Appendix 11

Section 11 *Japanese Design And Construction Guidelines For Seismic Retrofit Of Building Structures With Frp CompositesFRP sheet retrofit guideline*

presented by H. Fukuyama

JAPANESE DESIGN AND CONSTRUCTION GUIDELINES FOR SEISMIC RETROFIT OF BUILDING STRUCTURES WITH FRP COMPOSITES

Hiroshi Fukuyama [1]
Gustavo Tumialan [2]
Antonio Nanni [3]

[1] Department of Structural Engineering, Building Research Institute
1 Tatehara, Tsukuba, Ibaraki 305-0802, JAPAN
[2, 3] Department of Civil Engineering, University of Missouri-Rolla
224 Engineering Research Lab, 1870 Miner Circle, Rolla, MO 65409-0710, USA

ABSTRACT

The increasing uses of FRP materials for the strengthening and upgrade of buildings has motivated the international engineering community to produce guidelines for the proper design, handling and installation of the externally bonded FRP systems. Thus, independent efforts coordinated by different organizations such as the Japan Building Disaster Prevention Association (JBDPA) and the American Concrete Institute (ACI) have led to implementing appropriate provisions. The JBDPA guidelines mainly focus on seismic retrofitting of structural elements, which implies the strengthening for shear of deficient structural elements. This paper describes and comments on some of the design approaches provided by the JBDPA guidelines for the strengthening of reinforced concrete (RC) columns. This was one of the main targets of the Japanese experience on infrastructure strengthening, which became an imperative task after the post-earthquake observations of the damage caused by the Kobe earthquake in 1995. Finally, comparisons with the ACI guidelines for the strengthening of RC members with FRP systems are also formulated.

KEYWORDS
Construction, Design, Ductility, FRP Sheets, Flexural Capacity, Guidelines, RC Beams, RC Columns, Seismic Capacity Evaluation, Seismic Retrofit, Shear Capacity

INTRODUCTION

In 1995, the Hyogoken-Nanbu Earthquake caused to the city of Kobe the greatest disaster of the postwar era in Japan. As a result of the inflicted damage and to reduce the impact of potential seismic events in other parts of the country, the Building Research Institute of Japan promoted a program for the development of effective strategies for seismic retrofitting of buildings. One of the areas targeted by this program was the use of Fiber Reinforced Polymer (FRP) materials. In September 1999, the Japan Building Disaster Prevention Association (JBDPA) published the “Seismic Retrofitting Design and Construction Guidelines for Existing Reinforced Concrete (RC) and Steel-encased Reinforced Concrete (SRC) Buildings with FRP Materials”. These guidelines were developed based on the results of investigations conducted in Japan, mainly after 1995, and reflect the combined efforts of the Japanese academy, industry, and governmental agencies. This paper describes and comments on some of the design approaches provided by the JBDPA guidelines for the strengthening of RC elements.

SEISMIC CAPACITY EVALUATION

The “Seismic Capacity Evaluation Standards” (JPDPA, 1977 revised in 1990) and “Guidelines for Seismic Rehabilitation of RC Buildings” (JPDPA, 1977 revised in 1990) are used in conjunction with the guidelines for seismic retrofitting of RC buildings. These guidelines have been used since 1977 as an instrument to evaluate the seismic performance of existing RC buildings. Since these provisions represent the first step in the retrofitting process, their basic concepts are briefly described in this section. The seismic capacity of a building is quantified by the seismic index I_s, which should be estimated for every story and frame direction. It is defined as follows:

$$I_s = E_o \, S_D \, T \tag{1}$$

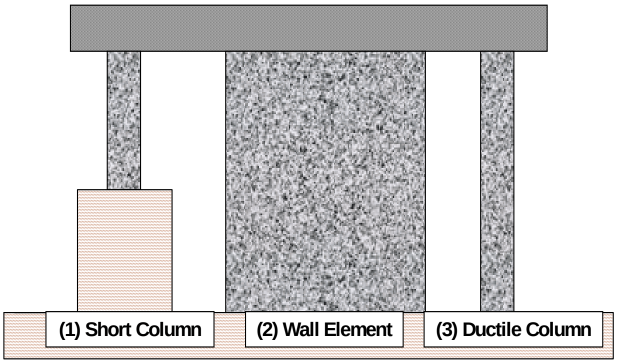
where E_o expresses the basic seismic index, S_D is the structural design index, which accounts for plan or story-height irregularities, gravitational and stiffness centroid eccentricities. T represents the time index to account for the degree of deterioration of the building, manifested by cracks and permanent deformations.

