Engineering 5 (2019) 1131–1138

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
High Performance Structures: Building Structures and Materials—Article

Material Mechanical Properties Necessary for the Structural Intervention of Concrete Structures

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ARTICLE INFO

Article history:
Received 18 September 2018
Revised 10 February 2019
Accepted 25 February 2019
Available online 30 September 2019

Keywords:
Structural intervention
High fracturing strain
No yielding
Low stiffness
Roughness
Fiber-reinforced polymer
Polymers

ABSTRACT

Structural intervention involves the restoration and/or upgrading of the mechanical performances of structures. In addition to concrete and steel, which are typical materials for concrete structures, various fiber-reinforced polymers (FRPs), cementitious materials with fibers, polymers, and adhesives are often applied for structural intervention. In order to predict structural performance, it is necessary to develop a generic method that is applicable to not only to steel, but also to other materials. Such a generic model could provide information on the mechanical properties required to improve the structural performance. External bonding, which is a typical scheme for structural intervention, is not applied for new structures. It is necessary to clarify material properties and structural details in order to achieve better bonding strength at the interface between the substrate concrete and an externally bonded material. This paper presents the mechanical properties of substrate concrete and relevant intervention material for the following purposes: ① to achieve better shear strength and ultimate deformation of a member after structural intervention; and ② to achieve better debonding strength for external bonding. This paper concludes that some of the mechanical properties and structural details for intervention materials that are necessary for improvement in mechanical performance in structures with structural intervention are new, and differ from those of structures without intervention. For example, high strength and stiffness are important properties for materials in structures without structural intervention, whereas high fracturing strain and low stiffness are important properties for structural intervention materials.

1. Introduction

Extending the life of existing structures is an efficient way in which the construction industry can contribute to sustainability. Repair and upgrading are used to extend the life of existing structures; the former involves the restoration of degraded structural performance, while the latter enhances structural performance. Both can be used to improve the structural performance. When improved structural performance is related to the mechanical properties of the structure—such as its strength and stiffness—repair and upgrading can be termed *structural intervention*.

Structural interventions have been implemented in many structures over a long period of time. Various intervention methods exist, with differing structural details and materials. However, standards and guidelines for structural intervention have not yet been fully developed. There are no relevant International Organization for Standardization (ISO) standards in the form of practical codes, although ISO issued its first standard for the maintenance and repair of concrete structures in 2014—ISO 16311, which is an umbrella code rather than a code of practice. The International Federation for Structural Concrete (*fib*) has issued MC2010 as the latest version of its model code, although this code does not cover intervention methods. The next model code will be MC2020, which will cover existing structures not included in MC2010, along with new structures. *fib* plans to cover structural intervention such that the design and execution of structural intervention can be basically conducted by following MC2020. ISO will soon start drafting its first structural intervention standard, which covers strengthening with cementitious overlay.

New concrete structures are mostly constructed with concrete reinforced by steel—two materials that bond well. However, structural interventions are often conducted with materials other than concrete and steel. Materials for intervention must properly connect to the substrate concrete, and the relevant connecting

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https://doi.org/10.1016/j.eng.2019.02.012
2095-8099/

methods are quite different from the bonding that occurs between concrete and embedded steel reinforcement in concrete structures. Failure of the bond between concrete and steel reinforcement rarely becomes a cause of member failure; however, failure of the connection between the substrate concrete and a structural intervention material often causes member failure. The differences between new concrete structures and structures with structural intervention make it difficult to prepare standards/guidelines for structural interventions, and also cause the following situations:

- The optimum material properties and structural details that are required to achieve the best structural performance after intervention are unknown;
- The type of material and the execution condition that are necessary to achieve long-term good structural performance are unknown.

This paper presents the mechanical properties that are suitable for various performances of structures with structural interventions.

2. Material properties necessary for tension and shear reinforcement

In the development of structural materials, attention has been paid to strength and stiffness. From a historical standpoint, it has been considered that the higher the strength/stiffness is, the better the material performance will be. Fig. 1 provides an interesting comparison of the available structural materials. A material with a higher strength generally shows higher stiffness but a smaller fracturing strain (i.e., smaller deformability). As is well known, carbon possesses high strength/stiffness, but its fracturing strain is small (1.5%). On the other hand, steel has a rather low strength but fractures in tension with a strain greater than 20%. The stiffness of steel before yielding is as high as that of carbon, but the secant stiffness in the post-yield range becomes smaller quickly and is smallest at its fracturing point. Another interesting fact is that the material cost is usually higher when the strength/stiffness of the material is higher. In a way, steel is an ideal material to assure high deformability of a structure, which is necessary for good seismic performance. In the design of concrete structures, it is not necessary to check the fracture of steel reinforcement, since steel generally does not fracture due to its high fracturing strain. This high material performance can be enjoyed at a small cost.

