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SEISMIC APPLICATION OF SUSTAINABLE FIBER MATERIAL

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ABSTRACT

Sustainable infrastructure materials would help infrastructure to minimize its burdens to natural and social environments. FRP with non-corrosiveness, which is an advantage to steel, can be a good example of sustainable infrastructure materials. However, the high material cost of typical FRP is a major obstruction against its practical application. The new type of fiber materials, whose fracturing strain is high and cost is low, can remove this obstruction. Life cycle cost of a structure with the new fiber could be less than that with steel due to the longer service life with the new fiber and than that with typical fiber materials (carbon and aramid) due to the lower initial cost. The fiber with a high fracturing strain could provide a better seismic performance than steel and typical fiber materials. This paper briefly introduces the seismic retrofit with the new fiber materials.

Keywords: material deformability, material cost, seismic retrofit, initial cost, LCC.

1 INTRODUCTION

Life cycle cost of infrastructure is the main issue for its sustainability. Sustainable infrastructure is to minimize the burden to natural and social environment over the period of its service life. Emission of substance causing global warming and toxic substance should be minimized. Consumption of energy and resources should be also minimized. Financial burden should be minimized for the social impact. Financial burden should be considered not only when infrastructure being constructed (Initial Cost) but also throughout the service life of infrastructure (Life Cycle Cost). The longer the service life is, the less the financial burden as LCC is.

Non-corrosive material such as FRP has been recognized as a more durable material than steel, which is the typical construction material. Thus, non-corrosive material is more desirable for infrastructure under corrosive environment, such as cold region where deicing agent is used and coastal region.

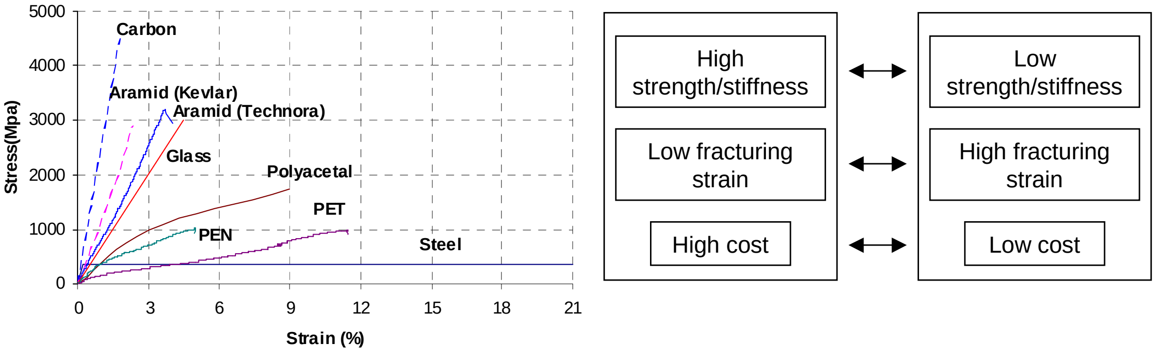
FRP should have the advantage to steel when LCC is considered, however the high IC with FRP is still a major obstruction against the application of FRP. Reduction of the material cost of FRP is thus practically desired.

This paper introduces the application of new type of fiber, whose fracturing strain is high, for seismic retrofit. The cost of the seismic retrofit with the new fiber is less than those with the typical fiber, carbon and aramid, to obtain the same seismic performance.

2 NECESSARY MATERIAL PROPERTY

2.1 Strength/Stiffness or Deformability?

Major drawbacks with FRP seismic retrofit for structures are the material brittleness and vulnerability to fire besides the high cost. One reason why we have been unable to remove these drawbacks is the fact that we have been emphasizing on strength and stiffness of the material. To achieve good seismic performance, high member deformability is desired besides high member strength/stiffness. The high member deformability can be achieved by high fracturing strain of material. A required member strength/stiffness is not necessarily supplied by high strength/stiffness materials. Low strength/stiffness materials can satisfy the required member strength/stiffness. The difference in material strength/stiffness only makes the difference in the required material amount. However a high fracturing strain can be achieved only by materials with a high fracturing strain. Materials of a low strength/stiffness generally come with a high fracturing strain and can be produced at a low cost, while materials of a high strength/stiffness show usually a low fracturing strain and require a high cost (see Fig. 1). The low strength of FRP at



bent is also due to the low fracturing strain.