The basic seismic index is a function of the strength index C, and the ductility index F. The basic seismic index E_o is expressed as:

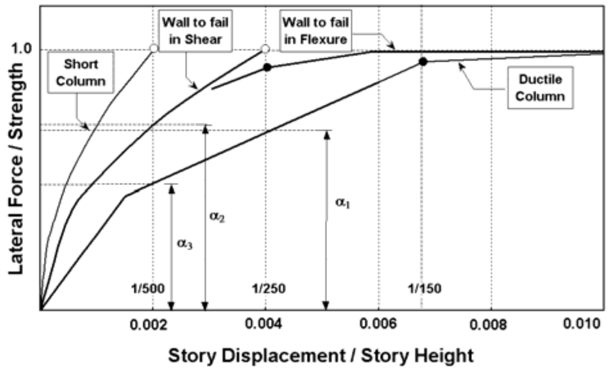
$$E_o = \frac{n+1}{n+i} \, f(C, F) \tag{2}$$

where ‘n’ is the number of stories and ‘i’ is the story being analyzed. The seismic index intends to represent the capability of the building story being analyzed to absorb energy. Thus, if a story is assumed to consist of a series of vertical members, such as those illustrated in Figure 1a, the load deflection curves for this story subject to a monotonic load can be represented by the curve shown in Figures 1b. The variable α represents the ratio between the lateral force acting in the element and the capacity of the element. For the computation of E_o, predetermined values for α and F are provided by the “Seismic Capacity Evaluation Standards”. The largest value obtained by using the equations illustrated in Figure 1c and 1d is used for the computation of I_s.

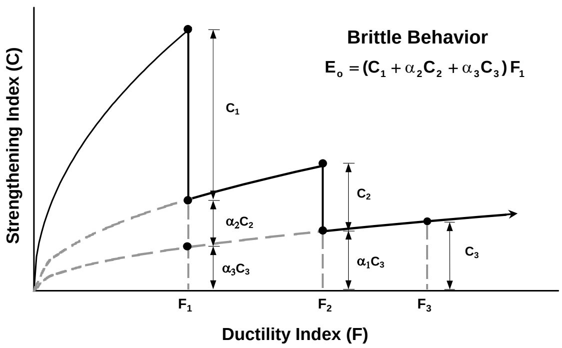
Three procedures are recommended to estimate I_s, which are dependable on the characteristics of the story to be analyzed. These procedures can be described as:



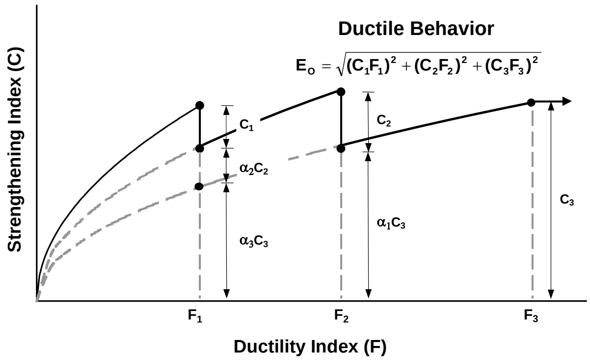
(a) Idealized Building Story



(b) Ideal Load vs. Displacement Curves



(c) Brittle Behavior



(d) Ductile Behavior

Figure 1: Seismic Capacity Evaluation

- The first procedure is the simplest, which is used for stories with a large density of walls. The ultimate strength is estimated based on the concrete shear strength and cross section area of columns and walls.
- The second procedure requires the calculation of the ultimate capacity and ductility of columns and walls. The beams are usually assumed to be rigid. This procedure is used for “weak column-strong beam” frames.
- The third procedure implies to calculate the ultimate capacity and ductility of the vertical members as well as beams. All the possible mechanisms of failure are taken into account.

Once the seismic index I_s is estimated, this value is compared to a limit index I_{so}. If the I_s index is larger than the limit index, the building is expected to have a good performance during a seismic event. Otherwise, the structures must be retrofitted to comply with the requirements of current building standards. Evaluations conducted on damaged buildings due to earthquakes indicated that whenever the I_s indices were less than 0.3 severe damage was observed. Also, when the values of the I_s indices were larger than 0.6, the damage observed in the buildings was moderate. This was evident from the evaluations performed to the building structures after the Hyogoken-Nanbu Earthquake in 1995, where a value of 0.6 indicated the border limit between severe and moderate damage. Thereby, the “Standards for Seismic Capacity Evaluation of RC Buildings” specify a value equal to 0.6 as limit index I_{so} to prevent collapse or severe damage. When the structures is found to be structurally deficient, new values for C and/or F have to be estimated to meet the structural demand.

SCOPE OF THE JBDPA GUIDELINES FOR STRENGTHENING WITH FRP

The Japanese guidelines for seismic retrofitting of RC building with FRP materials (JPDPA, 1999) provide specifications on the characteristics of the FRP materials commonly used in Japan, their proper handling and installation. Also, pertaining design and detailing recommendations are provided, which mainly target the shear strengthening of either columns or beams. Some of the main provisions are described in the subsequent sections. The guidelines are part of the "Guidelines for Seismic Rehabilitation of RC Buildings" (JPDPA, 1977 revised 1990), a comprehensive publication that documents different retrofitting methods utilized in Japan.

