding to two strength values f_j and f_m . Generally, f_m is designed as the peak strength of the hybrid composite. Zone II corresponds to the stress-strain zone between ϵ_y and ϵ_m , where significant strain hardening behavior of the hybrid FRP sheets is shown due to the existence of HS and HD fibers. The slope of the stress-strain curve in zone II represents the secondary stiffness of the hybrid FRP composites, which is an important parameter for evaluating the hybrid effects of stiffness. Zone III covers a range, from the fracture of HS fibers to the final failure of the hybrid FRP sheets. The advantage of HD fibers is that they may be fully exerted to obtain high ductility for the hybrid FRP sheets and a large deformation capacity for the strengthened RC structures. The ductility of hybrid FRP sheets is dependent on the final strain of the HD fibers. Some undulation in load (stress) may exist after the fractures of HM and HS fibers. The undulation affects the load carrying property of the hybrid FRP sheets and should be controlled to an acceptably small level by a rational hybrid design [36].

In terms of above idealized mechanical behaviors, the hybrid FRP sheet composed of HS and HD CFRP was investigated at first by Ibaraki Univ.^[37] Theoretically, the hybrid system allows an additional deflection in a RC beam after the high modulus carbon reaches its rupture strain and the load is totally transferred to the high strength carbon., where the high stress could be released in small increments. Consequently, debonding failure may be avoided by ultimate rupture. The fiber layers and proportions of different fibers were compared to control beams in the test. As shown in Fig-10, C1 represents high strength fibers, C7 represents high modulus ones and the numbers in front of C are the fiber layers. The dentate curve of 2C1C7-40 after yielding of beam indicates that the constant fractures of high modulus fibers redistribute stress and mitigate stress concentration contrasted to the control beam NR. Thus, it can be seen that the strengthened beams has shown significantly improved yielding load, much enhanced flexural stiffness, and sufficient ductility as compared to the reference RC beams. The capacity of the preloaded or precracked beams after strengthening can be fully restored to their original designs without damage.

On the basis of HS and HD hybrid CFRP sheet, further research was conducted to investigate flexural strengthening effectiveness with hybrid FRP of high strength (HS), high modulus (HM) and high ductility (HD)^[36]. As shown in Fig-11, the obvious enhancement of ductility of strengthened beams is obtained besides improved yielding load and enhanced flexural stiffness. It should be mentioned that without any accessional method of avoiding debonding, high ductility fibers cannot exert their potential ability in terms of Non-U-anchorage curve. This disadvantage could be ameliorated by adding U shape sheets in anchorage zone. As a result, significant improvements in ductility has been achieved comparing with none U-shape one in the test.

Besides direct material hybridization of different kinds of FRP, the idea of hybridization could also be applied to different parts of a structure with different properties' FRP, in terms of their mechanical characters. With this idea, a kind of FRP-RC hybrid structures are designed to be composed of external hybrid FRP shells and reinforced concrete core by Ibaraki Univ.^[38] In Japan a similar hybrid beam consisting of hybrid C-GFRP flanges and GFRP web was also developed by H. Mutsuyoshi et al.^[1], which was utilized as pedestrian deck.

For this kind of FRP-RC hybrid structures, the bonding of interior walls of the hybrid FRP shell and cast concrete is realized through epoxy resins under wet condition (wet bonding technique). The external FRP shells include high strength and modulus CFRP as longitudinal reinforcements and high ductility GFRP as both longitudinal and shear reinforcements. In addition, the external FRP shell provides the concrete core and steel rebar with effective protection against corrosion, as shown in Fig-12.

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It should be mentioned that the most difference between this FRP-RC beam and traditional one lies in the stage after yielding steel reinforcement. Due to the existence of post-yielding stiffness, the dramatic increase in deformation after yielding steel reinforcements can be effectively prevented and the load carrying capacity could be further improved. At different stages of this structure, different requirements could be achieved by defining several zones, which are expressed as serviceability stage, damage controllable stage and ultimate stage. This kind of FRP-RC beam can actually realize the seismic design methodology, namely "no damage during small earthquake, prompt recoverability during medium earthquake and no collapse during a large earthquake"^[38].