Figure 1: Comparison of strength, fracturing strain and cost of materials

The necessary material property for good seismic performance, therefore, is the high enough fracturing strain (high deformability). The necessary amount of material is determined by the material strength/stiffness. The best material is the one to cost least for the necessary amount. The cost here should include not only the material cost but also the construction cost.

2.2 Property Necessary for Flexural and Shear Reinforcement of Concrete Structures

High fracturing strain (high deformability) is necessary for both flexural and shear reinforcement of concrete structures in order to obtain high member strength and deformability. For shear reinforcement an elastic material is preferable to a yielding material. The reason can be seen in the following sections.

(1) Necessary property for member strength

In the case of steel reinforcement member strength is reached when concrete compression or tension failure occurs. In order to have a higher flexural and shear strength of a concrete member, flexural and shear reinforcement are supposed to carry a higher force by increasing strength or providing more amount of the reinforcement. The strength and amount of reinforcement is the primary factor for the member strength. This is the case, however, where the strength of reinforcement is reached when the member strength is reached. When the reinforcement strength is not reached, only concrete strength and stiffness of reinforcement (product of material stiffness and area) become controlling the member strength instead.

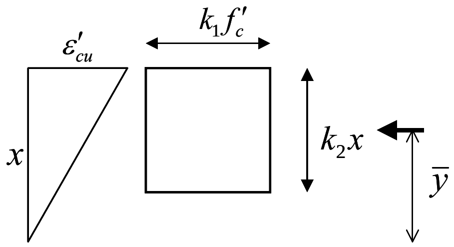
In the case of steel reinforcement tension fracture of reinforcement is practically not a cause of the member failure, since steel has a large fracturing strain. Thus, the strength and stiffness of reinforcement is only the property to be considered for the member strength.

If reinforcement material property is different from that of steel, the description of necessary property would be quite different. For simplicity it is assumed that the reinforcement is elastic without yielding until its fracture like FRP. Using the equivalent concrete stress block (see Fig. 2), the following equation can be derived to calculate the flexural strength of a concrete member whose cross section is as shown in Fig. 3:

$$M_{fu,c} = bk_2xk_1f'_c\left(d - \frac{k_2x}{2}\right) \tag{1}$$

where

$$x = \frac{-A_sE_s\varepsilon'_{cu} + \sqrt{\left(A_sE_s\varepsilon'_{cu}\right)^2 + 4k_1k_2bf'_cA_sE_s\varepsilon'_{cu}d}}{2k_1k_2bf'_c}$$



(2)

Figure 2: Equivalent concrete stress block

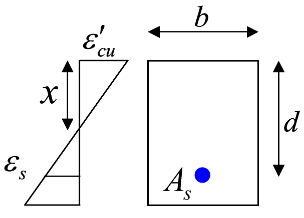


Figure 3: Flexural strength of member

The strain of reinforcement is given as below (see Fig. 3):

$$\varepsilon_s = \varepsilon'_{cu} \frac{d - x}{x} \tag{3}$$

The fracturing strain of the reinforcement, therefore, should be greater than the strain calculated by Eq. (3). Not only the stiffness, $A_s E_s$ but also deformability (fracturing strain) of reinforcement is necessary to achieve the required flexural strength of a member. As seen in Eq. (3), the necessary deformability depends on the stiffness of reinforcement, $A_s E_s$ and concrete strength, f'_c.

Strain of shear reinforcement at shear failure was investigated in the previous study [1], in which the prediction formula was presented. The shear reinforcement strain depends on stiffness of both flexural and shear reinforcement and concrete strength. To achieve the required shear strength of a member, both stiffness and deformability of shear reinforcing material have to be considered.

(2) Necessary property for member deformability

What is the necessary property in order to get a higher deformability, together with higher energy absorption, of a concrete member? It is obvious that a higher deformability is required for flexural reinforcement. Steel is an excellent material since it shows yielding followed by a great amount of plastic deformation. Because of these characteristics steel as flexural reinforcement can provide a concrete member a very high deformability as well as a very high energy absorption capability.