MATERIALS

The JBDPA guidelines describe the properties of PAN-class high-strength carbon fiber sheets, and aramid fiber sheets. In its turn, aramid is sub-classified as aramid 1 and aramid 2. Carbon fiber sheets are labeled based on the tensile strength of the fiber; whereas, the denomination of the aramid fiber sheets is based on the tensile strength in a width of one meter. The values of tensile strength and modulus of elasticity have been estimated from laminates made of carbon or aramid fibers bound in a resin matrix. Table 1 presents the properties of fibers bound by epoxy or methacrylate resin.

TABLE 1
PROPERTIES OF FRP SHEETS

Characteristic	**Carbon Fiber**		**Aramid Fiber**	
	3400 MPa Class	2900 MPa Class	Aramid 1	Aramid 2
Type of Fiber	PAN-class High-Strength		Homopolymer	Copolymer
Tensile Strength	≥ 3400 MPa	≥ 2900 MPa	≥ 2060 MPa	≥ 2350 Mpa
Young's Modulus	230^{+45}_{-15} GPa		118 ± 20GPa	78 ± 15GPa
Fiber Density	1.80 ± 0.05		1.45 ± 0.05	1.39 ± 0.05

The viscosity of the adhesive resins influences the efficiency of the strengthening work. Thus, if sagging is likely to occur, a resin of higher viscosity is recommended. Also, if smooth impregnation in the fiber is required, a resin with lower viscosity should be used. In the case of primers, epoxy and methacrylate resin are commonly used. Due to potential alterations of the hardening process, it is not allowed to use an epoxy-based primer in combination with a methacrylate-based adhesive or vice versa. In similar way, if the putty material is not compatible with the adhesive and primer resins, imperfect adhesion may occur.

DESIGN APPROACHES FOR STRENGTHENING OF COLUMNS

In order to determine the required amount of FRP strengthening, the Japanese guidelines provide expressions to calculate the flexural and shear strengths, and ductility index of RC members. The equations are based on those presented by the "Standards for Seismic Capacity Evaluation" and the "Guidelines for Seismic Rehabilitation of RC Buildings". These equations have been widely used for the design of new construction The definitions of the variables used hereafter are presented at the end of this paper.

Ultimate Flexural Capacity of Columns

The ultimate flexural capacity of a RC column is calculated from the following expressions, which are recommended by a guide for structural design of new buildings, which must comply with the "Japanese Building Standard Law".

For $N_{max} \geq N > N_b$:

$$M_u = \left[0.5a_g\sigma_y g_1 D + 0.024(1+g_1)(3.6-g_1)bD^2F_c\right]\left(\frac{N_{max}-N}{N_{max-}N_b}\right) \quad \text{(N-mm)} \tag{3a}$$

For $N_b \geq N \geq 0$:

$$M_u = 0.5a_g\sigma_y g_1 D + 0.5ND\left(1-\frac{N}{bDF_c}\right) \quad \text{(N-mm)} \tag{3b}$$

For $0 > N \geq N_{min}$:

$$M_u = 0.5a_g\sigma_y g_1 D + 0.5Ng_1 D \text{ (N-mm)} \tag{3c}$$

N_b, N_{max} and N_{min} can be computed from:

Balanced Axial Force:

$$N_b = 0.22(1+g_1)bDF_c \quad \text{(N)} \tag{4a}$$

Ultimate Axial Force in Compression:

$$N_{max} = bDF_c + a_g\sigma_y \quad \text{(N)} \tag{4b}$$

Ultimate Axial Force in Tension:

$$N_{min} = -a_g\sigma_y \quad \text{(N)} \tag{4c}$$

The shear force associated to the flexural capacity M_u can be computed as:

$$Q_{mu} = \frac{\alpha M_u}{h_o} \quad \text{(N)} \tag{5}$$

A α value equal to two may be used to estimate the shear arm. Figure 2 shows the agreement between the experimental and predicted values when using the previous equations.