4.3 Underwater strengthening method

Offshore infrastructures encounter severe natural surroundings like chloride attack, tsunami, tidal waves, earthquake etc. Reinforcement concrete and steel structures are vulnerable in severe environments, which may damage their durability and load carrying capacity. Also, the cost for regular inspection and repair is tremendous. Many offshore infrastructures built up after the second world war in Japan need renewal or life-span extension. At present, use of FRP composite members for offshore infrastructures in Japan is not as popular as in USA. The actual applications of FRP in offshore infrastructures in Japan are rather limited. Thereby, some studies on underwater behaviors of FRP materials, focusing on changing FRP's shape and making them more suitable for underwater structures, are performed at Ibaraki Univ. in Japan recent years^[39-42].

Considering the particularity of strengthening underwater structures, bonding and curing are two significant concerns. It is usually difficult for FRP sheets to bond evenly on the surface of underwater concrete elements due to the influence of water. For this sake, the application of FRP sheet strengthening underwater structures is restricted. Therefore, the special CFRP grids have been exploited to solve this problem. The procedure of strengthening underwater column with CFRP grids is shown in Fig-13^[40]. The first step is to treat the concrete pier's surface, and then paint it with an underwater type of epoxy resin to a thickness of about 2 mm. After, CFRP grids are bonded to the surface by pressing them into the adhesive layer. In the last step, the epoxy is re-painted to a total of 5 mm thick.

The sufficient bonding capacity between CFRP grid and concrete surface has been obtained through single-lap shear and three-point loading tests, whereas the same magnitude of capacity has been obtained with FRP grids, which only have 70% fibers compared with CFRP sheets. The load-displacement curves of CFRP grids, CFRP sheets and control beam are contrasted in Fig-14^[41].

As mentioned above, DFRP (Dyneema Fiber Reinforced Polymer) has wide prospects for the use of underwater strengthening since it has good energy-absorption and water-resistance behaviors, in addition to its high strength and ductility. Considering the majority of underwater structures are columns. Although DFRP is bonded poorly with resin, on columns, effective strengthening could be achieved by confining them, instead of increasing the bonding quality. Consequently, DFRP dry fibers could be wrapped around the columns without resin to rehabilitate or strengthen the columns efficiently. The seismic behaviors of concrete columns strengthened with DFRP, with and without resin, have been tested, as shown in Fig. 15. The curves indicate that seismic performance in both significantly improved with minimal resin influence. C-0 represents the control column and C-I and C-II are the strengthened columns by DFRP sheets with and without resin respectively.^[43]

4.4 High fracturing strain FRP in reinforced concrete piers

For seismic retrofitting of concrete piers, the most critical factor lies in the ductility behavior, not strength. High ductility could be achieved by hybrid FRP, as discussed above. Another method would be to strengthen the piers with high fracturing strain FRP directly. Typical fiber materials like CFRP or AFRP tend to fail early due to fiber breakage before the structures can fully utilize their reinforced strength due to their low fracturing strain. Fiber breakage causes a loss of confinement and a sudden loss of load-carrying capacity and directly limits the ductility potential. In the design procedure the limitation of fiber strain is used to determine the reinforced concrete (RC) piers strength capacity to avoid rupture of fiber material. In this case, high fracturing strain FRP should be the most suitable selection. Many researchers have proven the effectiveness of their application in shear and ductility enhancement through test. These new fiber materials such as PAF, PEN and PET, which have properties of large fracturing strain and low stiffness in comparison to aramid, carbon, and glass fibers, have been investigated for seismic strengthening of RC piers in Japan. The stress-strain relationships are compared with typical FRP materials as shown in Fig-2.

