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Material conditions necessary for strengthening concrete structures

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Abstract

The maintenance and repair of accumulated infrastructures to prolong their service lives is a major challenge in the construction field to achieve sustainability. Strengthening is often needed for deteriorated and inappropriately constructed structures. Structural ways and materials for strengthening are vary greatly, implying that we have not yet determined the optimum way for strengthening. External bonding, as a way of strengthening, has introduced a new type of failure mode, namely debonding (peeling). Material properties to improve debonding strength are new to structural engineers. Strengthening materials as a substitute of steel, such as fiber reinforced polymers (FRP), have quite different material properties. Conventional concepts for structural design and material are no longer true for those materials. As a structural material, durability is important, but we do not have enough data concerning the durability of the new strengthening materials. This paper explains the material properties and conditions necessary for strengthening, and suggests the necessity of closer collaboration between material scientists and structural engineers.

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Keywords: Debonding; adhesive layer; strengthening material; stiffness; fracturing strain.

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1. Introduction

All over the world enormous amounts of infrastructures have been constructed and accumulated. Many of them face natural disasters, such as earthquakes, tsunamis and tornados, but are not ready to survive safely, since the knowledge on the real impact by natural disaster was not sufficiently advanced when they were constructed;

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additionally, many infrastructures have been suffering from serious damage by various mechanical and environmental actions, such as fatigue, salt attacks, frost attacks and chemical attacks. In order to avoid the failure of satisfying the performance requirement, such as safety and serviceability, we need to strengthen those structures, which are vulnerable to natural disasters and damages induced by various actions. Strengthening is also needed for structures whose usage has been modified, causing design loads to increase.

Strengthening structures can prolong their service lives, so that we need to reconstruct new structures less frequently. By doing so, we can save resources and energy necessary during construction. This is a way for the construction industry to contribute in making the world sustainable.

This paper presents material properties necessary for the strengthening of concrete structures, which may be different from those well known for concrete and steel, primary material components of concrete structures.

2. Strengthening

2.1. Strengthening methodologies

External bonding of the strengthening material is the most typical strengthening method. There are three types of external bonding-related strengthening (see Fig. 1) :

- External bonding
- Overlaying
- Jacketing

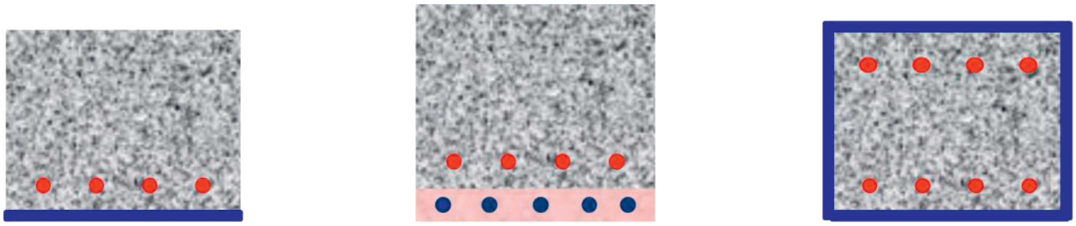
(a) (b) (c)

Fig. 1. Three types of strengthening, (a) External bonding. (b) Overlaying (spraying), (c) Jacketing

There are three major materials applicable for the above methods:

- Cementitious materials, including ordinary mortar and concrete
- Steel
- Fiber reinforced polymer (FRP)

For external bonding, strengthening materials such as steel and FRP, which are tension materials, are externally bonded to the surface of existing structure. In overlaying, a layer of strengthening material is externally bonded to the surface of the existing structure. The material used for overlaying is cementitious including ordinary mortar, in which tension material as tension reinforcement is usually placed, such as steel and FRP. The externally bonded layer for overlaying is much thicker than that for external bonding. Jacketing is to place a strengthening material layer, which can be cementitious material (including ordinary concrete), steel and FRP, to surround the cross section of the existing structure and to attach it by external bonding. In cases of external bonding and overlaying, the strengthening layer is attached on only one face of the existing structure, while strengthening layers are placed on all the faces (see Fig. 2).



(a) (b) (c)

Fig. 2. Comparison among three types. (a) External bonding, (b) Overlaying, (c) Jacketing

2.2. Key issues for strengthening

The primary differences between strengthening design for existing structures and ordinary design for new structures are as follows:

- Material properties
- Debonding as failure mode
- Effects of damages in the existing structure

In this paper the issues related to the difference in material properties and debonding as failure mode are discussed only.