Study on how to improve the deformability of a member failing in shear with and without flexural yielding is scarcely seen since it is simply considered that shear failure should be avoided due to its brittleness. A previous study shows that shear reinforcement, which is Polyacetal Fiber (PAF), an elastic material with a fracturing strain of 6 to 9%, can reduce significantly the brittle nature of shear failure and show even better ductility than steel shear reinforcement [2]. Another study shows that Polyethylene Terephthalate (PET) fiber, whose fracturing strain is 13.8%, as shear reinforcement improves ductility of concrete members failing in shear after flexural yielding [3]. It is considered that a certain stiffness of shear reinforcement is necessary to keep shear resisting capability of a concrete member and that yielding of steel shear reinforcement may result in too much reduction in the stiffness to keep the shear resisting capability. It is therefore that necessary property of shear reinforcement is a high deformability (fracturing strain) without yielding (or with constant stiffness).

The fact of the improved ductility for shear failure by applying elastic material with high fracturing strain as shear reinforcement may change the current design concept that prefers flexure failure prior to shear failure by adopting a greater value for the safety factor of shear strength than that of flexure strength.

3 NEW SEISMIC RETROFIT METHOD WITH HIGH FRACTURING-STRAIN MATERIAL

3.1 Duplex Jacketing of Concrete Member

Based on the knowledge on necessary property for shear reinforcement to enhance ultimate deformability of concrete members, a new retrofitting method was developed recently in Japan [4]. The new method, called as A-P Jacketing (duplex jacketing), applies two kinds of fiber: one with a high stiffness (Aramid fiber) and one with a high fracturing strain (PET fiber and Polyethylene Naphthalate (PEN) fiber), to other than hinge zone and hinge zone respectively as shown in Fig. 4 (a). The ultimate strength, fracturing strain, and elastic modulus in tension of PET are 923 MPa, 13.8 % and 6.7 GPa, while those of PEN are 1028 MPa, 4.5 % and 22.6 GPa, respectively. In a hinge zone high plastic deformation is expected, so that a material with a high fracturing strain is necessary for shear reinforcement. In the part other than hinge zone the deformation is expected to be much less but the required shear capacity is the same as in the hinge zone. The material with a high stiffness is selected so that required number of jacketed sheet layers is less, which may reduce construction cost. The material with a high fracturing strain can be applied for the part other than hinge zone as well, depending on the required amount of fiber, if the total construction cost would be less.