PAF can be used as continuous fiber reinforcement in winding the longitudinal reinforcement without impregnating resin. This type of PCFFR (Polyacetal continuous fiber flexible reinforcement) was investigated by Ueda et al. (2003)^[44-45] and the test results indicate that the shear strength and ultimate deformation are significantly improved by PCFFR, under the reversed cyclic loading. It should be mentioned that greater deformation was possible because of the absence of PCFFR fracture even at the ultimate deformation. Also PCFFR can ease the difficulty in arranging congested reinforcement due to their convenient winding around longitudinal reinforcement. A higher efficiency of construction could be achieved without impregnating

resin, especially for PCFFR

The other two types of high fracturing strain FRP, namely PET and PEN, have also been investigated to strengthen shear capacity and enhance ductility of reinforced concrete piers by Anggawidjaja and Ueda etc. (2006)^[46]. Fifteen RC piers in four experimental batches were constructed to represent a rectangular pier of a regular bridge, while the bottom part represented the footing of the pier that was wrapped by PET or PEN sheets. The test results show considerable improvement of ductility is achieved by these two fibers. Both PET and PEN show no tendency towards fiber breakage before the predefined ultimate deformation. Shear deformation increases rather rapidly after peak load and concrete shear capacity decreases with increasing shear deformation. The stiffness of fiber affects the development of shear deformation and the descending branch of the load-deformation curve after the peak load. A concept for determining the characteristic P- δ curves of RC piers strengthened with large fracture strain FRP materials, PEN and PET, has been proposed. They believe that the present JSCE seismic design equation proposed for RC piers underestimates the pullout deformation and the plastic flexural rotation at the starting point of the descending parts of P- δ curves of FRP strengthened RC piers. Hence new formulations should be put forward and verified by experimental results. Their formula for predicting the ultimate deformation of RC piers strengthened with large fracture strain FRP materials have been proposed and are accurate in comparison to experimental results^[42].

5. JSCE approach against IC debonding in FRP sheet flexural strengthened RC members

The Japan Society of Civil Engineers (JSCE) established a research committee in 1998 to advance the unified and more widely applicable design recommendations of FRP sheets for retrofitting or strengthening existing concrete structures, as well as the repair and enhancement of durability of concrete structures. Subsequent to the activities of this research committee, JSCE 2001 was published in both Japanese and English in 2001. Recently, a keen interest in further clarifying the debonding mechanisms has arisen between the externally bonded FRP and concrete substrate since the bonding interface proves to be weakest compared to the neighboring materials in the whole strengthening system. In this work, an approach to preventing intermediate crack (IC) debonding failure will be introduced due to its great importance to flexural strengthened members.

Similar to other design guidelines, JSCE recommendations classify the failure modes of FRP strengthened RC beams in flexure into five categories (see details in JSCE 2001). Among them for the sheet bonding system, mode (5), so called intermediate crack (IC) debonding failure, is most critical. To avoid IC debonding failure in the flexural strengthened members

(see Fig-16), JSCE Recommendations provide the following criteria:

$$\sigma_f \leq \sqrt{\frac{2G_f E_f}{n_t t_f}} \quad (1)$$

$$\Delta\sigma_f \leq \sqrt{\frac{2G_f E_f}{n_t t_f}} \quad (2)$$

Eqs.1 and 2 originate from the contribution by Wu and Niu (2000) [11]. However, since Eq.2 is not an explicit expression for calculating the strain limit in the FRP sheet, Eq. 1 is more often used in the engineering practice as a low bound to prevent the strengthened members from debonding failure. Recently, Wu and Niu (2007) [47] have improved Eq.2 toward a refined design solution. They maintained the format of Eq.2, but conceptually simplified the multi-cracks into one dominant crack in the mid-span (See Fig-17) and added two more equations to calibrate the fracture energy and define the equivalent bond length L_e' (See Fig.16) for the flexural strengthening cases as follows:

$$G_f = 0.644 f_c'^{0.19} \quad (3)$$

$$L_e' = \text{Max}(1.3\sqrt{E_f t_f} / f_c'^{0.095}, l_y) \quad (4)$$

where l_y = the yielding length of steel reinforcement. Wu and Niu (2007) have used their new model to predict the flexural capacity of 180 FRP strengthened RC beams they collected, and proved that their model exhibits good agreement with test datum, as shown in Fig. 18.