2.3. Material properties

Among strengthening materials there are conventional structural materials, concrete and steel; however, there are also other materials, such as fiber and polymer. A variety of fibers and polymers have been actually applied. This means that the mechanical properties of materials are quite different among strengthening materials. Steel is rather a unique material with yielding and large fracture strain. Due to this fact, the design equations for flexure and shear strength assume that the stress in steel is the yielding stress and that there is no steel fracture. For example, the design equations for shear strength in Japan are as follows:

$$\boldsymbol{V_{total} = V_c + V_s + V_f} \tag{1}$$

$$\boldsymbol{V_c = 0.2\sqrt[3]{f'_c}\sqrt[4]{1000/d}\sqrt[4]{100\rho_w}(bd)} \tag{2}$$

$$\boldsymbol{V_s = A_w f_{wy}(\sin\alpha_s + \cos\alpha_s)\, z/s} \tag{3}$$

where $\boldsymbol{V_{total}}$ is shear strength, $\boldsymbol{V_c}$, $\boldsymbol{V_s}$, $\boldsymbol{V_f}$ are contributions of concrete, shear reinforcement and FRP reinforcement respectively,$\boldsymbol{f'_c}$ is concrete strength (MPa), $\boldsymbol{d}$is effective depth (mm), $\boldsymbol{\rho_w}$ is the tension reinforcement ratio, $\boldsymbol{b}$ is web width (mm), $\boldsymbol{A_w}$, $\boldsymbol{f_{wy}}$, $\boldsymbol{\alpha_s}$, $\boldsymbol{s}$ are cross-sectional area, yield strength, angle to member axis and spacing of shear reinforcement, and $\boldsymbol{z}$ is the arm-length for truss mechanism. In fact $\boldsymbol{\rho_w}$ is represents the stiffness of tension reinforcement ($\boldsymbol{E_s A_s}$). Since Equation (2) was developed for steel-reinforced concrete, it does not have to include the elastic modulus ($\boldsymbol{E_s}$), a fixed value, as a variable. When the load reaches the member shear strength, stress in shear reinforcement can be assumed to be the yield strength. This assumption is appropriate since shear reinforcement stress is practically constant after the yielding. However, those issues are completely different for other strengthening materials. FRP has a different elastic modulus, so Equation (2) cannot be used directly. FRP does not show yielding and has a much smaller fracturing strain than steel. Therefore, a prediction of strain in shear reinforcement at shear strength is necessary. Equation (3), however, does not provide any information on the shear reinforcement strain at shear strength.

Jacketing can confine cover concrete outside tie reinforcement (shear reinforcement) (see Fig. 3). For a prediction of the confinement effect, the stiffness (or stress) of jacketing is necessary to calculate the confining stress. Thus, the problem with the equation for calculating the confining stress for materials other than steel would be the same as that of steel tension reinforcement for Equation (2) and steel shear reinforcement for Equation (3).

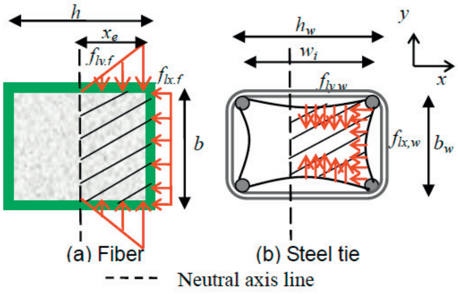


Fig. 3. Confinement effects by jacketing.

Jacketing is often applied for seismic retrofit, for which not only shear strength but also ultimate deformation should be predicted. Like in the case of shear strength, the design equation for ultimate deformation of steel-reinforced concrete members is not applicable to the case of concrete members strengthened by other materials, such as FRP.

2.4. Debonding as failure mode

External bonding creates the interface between substrate concrete and strengthening material layer, which would be the weak point as debonding could happen at the interface. There are three debonding modes (see Fig. 4):

- Intermediate crack (IC) debonding
- End peeling
- Concrete cover separation

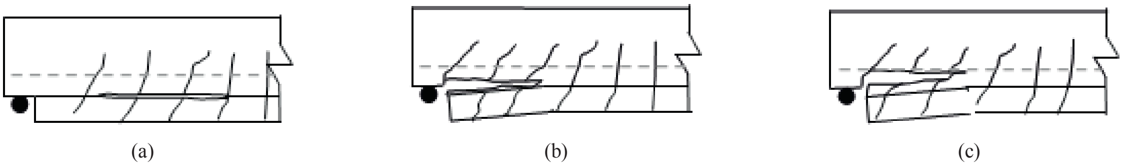


Fig. 4. Three types of debonding, (a) Intermediate crack debonding. (b) End peeling, (c) Concrete cover separation

In order to achieve member strength, such as flexure and shear strength fully, debonding should be avoided. For this reason we need to understand the debonding mechanism and predict the debonding strength. There are suitable material properties to achieve greater debonding strength and more ductile debonding behavior.