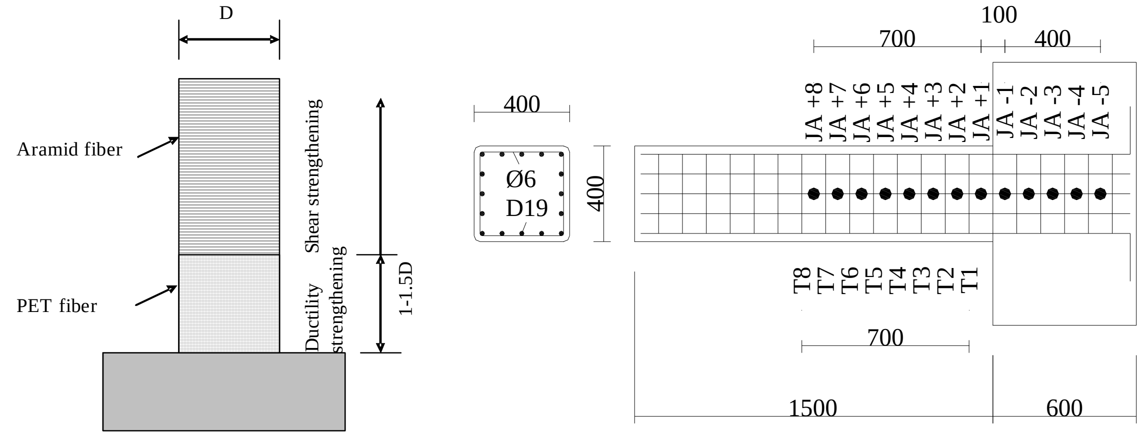
(1) Experimental outline

Two series of tests were conducted -- one for ductility enhancement and another for shear strength enhancement. The first series consists of 15 bridge pier specimens whose hinge zone was jacketed with fiber sheets with PET or PEN and the rest was jacketed with aramid fiber sheet (A-P Jacketing as shown in Fig. 4 (a)) except a reference specimen. Ten and five specimens were with a cross section of 400 x 400 mm and 600 x 600 mm, respectively (see Table 1 and Fig. 4 (b)) [3]. Two specimens with a cross section of 250 x 250 mm were tested for the second series (see Fig. 4 (c)) [5]. Load-deformation curves (envelopes) of some of the specimens are shown in Fig. 5.

(2) Enhance mechanism of deformability and shear strength

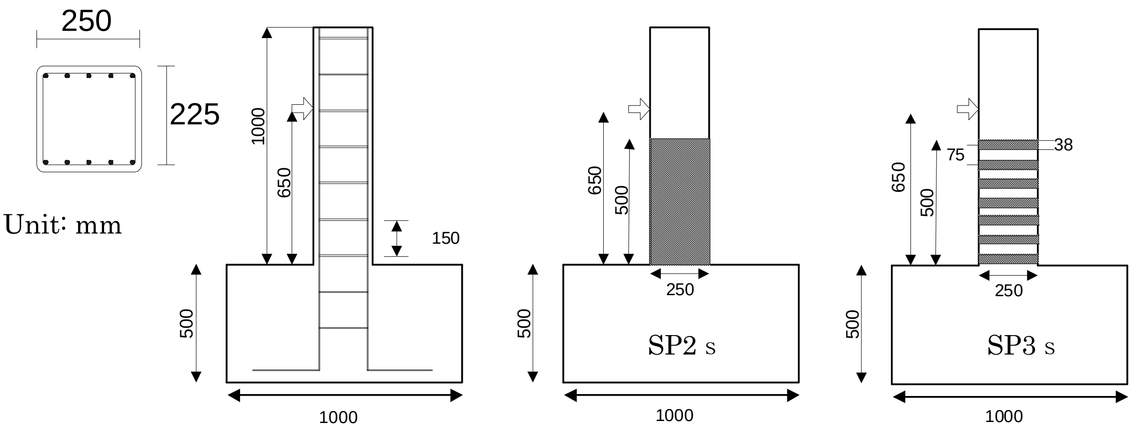
The ductility enhanced by PET jacketing increases with an increase in PET fiber ratio (comparing SP1, SP4 and SP5 in Table 1 and Fig. 5

(a), and SP8, SP7 and SP6 in Table 1). PEN jacketing also increases the ductility (comparing SP1 with SP3 in Table 1). At ultimate deformation δ_u, no fracture was observed with PET and PEN fiber sheets (see Fig. 6), while the aramid fiber sheet fractured in SP2. No fracture or yielding of jacketed sheets can be considered to not only improve the ductility ratio, but also reduce negative slope of the falling branch in the load-deformation curve (see Fig. 5 (a)).