Furthermore, to simplify formula format and make the results more precise, the regression method was applied to derive the flexural capacity of external bonded beams in terms of over 200 testing datum collected from the existing literatures by Said and Wu (2007) [48], as shown in Eq.5. The comparison results are shown in Fig. 18 with six representative models.

$$\varepsilon_{deb} = 0.23(f_c')^{0.2} / (E_f t_f)^{0.35} \quad (5)$$

For realistic behavior predictions of FRP-strengthened structures, the instantaneous response of FRP-concrete interface under static loads, but also the influence of long-term deterioration processes is of significant interest. In the last two decades, great achievements have been directed at understanding the bonding and debonding behavior of FRP-concrete interface and developing different evaluation methods based on bond strength. It was difficult to understand and model the creep fracture along FRP-concrete interfaces. In this field, extensive research has been directed at investigating the performance of FRP-concrete interfaces, and developing constitutive models for that type of strengthening. Recently in Japan, Wu and Diab (2007) [49-50] adopted a nonlinear viscoelastic model to describe the creep of FRP-concrete adhesive layer and creep fracture propagation along the FRP-concrete interface. The results demonstrate the reliability of the proposed model and its capability to predict the time-dependent debonding propagation along FRP-concrete interface. It has also been shown that the

model can be used to predict a wide range of creep fracture, not only under sustained loadings, but also under high sustained loadings.

In summary, current JSCE Recommendations show a clear theoretical background based upon fracture mechanics for preventing debonding failures in FRP sheet flexural strengthened members and also provide a reasonable safe margin for the strain limit in FRP sheets for practical design purposes. Recently, many models related to the IC debonding have been developed and are being developed using the bond parameters obtained from the pull-out tests and incorporating the geometry information of strengthened members. Undoubtedly, better test databases and enhanced understanding of the interface bond mechanisms have improved the accuracy of the IC debonding strength prediction by employing more empirical factors.

Conclusions

After twenty years of development, FRP has been accepted widely in the rehabilitation and strengthening of structures in Japan. Also, experience and achievements have been occurred in the fields of FRP materials' behaviors, calculation theories and design methods. However, the potential advantages of FRP still could not be utilized sufficiently due to traditional design theory, such as the manner in which to consider post-yielding stiffness of FRP strengthened structures and FRP's self-monitoring properties in structural health monitor. Although many creative and innovative studies have been conducted, FRP is still a long way from being a mainstream construction material in civil infrastructures. Therefore, in the future, the direction of FRP's development in civil infrastructures should be centered on making sufficient use of FRP's potential abilities. For this purpose, it is required to integrate a system with long-life, damage control and recoverable structures on the basis of performance design principles.

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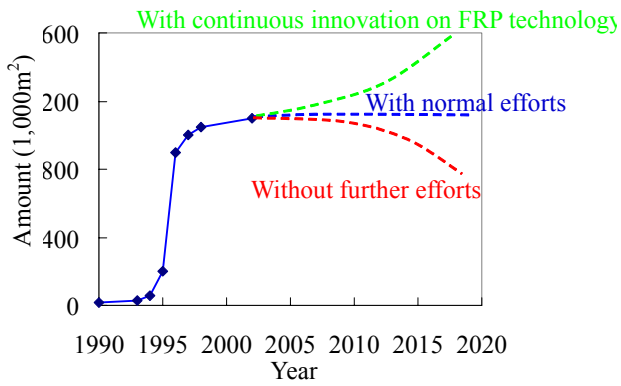


Figure-1. Developing trend of FRP annual amount (For example of CFRP sheets)