3. Material conditions for strengthening

3.1. Material properties for higher shear strength and ultimate deformation

There are many structural materials. Fig. 5 compares stress-strain relationships of typical materials. Carbon, which is a typical strengthening material, shows very high strength/stiffness but a very small fracturing strain (1.5%). On the other hand, steel, which is a fundamental structural material, has low strength but a high fracturing strain. Before yielding, the stiffness of steel is as high as high stiffness carbon but stiffness dramatically decreases after yielding. Between carbon and steel there are various materials. The general tendency is that materials whose strength is high have high stiffness but low fracturing strain. Polyethylene terephthalate (PET), which is a thermoplastic polymer resin of the polyester family, is a material whose strength is lower than carbon but whose fracturing strain is higher. Polyacetal fiber (PAF) has similar properties [1]. Another interesting fact is that the price of material is generally higher for higher strength.

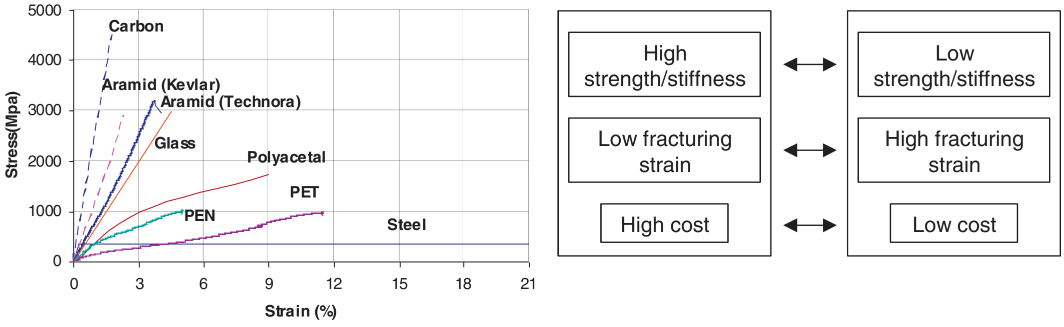


Fig. 5. Comparison of stress-strain relationships of various materials.

As we discussed in Section 2.3, shear strength depends on the strength and stiffness of reinforcement. In this sense, a material with high strength/stiffness would be better than a material with low strength/stiffness. However, the material with low strength/stiffness can replace the material with high strength/stiffness. If the necessary strength for reinforcement is achieved by the material with a strength of 2,000 MPa and cross-sectional area of 1,000 mm^2, the material with a strength of 200 MPa and an area of 10,000 mm^2 can also provide the necessary strength (Fig. 6).

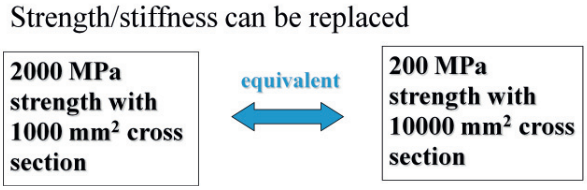


Fig. 6. Comparison of high and low strength/stiffness materials.

The sudden breakage of FRP as reinforcement is a drawback. It indicates that the greater fracturing strain of material is preferable to achieve better member strength. For members subjected to high seismic effects, plastic deformation becomes quite high in the so-called plastic hinge zone, meaning that the material would be subjected to relatively high strain. High fracturing strain can be achieved by only materials with a high fracturing strain but not materials with a low fracturing strain.

According to the study by the author's group [2], the shear strength of reinforced concrete members depends on the stiffness of both tension and shear reinforcement; the higher the stiffness of tension and shear reinforcement, the higher the concrete contribution. The post-peak behavior of concrete members can be explained as the decrease in the potential shear strength (or remaining shear strength) with the decrease in stiffness of tension and shear reinforcement (see Fig. 7). Generally the less amount of shear reinforcement gives an earlier reduction in shear reinforcement stiffness; thus, the post-peak region comes earlier.

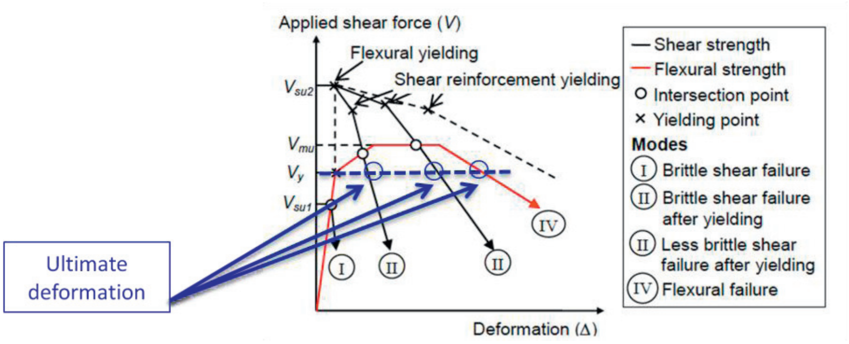


Fig. 7. Comparison of high and low strength/stiffness materials.