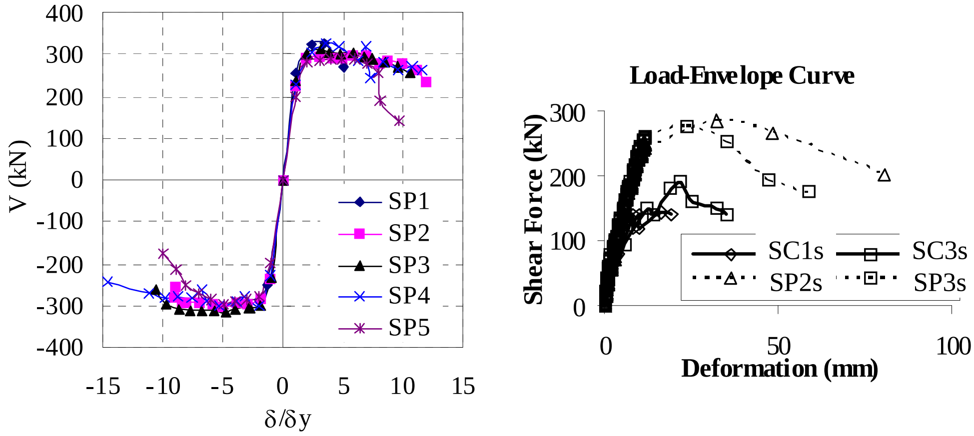
(a) A-P Jacketing

(b) Specimens SP1 to SP10



(c) Specimens SP2s and SP3s

Figure 4: Specimens



(a) Specimens SP1 to SP5

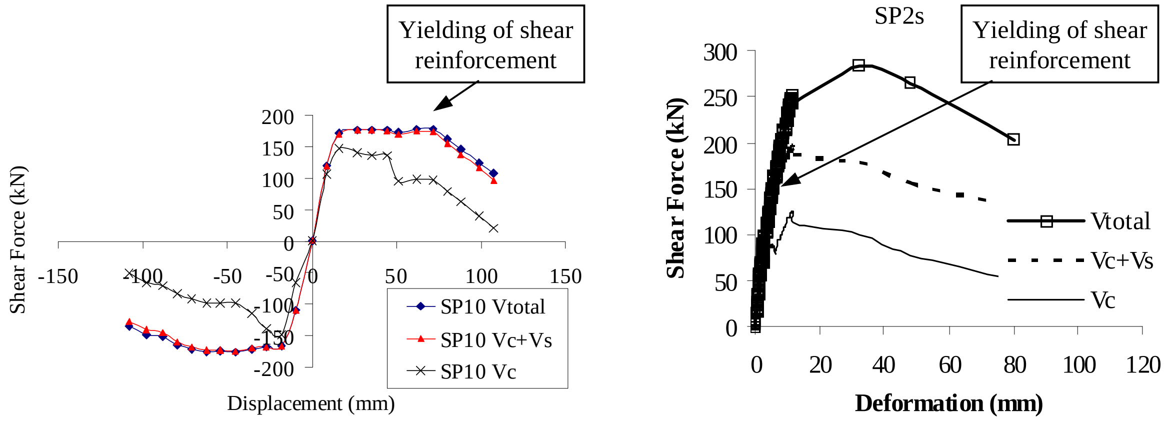
(b) Specimens SC1s, SC3s, SP2s and SP3s

Figure 5: Load-Deformation Curve (Envelope)

Table 1: Specimens

Specimen	f_c'	*a/d*	ρ_t (%)	ρ_w (%)	ρ_f (%)	Fiber	V_c (kN)	V_s (kN)	V_f (kN)	V_{mu} (kN)	$\frac{V_c+V_s}{V_{mu}}$	$\mu^{1)}$	Cross-section
SP1	29.5	3	2.87	0.16	-	-	151	79	-	288	0.8	5.09	$1^{2)}$
SP2	29.5	3	2.87	0.16	0.13	$A2^{5)}$	151	79	213	288	0.8	11.84	1
SP3	29.5	3	2.87	0.16	0.38	PEN	151	79	201	288	0.8	10.65	1
SP4	29.5	3	2.87	0.16	0.37	PET	151	79	184	288	0.8	11.42	1
SP5	31.7	3	2.87	0.16	0.19	PET	155	79	90	290	0.8	7.98	1
SP6	31.7	4	2.87	0.16	0.12	PET	155	79	60	223	1.05	9.05	1
SP7	31.7	4	2.87	0.16	0.06	PET	155	79	30	223	1.05	8.46	1
SP8	31.7	4	2.87	0.16	-	-	155	79	-	223	1.05	7.40	1
SP9	31.7	4	3.59	0.16	0.12	PET	169	79	60	267	0.93	8.76	1
SP10	31.7	4	2.15	0.16	0.06	PET	151	79	30	177	1.3	10.41	1
SP11	31.7	4	2.82	0.2	0.25	PET	318	206	264	463	1.13	8.52	$2^{3)}$
SP12	31.7	4	2.82	0.2	0.125	PET	318	206	132	463	1.13	7.54	2
SP13	34.5	3	2.82	0.2	0.29	PET	327	105	308	637	0.84	7.76	2
SP14	23.7	3	2.82	0.09	0.42	PET	289	83	441	612	0.61	4.12	2
SP15	31.1	3	2.82	0.09	0.42	PEN	316	83	469	641	0.62	6.87	2
SC1s	28.4	2.9	4.5	0.15	-	-	80	29	-	255	0.43	-	$3^{4)}$
SC3s	29.0	2.9	4.5	0.15	0.032	Carbon	81.5	29	44	255	0.43	-	3
SP2s	35.4	2.9	4.5	0.15	0.67	PET	87	29	97	257	0.45	5.19	3
SP3s	36.7	2.9	4.5	0.15	0.35	PET	88	29	50	257	0.45	2.97	3