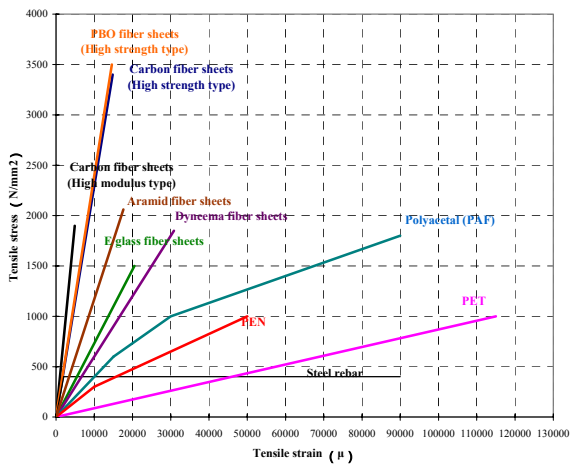


Figure-2. Stress and strain relationships of different fiber composite

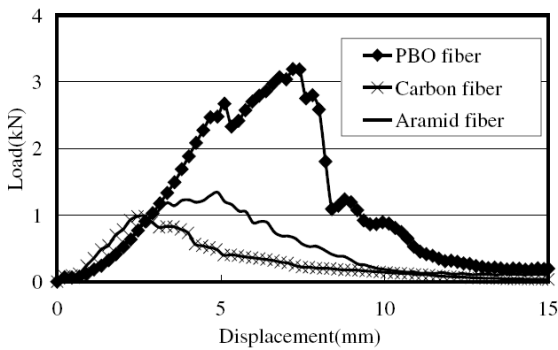


Figure-3. Results of impact test

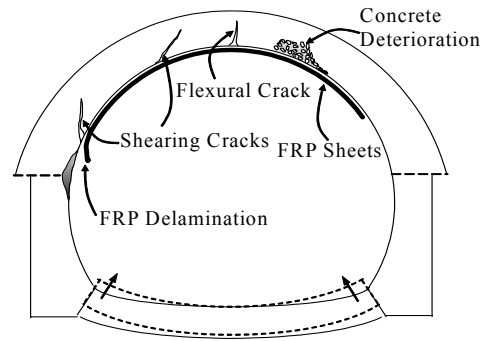


Figure-4. FRP strengthening in tunnel lining

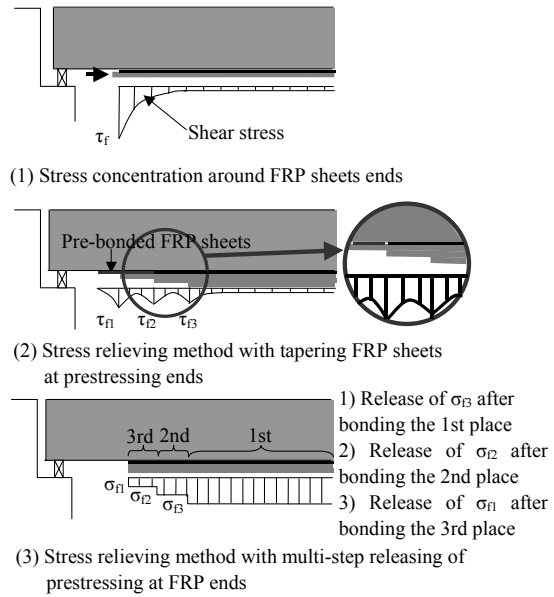


Figure-5 Two methods for relieving end stress concentration

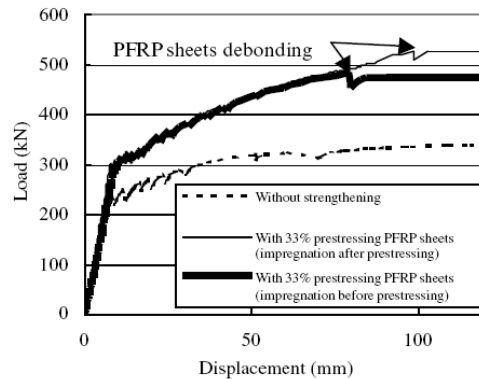


Figure-6 Load-Deflection Curves of Prestressing FRP strengthened beams