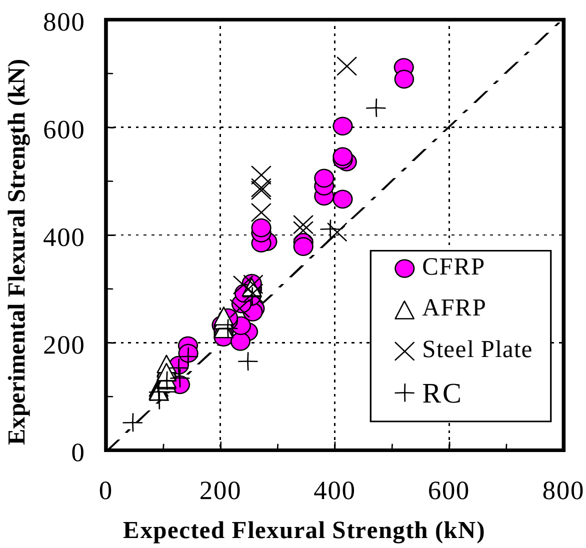


Figure 2: Validation of the Equation for Flexural Strength of Columns

Ultimate Shear Capacity of Columns

The equation used to quantify the shear capacity of an RC member strengthened with FRP composite systems is also similar to that used for structural design of new buildings. The only modification is the addition of the product $p_{wf}\sigma_{fd}$ to the summation $\Sigma p_w\sigma_{wy}$, which intends to take into account the contribution of the FRP reinforcement. Thus:

$$Q_{su} = \left[\frac{0.053 p_t^{0.23}(17.6 + F_c)}{M/Qd + 0.12} + 0.845\sqrt{\sum p_w \sigma_{wy}} + 0.1\sigma_o \right] bj \qquad \text{(N)} \tag{6a}$$

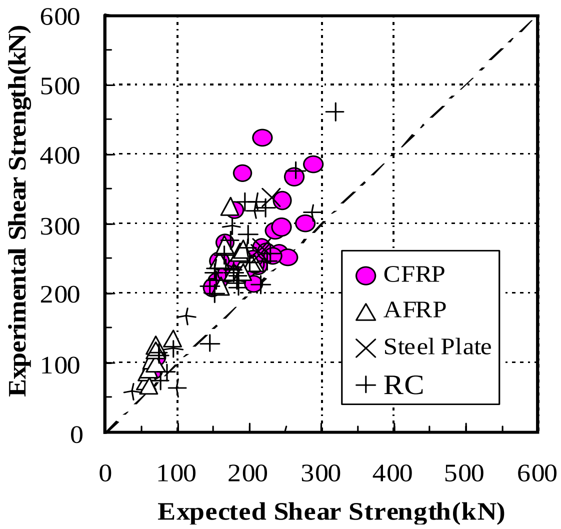
where:

$$\sum p_w \sigma_{wy} = p_{ws}\sigma_{wys} + p_{wf}\sigma_{fd} \leq 10\text{MPa} \tag{6b}$$

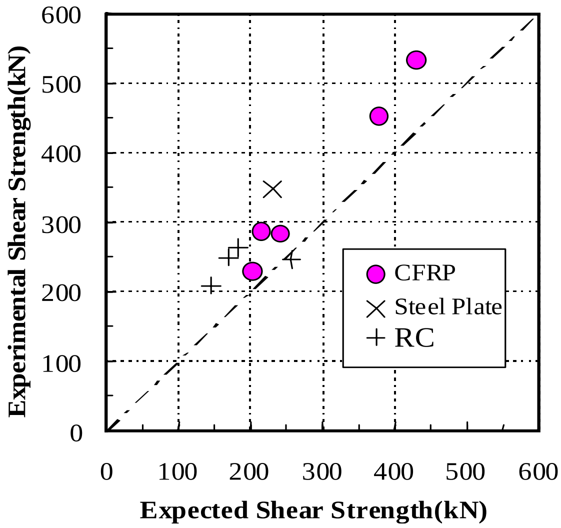
An upper limit of 10 MPa is imposed to $\Sigma p_w\sigma_{wy}$ based on the fact that a larger amount of strengthening would not significantly increase the shear capacity of the strengthened member. Equation 6a can also be applied to predict the ultimate capacity of columns failing by bond splitting, and columns having longitudinal round reinforcing bars.

Another consideration to mention is that the value of the shear span-to-depth ratio expressed as M/Qd must not be less than one nor larger than three. The tensile strength of FRP for shear design is estimated as: $\sigma_{fd} = \min\{E_{fd}\varepsilon_{fd}, 2/3\sigma_f\}$. The value of ε_{fd} equal to 0.7% is adopted based on previous investigations, which have shown that the measured strain in the FRP laminate at the final stage, was between 0.5% and 1.5%. These investigations have also shown that specimens strengthened with a large amount of external reinforcement ($p_{wf}E_{fd}$) possessed smaller strains at failure. Along with the first consideration, to avoid the rupture of the FRP laminate, a value of two-thirds of the tensile strength of the FRP laminate was adopted as a margin of safety, when designing for shear.

Figure 3 illustrates a good agreement between experimental and predicted values for shear strength of RC members strengthened with FRP material when shear failure (rupture of the laminate or compression failure of the concrete strut) and bond splitting are observed.