Note: 1) Ductility ratio (=δ_u/δ_y), 2) 400x400 mm, 3) 600x600 mm, 4) 250x250 mm, 5) Aramid of high strength type whose ultimate strength is 3246 MPa, fracturing strain is 4.1 % and elastic modulus is 79.5 GPa. 6) Notations: f_c' is concrete strength, *a/d* is shear span to depth ratio, ρ_t, ρ_w, ρ_f are ratios of tension reinforcement, stirrup and fiber sheet, V_c, V_s, V_f are concrete, stirrup and fiber sheet contribution in shear, V_{mu} is bending strength in terms of shear force.



(a) Specimen SP10

(b) Specimen SP2s

Figure 7: Shear Force Contributions

Figure 6: High plastic deformation with PET fiber jacketing

A previous study on shear strength of concrete beams with shear reinforcement [1] indicates that shear strength depends on stiffness of both flexural and shear reinforcement. If we apply this fact to reinforced concrete columns in which the flexural yielding takes place before the shear strength is reached, the following can be said (see 3.2). Once yielding of flexural reinforcement, which means the reduction in stiffness, takes place, the potential shear strength starts to decrease. Yielding of shear reinforcement, which means not only reduction in the stiffness but also no increase in shear force component carried by shear reinforcement, further decreases the potential shear strength. Fig. 7 (a) shows the shear force components by concrete, steel shear reinforcement and PET fiber sheet, the last two of which were calculated using their measured strains. The concrete component starts to decrease after the flexural yielding and decreases even faster after the shear reinforcement yielding. The load-carrying capacity decreases because the load-carrying capacity in shear (potential shear strength) becomes smaller than that in flexure. Small contribution of PET fiber sheet can be found only after the yielding of steel shear reinforcement in Fig. 7 (a).

It seems that stiffness of both flexural and shear reinforcement controls the potential shear strength. This means that FRP jacketing, which adds the stiffness of shear reinforcement, increases the potential shear strength resulting in enhancement of ductility and more ductile manner with falling load-carrying capacity. However, fracture of FRP would instantly eliminate the FRP contribution. PET fiber with a large fracturing strain can keep its contribution and contribute better than steel reinforcement which is likely to yield at ultimate deformation.

Similar observations can be made with specimens SP2s and SP3s, which were originally designed to fail in shear based on the JSCE formula for carbon and aramid fiber sheet jacketing [6]. Both specimens showed shear failure after flexural yielding around 220 kN (see Fig. 5 (b)). The load-deformation curves of SP2s and SP3s are compared with those of companion specimens with no jacketing (SC1s) and carbon fiber sheet (SC3s) with stiffness greater than those in SP2s and SP3s. Specimens SC1s and SC3s show rather brittle behavior and smaller shear strength. In specimen SC3s the carbon fiber sheet fractured. Shear force components in specimen SP2s are shown in Fig. 7 (b). After yielding of steel shear reinforcement the concrete component increases with a smaller rate and the component of PET fiber sheet becomes more significant. The concrete component starts to decrease after the flexural yielding.

In order to estimate the ultimate deformation we have to predict shear deformation in hinge zone. The experimental results indicate that shear deformation increases with total deformation and more quickly after yielding of flexural and shear reinforcement. It can be more than 10 % of the total deformation at ultimate deformation.

3.2 New Ultimate Deformation Model

The ultimate deformation of members with shear reinforcement of high deformability cannot be predicted by the existing empirical models for members with steel shear reinforcement which yields at ultimate and for members with carbon or aramid FRP jacketing which often fractures at ultimate.