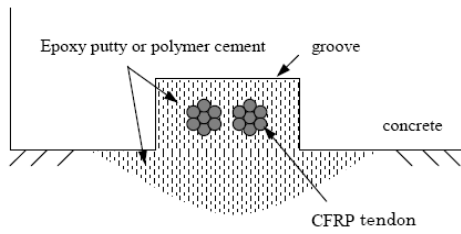


Figure-7 Embedded NSM and additional overlay

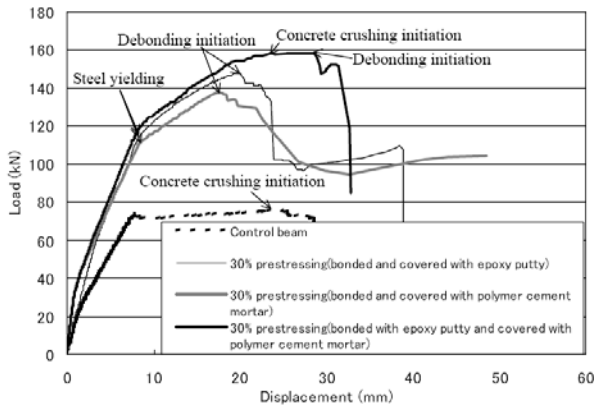


Figure-8. L-D curves of specimens with prestressing NSM tendons

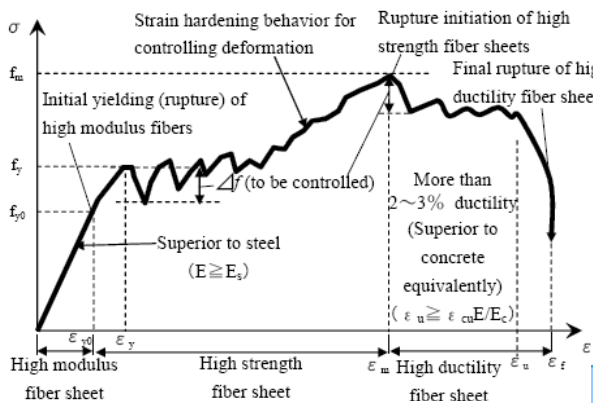


Figure-9. Idealized stress-strain behavior of hybrid FRP composites

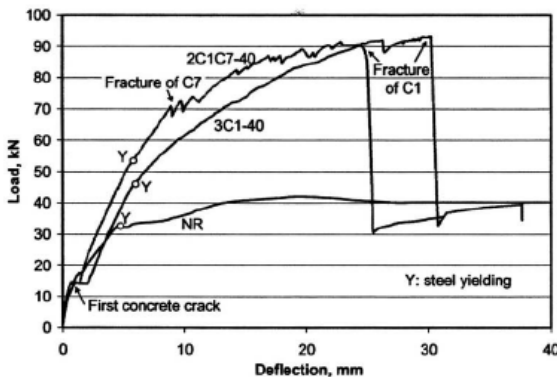


Figure-10 Load-Deflection Curves of HS and HM CFRP strengthened beams

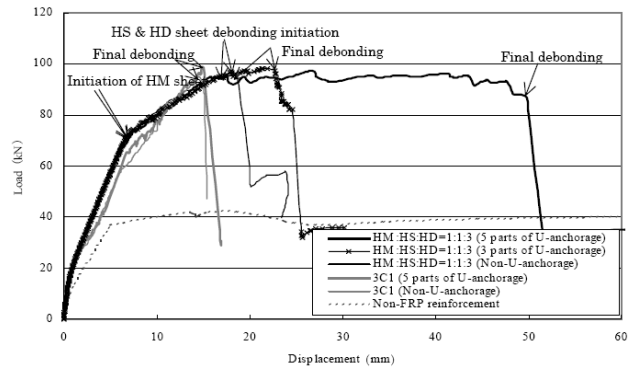