Once steel shear reinforcement yields, the stiffness reduces dramatically, resulting in the reduction in the shear strength. At the peak of the shear strength, the strain of shear reinforcement is around a few percentages at most. In the plastic hinge zone the strain of shear reinforcement at ultimate deformation could be more than 5% but less than 10%. Considering those facts, the best shear reinforcement is without yielding and with a fracturing strain of more than 5%. Carbon, aramid and glass fiber do not have high enough fracturing strain, while steel would exhibit the yielding. The best option would be a material without yielding but with a fracturing strain higher than 5% (Fig. 8). PET and PAF are the best options.

Experimental results of concrete columns with PET jacketing show a good enhancement of both shear strength and ultimate deformation, which are better than those of columns with carbon FRP (CFRP) jacket as shown in Fig. 9 [3,4]. This is because PET did not show the fracture at ultimate deformation in most of the specimens as shown in Fig. 10 [5]. In one specimen we observed fracture of tie reinforcement but did not that of PET jacket.

A cost comparison was made between PET jacketing and aramid jacketing for a column of a railway viaduct in Japan as shown in Fig. 11. The cost of PET jacketing is significantly lower than that of aramid jacketing. In fact the case of PET jacketing in this comparison, PET was only applied in the hinge one, while aramid was applied for the rest part where plastic deformation was not large. It is called “duplex jacketing”. Thus, if PET jacket was applied entirely, the cost would be even less. Generally the cost of carbon jacketing is similar to or could be more than that of aramid jacketing. There are practical applications to viaduct columns in Japan (Fig. 12).

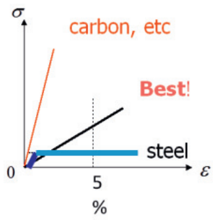


Fig. 8. Best materials for shear reinforcement.

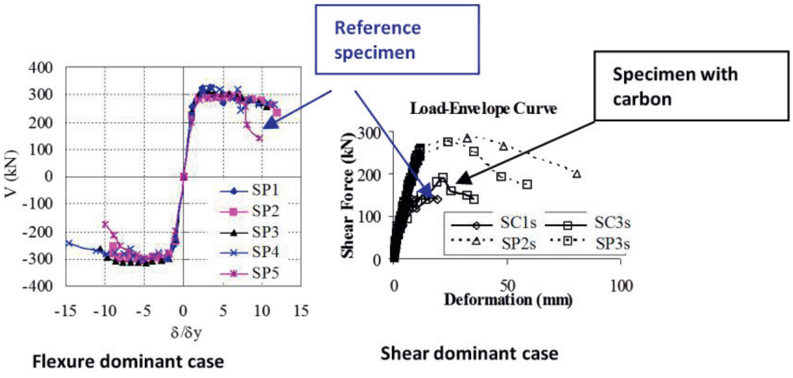
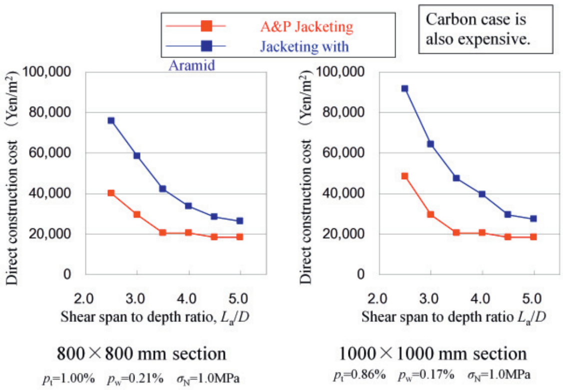


Fig. 9. Enhancement of shear strength and ultimate deformation by PET jacketing.

Fig. 10. PET jacket without fracture in hinge zone.



Carbon case is also expensive.

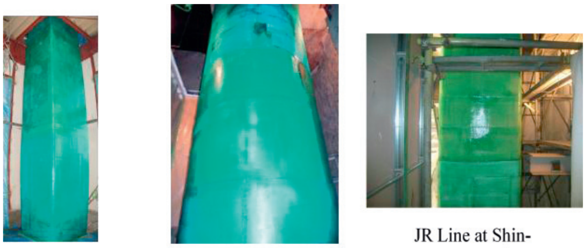
800×800 mm section

p_t=1.00% p_w=0.21% σ_N=1.0MPa

1000×1000 mm section

p_t=0.86% p_w=0.17% σ_N=1.0MPa

Fig. 11. Cost comparison of PET jacketing with aramid jacketing.



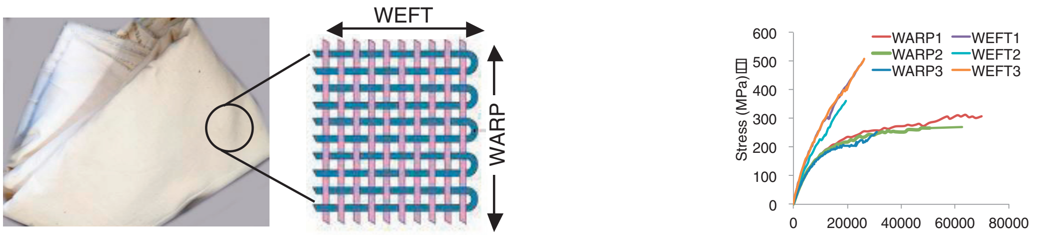
Tobu Line near Tokyo

JR Line at Osaka station

JR Line at Shin-Sapporo station

Fig. 12. Practical applications of PET jacketing.