The new model to predict relationship between load (or shear force) and deformation (or displacement) of linear concrete members such as columns and beams with and without flexural yielding was presented by the recent study [7], [8]. The model consists of two components, which are strength model (or model to predict degradation of potential shear strength with deformation) and deformation model. The deformation model consists of models for flexural, shear and pullout deformation. The deformation model can be applied to both cases with and without external reinforcement (jacketed reinforcement) and to both cases with steel and FRP reinforcement. Since the deformation model can predict shear reinforcement strain, the ultimate deformation with and without shear reinforcement fracture can be calculated.

The basic concept of the strength model is that the potential shear strength of a linear member depends on stiffness of flexural and shear reinforcement. This concept was taken from the study by Sato, et al [1], which presents a model for shear strength of a linear member with flexural/shear reinforcement of steel/FRP. In the model potential shear strength (V in Fig. 8) decreases with reduction in stiffness of flexural and shear reinforcement, which is caused by yielding of steel. In fact the yielding of steel flexural and shear reinforcement reduces the potential shear strength carried by concrete (V_c in Fig. 8). The potential shear strength is greater than the potential flexural strength (V_u in Fig. 8) at small deformation but becomes smaller after the yielding of steel reinforcement, as a result the load-carrying capacity of a member reduces with deformation.

The shear deformation model is the extended version of the shear deformation model for concrete members without flexure yielding, which is presented by the previous study [9]. In the model shear deformation is considered as deformation of truss in which concrete compression strut is contracted and tension strut (shear reinforcement) is elongated (see Fig. 9).

The new model for evaluating ultimate deformation needs further study to refine the flexure deformation model since the flexural deformation in hinge zone cannot be predicted well at present. The results of the further study will be presented in the near future.