Figure-11. Load-deflection behavior of HS, HM, and HD FRP strengthened beams

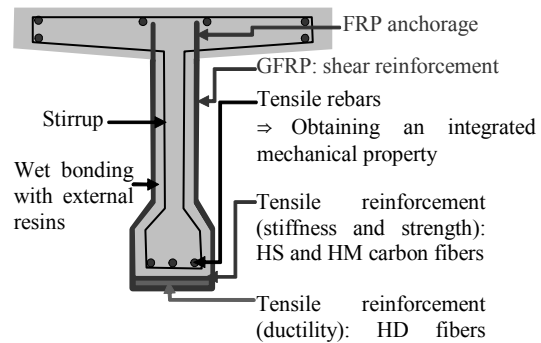


Figure-12. Composition of proposed FRP-RC T girder

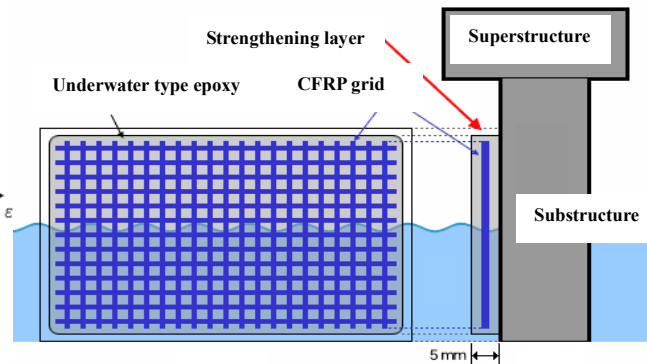


Figure-13. Underwater bonding procedure

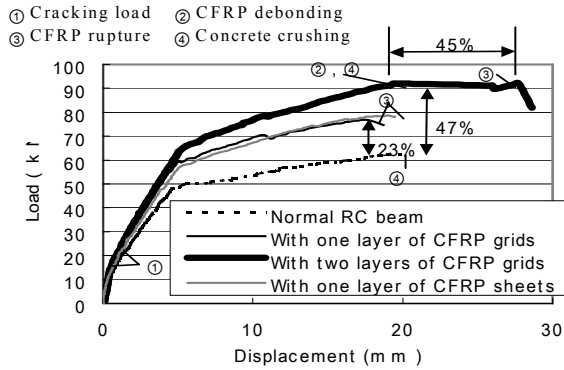


Figure-14. Comparison with strengthened beams using CFRP grids and sheets

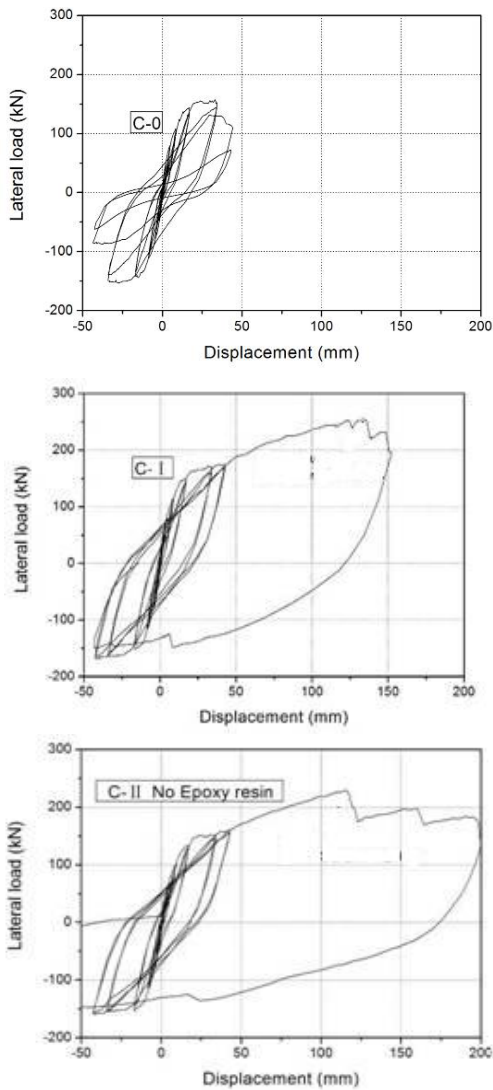


Figure-15 Lateral load-displacement responses