Strengthening materials can be natural. Flax fiber was applied for jacketing [6]. Beam specimens were jacketed with flax fiber fabric, in which fibers are arranged in two orthogonal directions: warp and weft directions (Fig. 13). The fracturing strain in the warp direction is greater than 5% and slightly smaller than that of PET. The strength and stiffness in the weft direction are greater than those in the warp direction and slightly smaller than those of PET. All the jacketed specimens reached the peak load immediately after the flax fiber sheet fractured along the primary diagonal crack (Fig. 14). The shear strength was enhanced for all the specimens (Fig. 15). The load-displacement relationships of flax fiber jacketed specimens are comparable to that of PET jacketed specimens (SP4 in Fig. 16). Natural fibers with proper strength/stiffness and fracturing strain can be used as jacketing material.



(a) Flax fiber fabric

(b) Stress-strain relationships of flax fiber fabric

Fig. 13. Flax fiber.

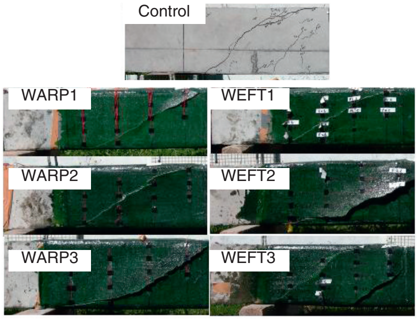


Fig. 14. Failure mode of flax fiber jacketed specimens.

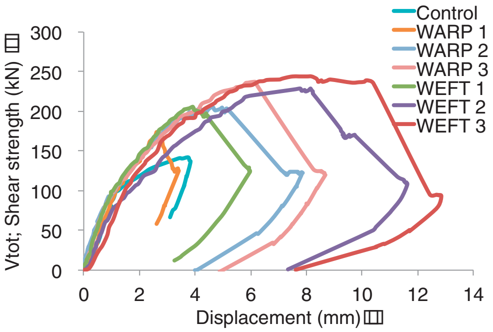


Fig. 15. Load-displacement relationships of flax fiber jacketed specimens.

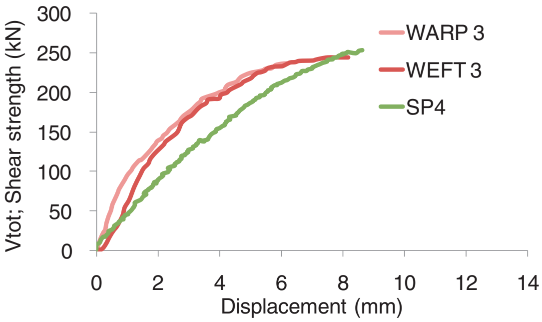
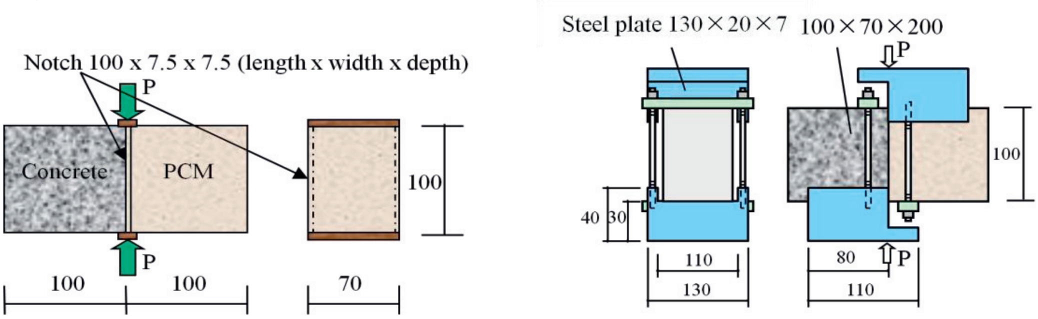


Fig. 16. Comparison of load-displacement relationships of flax fiber jacketed specimens with PET fiber jacketed specimen.