(a) Shear Failure



(b) Bond Splitting Failure

Figure 3. Validation of the Equation for Shear Strength of Columns

Ductility Factors and Ductility Index of Columns

The ductility index F is a function of the ductility factor μ, and can be expressed by the following relationships obtained from a degrading tri-linear hysteresis model.

$$F = \phi\sqrt{2\mu - 1} \tag{7a}$$

where:

$$\phi = \frac{1}{0.75(1 + 0.05\mu)} \tag{7b}$$

The ultimate ductility factor μ of columns strengthened with FRP materials is expressed as the margin ratio of the shear strength to the shear force associated to the flexural strength. This factor can be calculated as follows:

$$\mu = 10\left(\frac{Q_{su}}{Q_{mu}} - 0.9\right), \text{ where } 1 \le \mu \le 5 \tag{8}$$

It is known that the ultimate shear strength increases when the axial force in the column is increased. Also, the ultimate flexural strength decreases when the axial force is larger than the balanced axial force. This will cause that the associated shear force Q_{mu} decreases, leading to a larger value of ultimate ductility factor μ. Thereby, to avoid the use of larger ductility values, the code specifies to calculate Q_{mu} based on the balanced moment, whenever the axial force exceeds the balanced axial force.

DESIGN APPROACHES FOR STRENGTHENING OF BEAMS

Ultimate Flexural Capacity of Beams

The ultimate flexural capacity of RC beams is computed by using the following equation:

$$M_u = 0.9 a_t \sigma_y d \qquad \text{(N-mm)} \tag{9}$$

The flexural capacity may also be calculated with equation 3b considering a value of axial force equal to zero. The equations provided for the guidelines are for strengthening rectangular RC beams; the influence of the reinforcement of slabs is not considered. The shear force associated to the flexural capacity M_u is calculated as:

$$Q_{mu} = \frac{\alpha M_u}{L_o} \quad \text{(N)} \tag{10}$$

Ultimate Shear Capacity of Beams

To estimate the ultimate shear capacity of RC beams strengthened, the term representing the influence of the axial force in equation 6a is dropped, thus equation 11 is obtained. Similarly to the case of columns, the value of the shear span-to-depth ratio, M/Qd, must not be less than one nor larger than three. In addition the term $\Sigma p_w \sigma_{wy}$ must satisfy the relationship given by equation 6b.

$$Q_{su} = \left[\frac{0.053 p_t^{0.23}(17.6 + F_c)}{M/Qd + 0.12} + 0.845\sqrt{\sum p_w \sigma_{wy}} \right] bj \qquad (N) \tag{11}$$

Figure 4 compares the experimental and predicted values for the maximum strength of RC beams strengthened in shear with FRP materials. It is observed that the calculated values by using equation 11 are on the safe side.

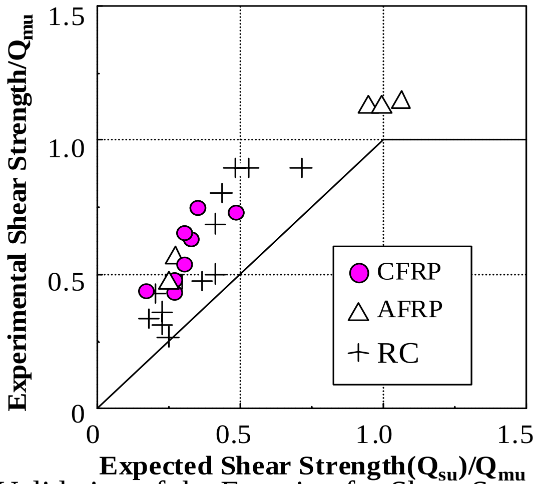


Figure 4: Validation of the Equation for Shear Strength of Beams

SPECIAL PROVISIONS

Strengthening Without Removal of Mortar Finishing

An advantage of using FRP materials for strengthening RC elements is that the disruption to the building occupants or other individuals in the nearby area is minimum. One source of disruption is that caused by noise, dust and vibration when removing the finishing mortar. Surfaces finished with mortar were very common in Japan up to the mid-1970s, when the need for mortar finishing was basically eliminated with the improvement the formworks. As a principle, the Japanese guidelines require the removal of finishing mortar for strengthening of columns. However, the guidelines present special specifications for the strengthening of RC rectangular columns without removing the finishing mortar, which can be carried out when appropriate control during the execution of the strengthening work is provided. These specifications are based on previous experimental programs, which demonstrated that the shear capacity and ductility are not reduced when columns are wrapped around with FRP materials with the presence of finishing mortar. In addition, based on those researches, in order the strengthening to be effective, any existing cracks on the finishing mortar have to be repaired prior to installing the FRP system. It is also specified that surfaces of mortar finishing painted with layers of thick painting materials may remain. The bond strength of these materials must be at least 1 MPa; in addition, they must not have any adverse chemical reaction with the epoxy adhesives. It is not recommended to attach FRP materials to surfaces constituted of plastering, finishing tiles, wallpaper, etc.