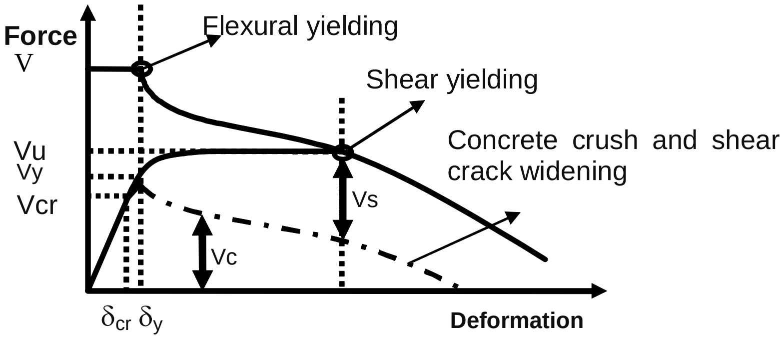


Figure 8: Strength model with concept of potential shear strength

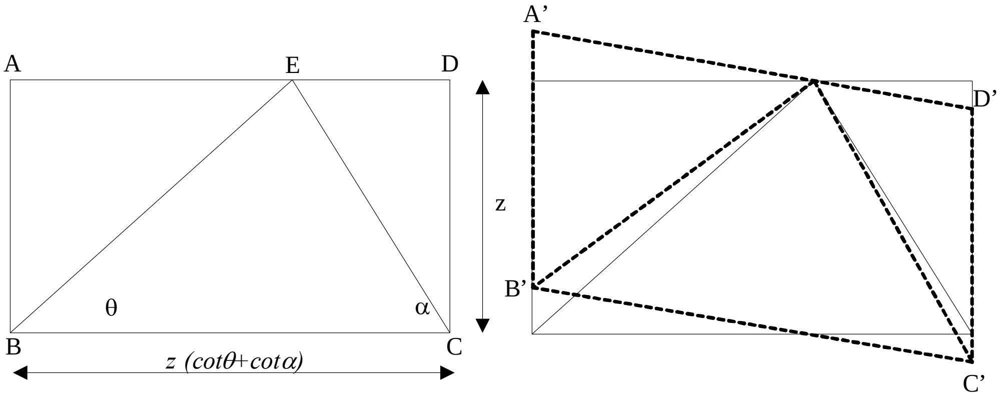


Figure 9: Shear deformation model with concept of truss deformation

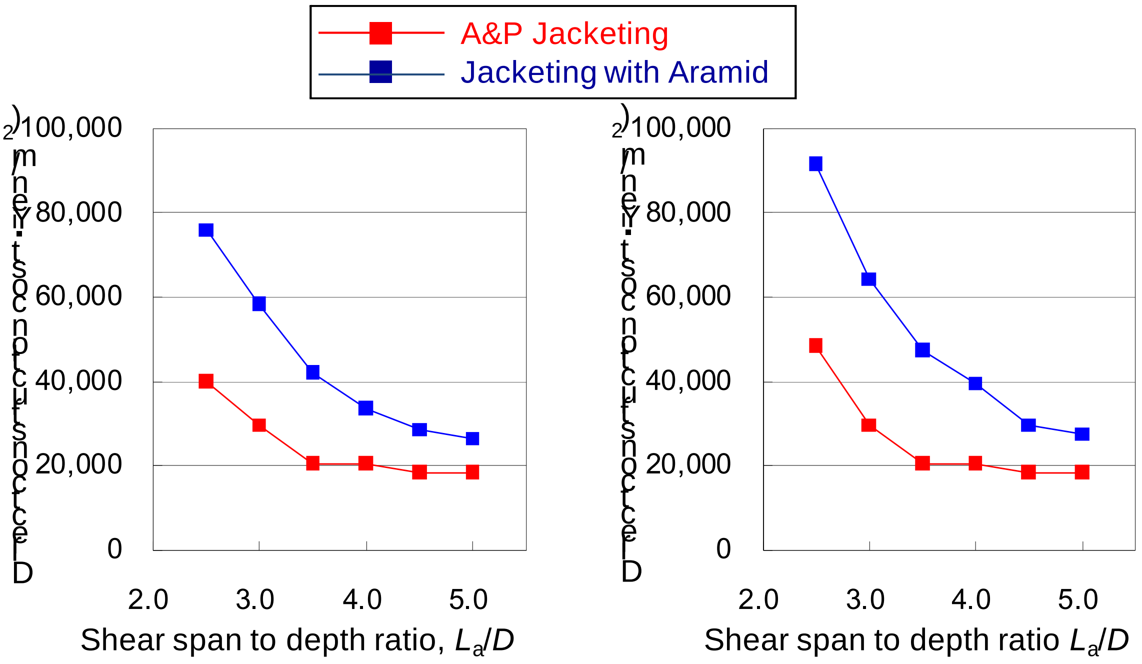
3.3 Cost Comparison and Practical Application

The cost comparison among seismic retrofit methods with different fiber materials depends on the type of structure. There is a initial cost comparison for railway viaduct in Japan [10], which shows that the duplex jacketing (Aramid & PET Jacketing or A&P Jacketing) costs from a half to two thirds of the jacketing with aramid alone (see Fig. 10). The cost with the jacketing with carbon is expected to be 1.5 times of that of the jacketing with aramid. On the other hand, the cost of the jacketing with PET for both hinge zone and other than hinge zone is less by 1,500 to 3,000 JPY/m^2 than that of A&P Jacketing.

Because of the better cost performance the duplex jacketing has been applied to various practical seismic retrofit cases for railway structures in Japan. The jacketing with PET alone, however, has not been applied to practical case yet.

4 CONCLUDING REMARKS

Sustainable infrastructure materials should be durable so that life cycle cost of infrastructure would be less. Many FRP materials have an advantage to steel due to the non-corrosiveness. However, the high material cost of FRP prevents the practical application from being spread widely. The new type of fiber materials, whose fracturing strain is high and cost is low, could be a good solution to reduce initial cost so as to reduce the barrier against FRP application. Furthermore, the fiber with high fracturing strain can provide a better solution for obtaining good seismic performance of structures than conventional fiber materials and steel.



800 × 800 mm section

p_t=1.00% p_w=0.21% s_N=1.0MPa

1000 × 1000 mm section

p_t=0.86% p_w=0.17% s_N=1.0MPa

Figure 10: Cost comparison of duplex jacketing

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