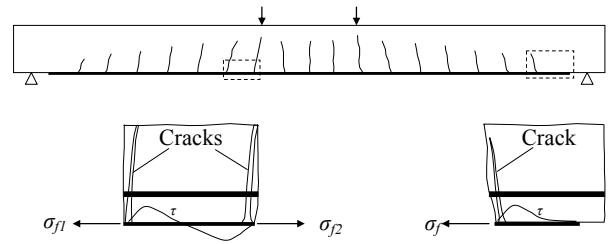


Figure-16. JSCE IC Debonding Criteria based on Wu and Niu (2000) Model^[11]

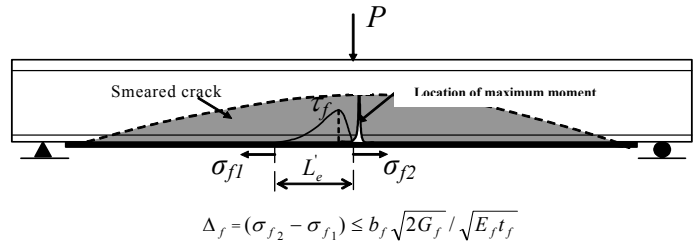
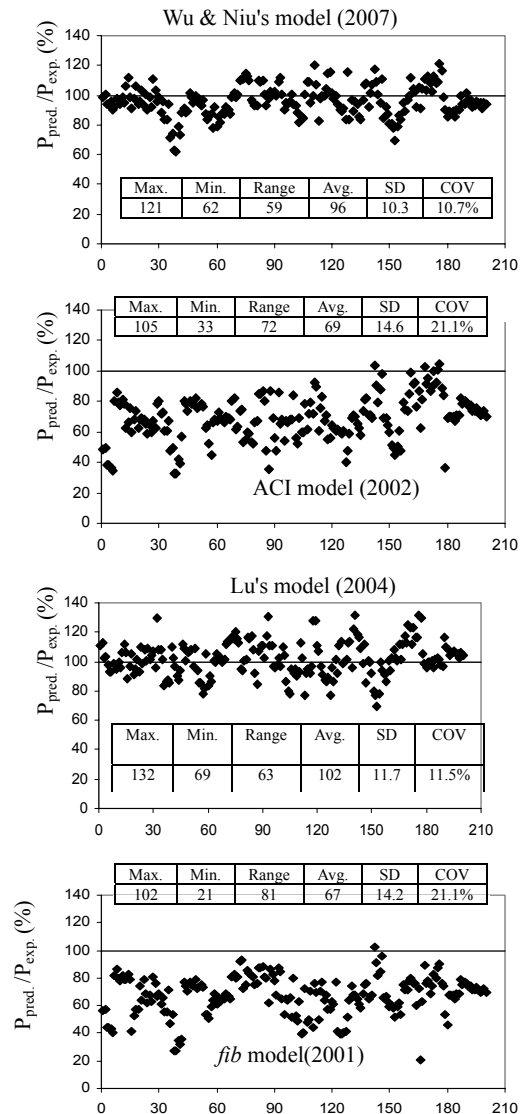
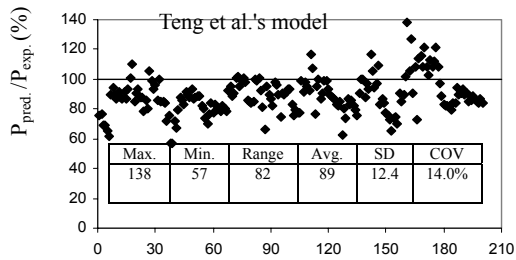


Figure-17 Wu and Niu (2007) IC Debonding Criteria for Flexural Strengthening Case





Figure–18 Comparison with computing value and test datum of different models

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