The survey of the conditions of the finishing mortar should be based on the number of years of service of the structure, the surface conditions, history of previous repair works and characteristics of finishing mortar. The strength of the mortar is estimated by means of any suitable tool such as Schmidt rebound hammers. Defining t_m as the thickness of finishing mortar and D as the largest cross sectional dimension of the column the following recommendations are provided for the design of the strengthening:

- If $t_m \leq D/15$ and the results of the survey indicate that the mortar finishing can remain, the design is conducted as the mortar finishing had been removed.
- If $t_m > D/15$, the mortar finishing needs to be removed unless a special study is conducted.

In any case, with or without removal of mortar finishing, the lap length is specified to be larger than 200 mm. The radius corner must be larger than 10 mm when AFRP is used, and larger than 20 mm for the case of CFRP wrapping. Due to concrete cover consideration, the radii should not exceed 30 mm for any case.

Anchoring Systems

FRP systems that do not completely wrap the entire section will likely peel off from the concrete surface. To develop larger tensile stresses in the laminate, mechanical anchorages can be used at the termination points. Previous investigations demonstrated the use of Schemes C, D, E and F in Figure 5, increased the shear capacity. However, these schemes may not be effective in beams having short span or when the amount of reinforcement increases. It has been observed that the beam can split from the slab along the corners, as illustrated in Scheme C. To account for this, it is advisable to check the level of shear stresses at those corners to foresee the splitting. If the splitting is likely to occur, the guidelines recommend the use of anchorage schemes as those labeled as Schemes A and B.

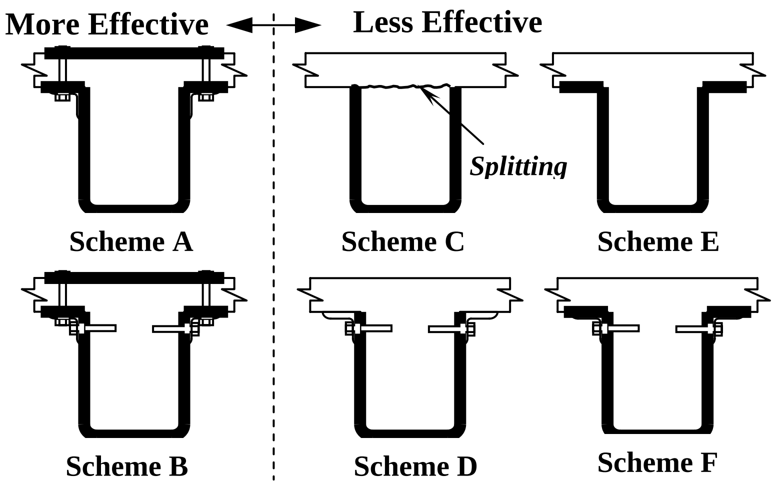


Figure 5: Anchorage Schemes

Specifications should be provided to fully guarantee the effectiveness of angles and bolts, which will ensure the increase of shear strength. The specifications should include the number and strength of bolts. Also, the "L" shapes must be designed to avoid rotation or plastic deformation caused by the tensile stresses in the laminate. Since the corners are not necessarily at 90^o degrees, the designer should also provide specifications on the corner preparation and anchorage installation procedures.

CONSTRUCTION PRACTICE

Execution of the Strengthening Work

The work activities related to the strengthening of RC building structures should comply with the Contractors Law of the Ministry of Land, Infrastructure and Transport of Japan. The JBDPA guidelines provide adequate guidance for strengthening RC members with different combinations of continuous fibers and impregnating resins. These combinations include CFRP/epoxy resin, CFRP/methacrylate, and AFRP/epoxy resin. In its turn, the resins can be one-part or two-parts. Since there are no test results available on AFRP/methacrylate, specifications about this particular combination are not provided. Depending on the fiber-resin combination to be used, the required weight by square meter and the time interval for each step of the FRP installation are specified. As an example, Table 2 presents some specifications when FRP sheets are attached by using epoxy resins or a methacrylate resins.

The strengthening work requires to be inspected after the installation of the FRP systems. This is done to ensure the absence of defects such as blisters, partial peeling and residual resin. If blisters are observed, a resin compatible with the primary resin can be injected. When partial peeling is observed, it is recommended to remove the attached area without damaging the FRP lower layers, and replace it with a new sheet. The new sheet should overlap the existing sheet at least 200 mm. If residual resin is detected, it should be removed using sandpaper without damaging the FRP sheet.