Consider a case in which the results of the design show that a material of 1000 mm^2 at 3000 MPa is required. This material can be substituted by a material with a lower strength of 300 MPa by providing an amount of 10 000 mm^2. In another word, a material with lower strength can be a substitute for a material with higher strength when the necessary amount is increased.

What about a case in which the results of the design require a material with high deformability? Seismic design, which requires high plastic deformation of members, may require a tension material with 5% fracturing strain. It is practically impossible to achieve this deformability with material with a fracturing strain lower than 5%. This is one of the reasons why fiber-reinforced polymer (FRP) with high-strength fiber, such as carbon and aramid, cannot be practically applied as tension reinforcement.

The above cases relate to necessary properties of tension reinforcement; however, shear reinforcement is different. Ductility (or deformability) of a member comes mostly from elongation of the tension reinforcement rather than elongation of the shear reinforcement. Therefore, deformability of the shear reinforcement is not required as much as that of the tension reinforcement. The shear strength of the member depends on the stiffness of both shear and tension reinforcement [1], which means that the shear strength decreases with increasing member deformation after the yielding of tension and shear reinforcement. It is obvious that fracture of the shear reinforcement means a total loss of stiffness, which should be avoided to retain shear strength. Considering these facts, it is clear that the best material for shear reinforcement is one with moderately high stiffness and moderately high fracturing strain, but without yielding. Experimental facts, such as those from Ref. [2], show that a fracturing strain of 5% can be high enough for shear reinforcement in order to avoid fracture for good seismic performance. According to Fig. 1, some organic fibers, such as polyacetal fiber and polyethylene terephthalate (PET) fiber, have better mechanical properties than steel and carbon for shear reinforcement. Fig. 2 shows the high deformation of a PET fiber jacket without fracturing during the reversed cyclic loading test of a column specimen. The PET fiber jacketing demonstrated an enhancement of ductility for specimens in a flexure-dominant case (Fig. 3(a)) and both strength and ductility in a shear-dominant case (Fig. 3(b)) [2]. The PET fiber sheet jacketing showed higher strength and ductility than a carbon fiber sheet jacketing, since the carbon fiber sheet fractured but the PET did not. The cost of PET fiber sheet jacketing is less than that of conventional fiber sheet jacketing. Fig. 4 compares aramid fiber sheet jacketing with duplex jacketing, in which aramid fiber sheet is partially replaced by PET fiber sheet (A&P Jacketing), with full aramid fiber jacketing. The cost of

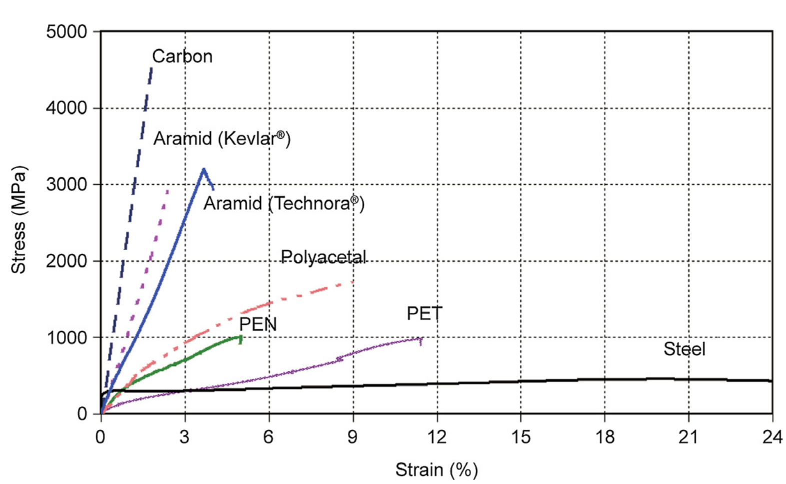

Fig. 1. A comparison of the stress–strain relationships of various structural materials. PEN: polyethylene naphthalate; PET: polyethylene terephthalate.