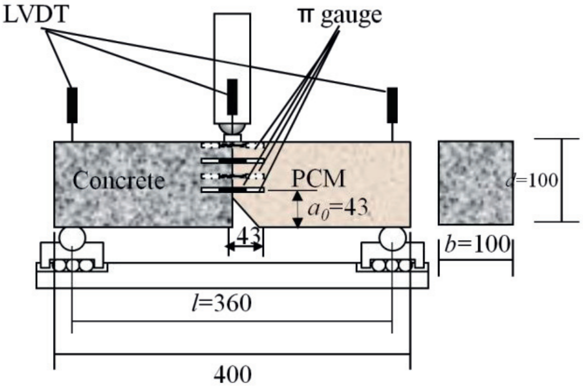
3.2. Material properties for higher debonding strength

In order to have higher debonding strength, we need to understand the debonding mechanisms of each debonding mode. Both IC debonding and end peeling take place at the interface between the strengthening layer and the substrate concrete. The initiation point of debonding for IC debonding is at the side of the loaded strengthening layer, while that of end peeling is at the free side. Concrete cover separation takes place along the tension reinforcement in substrate concrete. Shear stress and normal tension stress acts at the debonding surface. Depending on the acting stress, the corresponding bond strength is shear bond, tension bond or flexure bond strengths. We also need to know the bond strength under combined stresses. Fig. 17 shows test methods for shear, tension and flexure bond strengths in the case of a PCM-concrete interface.



(a) Splitting tensile test (unit: mm)

(b) Direct shear test (unit: mm)



(c) Three point bending test setup (unit: mm)

Fig. 17. Test methods for interface bond strengths.

It is rather obvious that the interface roughness between the strengthening layer and substrate is an important factor for bond strength. The roughness can be quantified by the standard method (Fig. 18). The relationships between the interface roughness, R_a and bond strengths for PCM-concrete interface are shown in Fig. 19 [7]. The bond strengths and fracture energy increase with the roughness. However, there are ceilings of bond strengths and fracture energy, meaning that an optimum roughness exists.

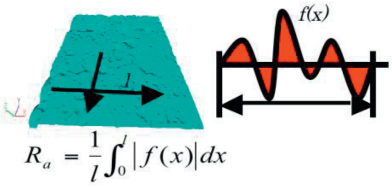
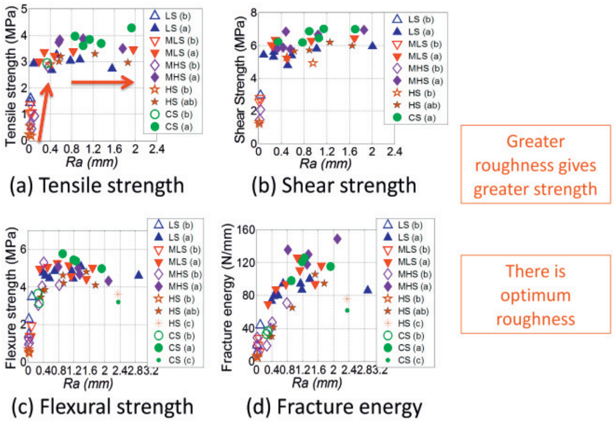


Fig. 18. Quantification of roughness.



(a) Tensile strength (b) Shear strength

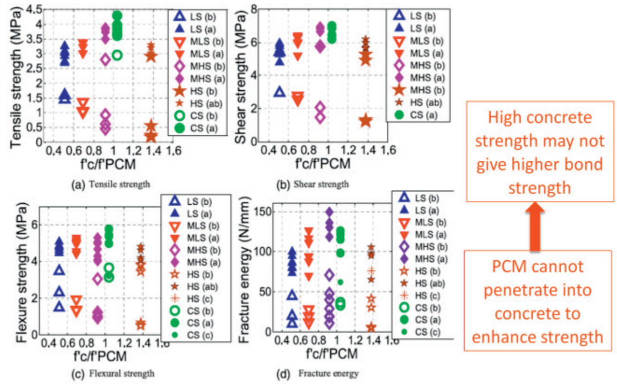
Greater roughness gives greater strength

(c) Flexural strength (d) Fracture energy

There is optimum roughness

Fig. 19. Effects of interface roughness on bond strengths.

The higher substrate concrete strength does not necessarily provide a higher interface bond strength for a PCM-concrete interface. In the case of high strength concrete polymer, the PCM may not penetrate into surface layer of substrate concrete, resulting in less bond strength. Fig. 20 shows that the bond strengths decrease with an increase in the ratio f'_c/f'_{PCM} in the case of adhesion failure or bond failure right at the interface (see symbols with (b) in the figure) [7]. This fact implies that there exists the optimum substrate concrete strength for strengthening material.



High concrete strength may not give higher bond strength

PCM cannot penetrate into concrete to enhance strength

Fig. 20. Effects of interface roughness on bond strengths.