TABLE 2
SPECIFICATION FOR INSTALLATION OF FRP WITH ONE-PART RESINS

Process	FRP/Epoxy Resin		FRP/Methacrylate Resin	
	Weight of Material (kg/m^2)	Time Interval	Weight of Material (kg/m^2)	Time Interval
Primer	0.2-0.3	≥4 hrs., within 3 days	0.075-0.1	≥60 min.
First layer of resin	0.4-0.5	Immediately	0.4-0.5	≥5 min.
FRP sheet installation	1.15 m^2/m^2	≥ 2 min. (for fabric type); ≥ 20 min. (for pre-preg type), within 90 min.	1.5 m^2/m^2	Within10 min.
Second layer of resin	0.3-0.4	Immediately	0.4-0.5	Within10 min.
Air voids elimination	-----	≥4 hrs., within 3 days	-----	≥60 min.

Contractor Qualifications

The engineers and technicians, carrying out the strengthening work, must have been properly trained on the handling of the raw materials and installation of FRP systems. Manufacturers and public agencies involved with the use FRP materials provide appropriate professional training and certification.

COMPARISON WITH THE ACI-440 GUIDELINES

The ACI committee 440 (2001, document under review) has developed guidelines for the strengthening of RC structures with FRP. A comparative study between JBDPA and ACI guidelines was conducted through trial design for strengthening of a column as follows. The shear capacity of an interior square column of 650 x 650 mm dimensions requires upgrade. A complete wrapping scheme (Carbon/Epoxy system) has been selected to upgrade the shear capacity of the column. The ductility index F is estimated as 2.5. Determine the additional reinforcement. The “un-factored” axial forces are Dead Load equal to 1500 kN, Live Load equal to 450 kN, and Seismic Load equal to +/- 15 kN. Figure 6 shows the shear strength as a function of the number of plies wrapping the column. It has shown that the recommendations provided by ACI-440 allow for a larger contribution of the FRP reinforcement shown in the figure. The JBDPA guidelines express the contribution of the shear reinforcement as the square root of the summation of the steel and FRP contributions. Compared to the ACI guidelines, where the shear strength is expressed as the summation of concrete, steel and FRP, this approach increases the difference in the values of FRP shear contribution when the number of plies is increased.

Material Properties : Fc = 21 MPa, σ_y = 345 MPa, σ_{wys} = 295 MPa
Area Longitudinal Bars: 387mm^2, Area Transversal Bars: 64 mm^2 (spacing=200 mm)
FRP Properties : σ_f = 3400 MPa, E_{fd} = 230 GPa, Thickness per ply = 0.167 mm

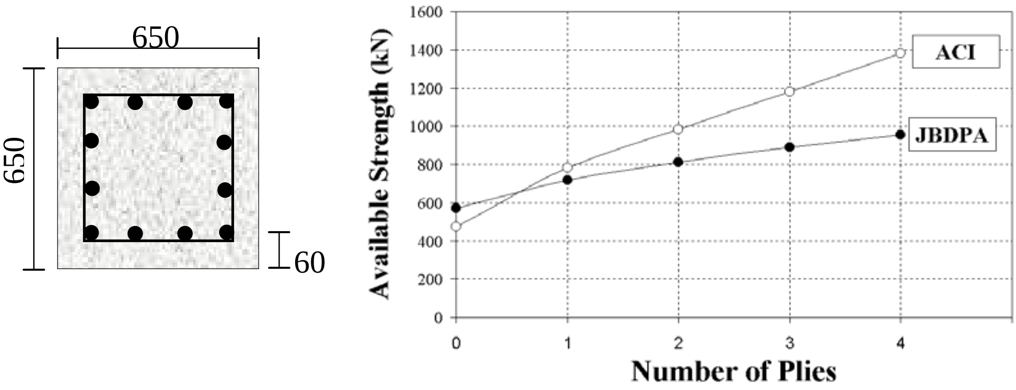
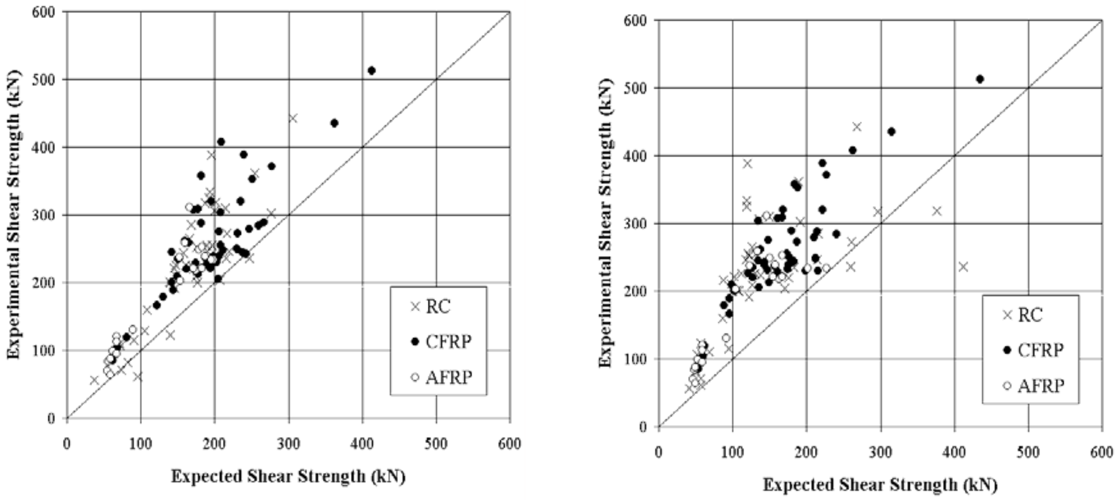


Figure 6: Shear Strength vs. Number of Plies

In Figures 7, to correlate experimental and expected values according to the JBDPA and ACI codes, data obtained from over one hundred columns tested in Japan was used (Tumialan et. al, 2001). Most of these specimens were strengthened with one or two plies of FRP laminates; mainly, carbon and aramid. It should be noted that both codes provide appropriate estimations with proper conservative values. It is also observed that the JBDPA approach provides less data dispersion.



(a) JBDPA Code (b) ACI Code

Figure 7: Experimental vs. Expected Values

FINAL REMARKS

Some of the most important provisions of the Japanese guidelines for the retrofitting of RC building structures with FRP materials are presented. The JBDPA guidelines condense the research on seismic retrofitting of RC building structures using FRP materials, which has been conducted in Japan mainly after the Kobe Earthquake. These provisions deal with the proper handling, design and installation of FRP systems used in Japan. Special considerations as the detailing of anchorage and strengthening of columns in the presence of finishing mortar are described. Comparisons with the guidelines provided by the ACI-440 are also presented.

NOTATION

a_g	:	Overall area of the longitudinal reinforcement of the column (mm^2)
a_t	:	Area of the reinforcement in tension of a column or beam (mm^2)
a_v	:	Area of shear reinforcement within a distance equal to the spacing "s" (mm^2)
b, D	:	Dimensions of the columns ($D \geq b$) (mm)
d	:	Effective depth (Distance from extreme compression fiber to centroid of longitudinal tension reinforcement) (mm)
E_{fd}	:	Modulus of elasticity of the FRP (Mpa)
F	:	Ductility Index
F_c	:	Compressive strength of concrete (Mpa)
g_1	:	Ratio of distance between the centers of longitudinal reinforcement in tension and compression to the column width.
h_o	:	Clear height of column
j	:	Distance between the tensile and compressive force resultants. (In columns: $j = 0.80D$. In beams: $j = {}^7/_8\ d$)
M_u	:	Ultimate Flexural Capacity (N-mm)
M/Q	:	Shear span (mm). A value equal to half of the column height can be used
N	:	Axial Force in the Column (N)
p_t	:	Ratio of tensile reinforcement = a_t/bd (%)
p_{ws}	:	Ratio of existing shear steel reinforcement to area of contact surface = a_v/bd (%)
p_{wf}	:	Ratio of FRP reinforcement to area of contact surface = Area FRP/bD (%)
Q_{mu}	:	Shear force associated to the ultimate flexural capacity (N)
Q_{su}	:	Ultimate Shear Capacity (N)
ε_{fd}	:	Effective Strain of the FRP, taken as 0.7%
μ	:	Ultimate ductility factor
σ_y	:	Specified yielding strength of the longitudinal reinforcement (MPa) For round steel bars: f_y = 295 MPa For deformed steel bars: f_y = specified strength + 49 (MPa)
σ_{wys}	:	Specified yield strength of the existing transversal reinforcement (MPa)
σ_{fd}	:	Tensile strength of FRP for shear design (MPa)
σ_f	:	Tensile Strength of FRP (MPa)
σ_o	:	Axial stress (MPa), no larger than 7.84 Mpa

REFERENCES

American Concrete Institute (ACI), Committee 440. (2001, document under review), Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures

Japan Building Disaster Prevention Association (JPDPA). (1977 revised in 1990), Standards for Seismic Capacity Evaluation of RC Buildings, (in Japanese)

Japan Building Disaster Prevention Association (JPDPA). (1977 revised in 1990), Guidelines for Seismic Rehabilitation of RC Buildings, (in Japanese)

Japan Building Disaster Prevention Association (JPDPA). (1999), Seismic Retrofitting Design and Construction Guidelines for Existing Reinforced Concrete (RC) and Steel-encased Reinforced Concrete (SRC) Buildings with FRP Materials, (in Japanese)

Tumialan G., Nakano K., Fukuyama H., and Nanni A. (2001), Japanese and North American Guidelines for Strengthening Concrete Structures with FRP: a Comparative Review of Shear Provisions, Proceedings of the Fifth International Conference on the use of Fibre Reinforced Plastics for Reinforced Concrete Structures (FRPRCS-5), Thomas Telford Ltd (paper submitted).