For IC debonding of interface between substrate concrete and FRP/steel, there are factors other than roughness for debonding strength. The study by the authors' group proposed the following equation for debonding strength (shear bond strength), $P_{\max}$ [8]:

$$P_{\max} = \sqrt{2b_f E_f A_f G_f} = b_f\sqrt{2E_f t_f G_f} \tag{4}$$

$$G_f = 0.446(G_a/t_a)^{-0.352} f'_c{}^{0.236}\left(E_f t_f\right)^{0.023} \tag{5}$$

whereb_f, E_f, A_f, t_f, G_f are width, elastic modulus, area, thickness, and interfacial fracture energy of externally bonded strengthening layer such as FRP and steel. G_a, t_a are the shear modulus and thickness of the adhesive layer. As Equations (4) and (5) indicate, the debonding strength increases with a decrease in the shear stiffness of the adhesive layer, G_a/t_a (Fig. 21). The relationship between the local bond stress and slip shows that the smaller shear stiffness of the adhesive layer provides less stiffness and peak bond stress, but exhibits a much more ductile behavior, resulting in greater fracture energy (Fig. 22). This fact implies that the insertion of a soft adhesive layer could improve the debonding behavior. The application of urethane as a soft layer is under study.

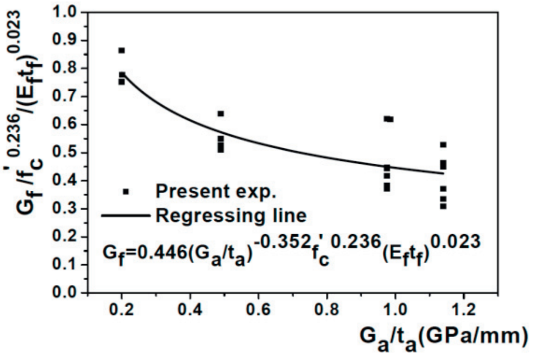


Fig. 21. Effects of shear stiffness of adhesive layer on shear bond strength.

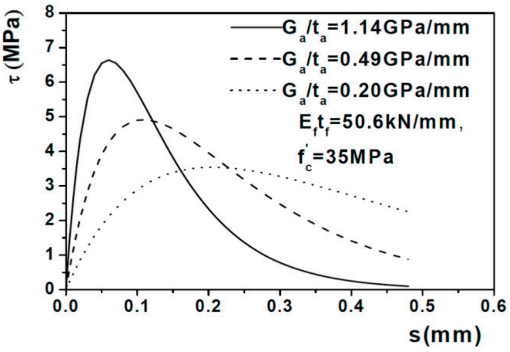


Fig. 22. Effects of shear stiffness of adhesive layer on bond stress-slip relationship.

The primary purpose of strengthening is to enhance member strength, such as flexure and shear strength. Generally the member strength increases as the amount of strengthening material increases. The blue line in Fig. 23 indicates that the flexure member strength increases as the ratio of reinforcement amount in strengthening layer to reinforcement amount in substrate concrete, A_s/A_r, increases. However, the A_s/A_rratio reduces the debonding strength with concrete cover separation [9,10]. Therefore, there is an optimum amount of tension reinforcement in the strengthening layer, which provides the effective strengthening capacity. The effective strengthening capacity depends on various factors. As shown in Fig. 24, the effective strengthening capacity becomes greater with:

- narrower/thicker bonded zone,
- bonded zone closer to zero moment point,
- smaller stiffness of strengthening reinforcement,
- larger strength of strengthening reinforcement.

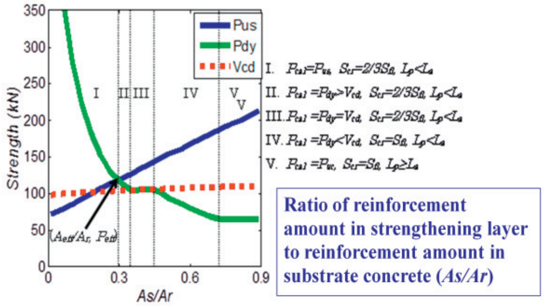
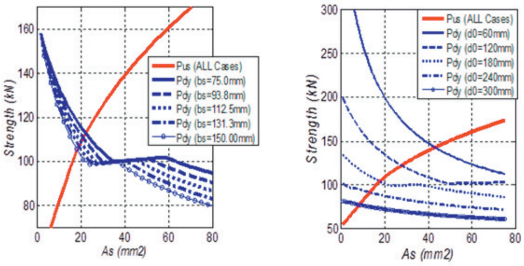
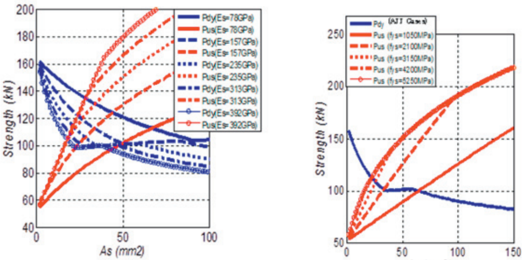


Fig. 23. Effective strengthening capacity.



(a) Bond width/thickness (b) Distance to zero moment point



(c) Stiffness of strengthening reinforcement (d) Strength of strengthening reinforcement

Fig. 24. Factors for effective strengthening capacity.

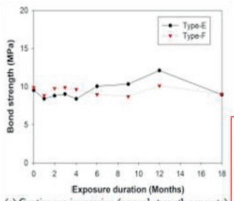
The long-term performance of strengthened members should be achieved. For this purpose, the long-term debonding strength needs to be clarified. However, there are not enough studies to conclude this behavior.

Previous studies reported that moisture reduces bond strengths of a substrate concrete-FRP interface. However, the degree of reduction varies significantly [11]. Fig. 25 shows the experimental results of the author's group. There is no clear explanation for the variation of the degrees of reduction. When the moisture effects are observed, the debonding failure mode tends to be that of adhesion failure rather than cohesion failure. The author's group is currently conducting a long-term exposure test to determine the moisture effects for 6 different FRP externally bonded systems, which are internationally applied to practical cases.

Studies on the long-term performance of concrete-cementitious material interface for overlaying are even rarer. At concrete-cementitious material interface there exists a weak layer [12]. This means that a cohesion failure of a cementitious material is less likely to occur. The lesser between the adhesion strength right at the interface or the cohesion strength of substrate concrete, would determine the bond strength. The tension bond strength under freeze-thaw cycles was experimentally investigated with composite specimens consisting of concrete at one side and a cementitious material at the other side (see Fig. 17). The specimens were not sealed during freeze-thaw cycles. For the case of air-entrained (AE) of ordinary mortar, the specimens showed adhesion failure except for the specimens with 300 FTC that showed cohesion failure of concrete (Figure 26). This is because the concrete was non-AE and its cohesion strength became less than the adhesion strength after 300 FTC (Fig. 27). For the case of PCM as cementitious material, the adhesion strength is weaker than the cohesion strength of non-AE concrete and PCM with any number of FTC. The adhesion strength decreases as FTC increases, although the PCM cohesion strength does not decrease (Fig. 28). It implies that FTC significantly affects the weak layer of PCM, although PCM itself has a good resistance against FTC.

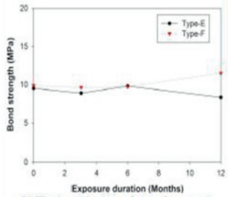
Since polymer in PCM is sensitive to temperature, the author's group is conducting a series of experiments to investigate the effects of temperature on the concrete-PCM interface bond strength. The preliminary test showed that temperature at bond testing could be more important than temperature during exposition.

It is worthy to mention that the interface properties may not be predicted by the properties of the strengthening material.

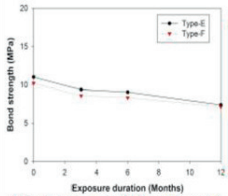


(a) Continuous immersion (normal strength concrete)

Negligible reduction in bond strength for normal strength concrete



(b) Wet-dry cycles (normal strength concrete)



(c) Continuous immersion (high strength concrete)

Reduction in bond strength for high strength concrete

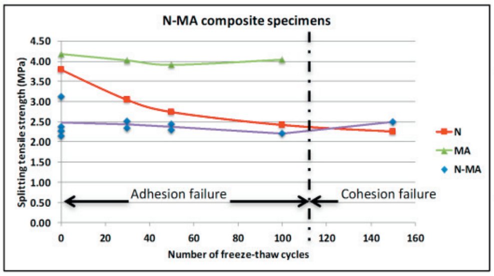
Fig. 25. Effects of moisture exposition on concrete-FRP interface bond strength.

Adhesion failure

Cohesion failure

Fig. 26. Adhesion and cohesion failure.

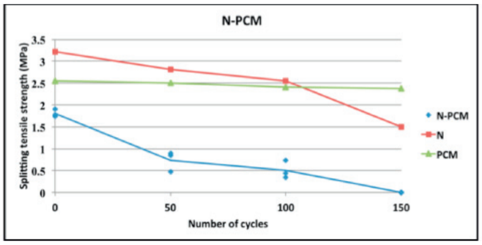
Splitting strength of mortar with air-entraining agent does not decrease



Mortar-concrete interface tension bond strength does not decrease

Fig. 27. Tension bond strength of concrete-mortar interface.

Splitting strength of PCM does not decrease



PCM-concrete interface tension bond strength does decrease

Fig. 28. Tension bond strength of concrete-PCM interface.

4. Concluding remarks

- Material conditions suitable for strengthening are quite different from those for concrete and steel in concrete structures.
- Material conditions suitable for the following structural performances should be further examined:
  - Better ultimate shear strength and deformation,
  - Better bonding strength for various debonding failure modes,
  - Better long-term performance under moisture, temperature, and fatigue effects.
- A general design approach for strengthening, which differs from that of ordinary reinforced concrete, is necessary to accommodate new materials.
- To achieve better strengthening, we need to understand more precisely the necessary conditions for materials and develop new materials to accommodate such conditions. For this purpose, a closer collaboration between material scientists and structural engineers is strongly suggested.

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