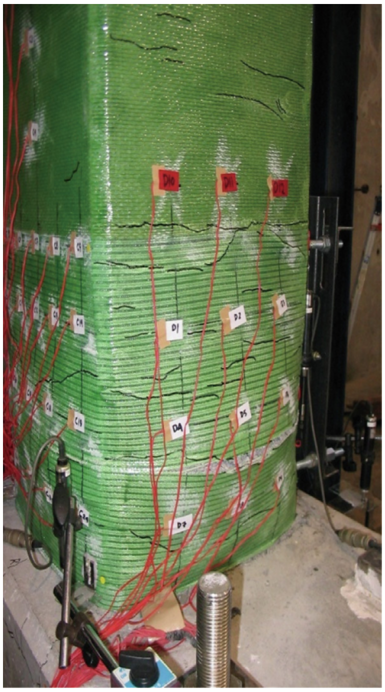

Fig. 2. A PET fiber sheet jacket showing high deformation without fracturing.

the former is much less than that of the latter, but both achieve the same seismic performance.

In order to determine the optimum material properties in terms of tension and shear reinforcement, it is necessary to apply a generic model to predict the load–deformation relationship, which can be applied to reinforcement with any material [1]. The generic model can predict the remaining shear strength under any deformation, which is the summation of the flexural and shear deformation. Fig. 5 shows how the remaining shear strength decreases as the deformation increases. The reduction in the remaining shear strength is caused by the reduction in the stiffness of the tension and shear reinforcement, $\rho_f E_{fe}$ and $\rho_w E_{we}$. Based on a numeric parametric study, the following equations were derived to estimate the remaining shear strength V_{su}, which is the summation of the concrete contribution V_c and the shear reinforcement contribution V_{s+f}; and the strain in shear reinforcement $\bar{\varepsilon}_w$.

$$V_{su} = V_c + V_{s+f} \tag{1}$$

$$V_c = \beta_d \beta_p \beta_s \beta_w f_{vc} bd \tag{2}$$

$$V_{s+f} = bL_{web}(\rho_w \sigma_w + \rho_f \sigma_f) \tag{3}$$

where the coefficients

$$f_{vc} = 0.2\sqrt[3]{f'_{ce}}$$

$$\beta_d = \sqrt[4]{a/d}$$

$$\beta_p = \sqrt{P/(2.5A_g f'_{co})}$$

$$\beta_s = \sqrt[4]{\rho_s E_{se}}$$

$$\beta_w = \sqrt[4]{\rho_w E_{we} + \rho_f E_{fe}}$$

$$\sigma_w = \bar{\varepsilon}_w E_{we}$$

$$\sigma_f = \bar{\varepsilon}_w E_{fe}$$

$$\bar{\varepsilon}_w = \frac{0.066}{\sqrt{a/d}+1}\left[e^{-0.12\sqrt{\rho_w E_{we}+\rho_f E_{fe}}+\left(4/\sqrt{\rho_s E_{se}}\right)-0.2\sqrt{f'_{ce}}}\right]\left[1+\left(\frac{\sigma'_n}{f'_{ce}}\right)^{0.2}\right] \tag{4}$$

and b is the width of the cross-section; a is the shear span; d is the effective depth; L_{web} is the projected shear crack length to the member axis; ρ_s and E_{se} are the ratio and secant modulus of tension reinforcement, ρ_f and ρ_w (σ_f and σ_w) are the ratio (stresses) of FRP and steel shear reinforcement, respectively; E_{fe} and E_{we} are the secant modulus of FRP and steel shear reinforcement, respectively; f'_{co} and f'_{ce} are the unconfined and confined concrete compressive strength, respectively; P is the axial force; A_g is the concrete gross section, and σ'_n is the axial compressive stress.

Shear deformation can be predicted by the truss analogy while considering tension shift, which is the increase in tensile force within tension reinforcement due to shear cracking. In Fig. 6, the truss analogy shows two components of shear deformation, Δ_{s1} and Δ_{s2}, which can be calculated by Eqs. (5) and (6).

$$\Delta_{s1} = \frac{\Delta l_{st,c}}{\sin\theta} = \frac{V_{s+f}}{E_{ce} b(\cot\theta + \cot\alpha)\sin^4\theta} \tag{5}$$

$$\Delta_{s2} = \frac{\Delta l_{st,t}}{\sin\alpha} = \frac{V_{s+f}}{E_{we}(\cot\theta + \cot\alpha)\left[\frac{1}{S}\left(A_w + \frac{E_{ce}A_{ce}}{E_{we}}\right) + \frac{E_{fe}}{E_{we}} t_f\right]\sin^3\alpha} \tag{6}$$

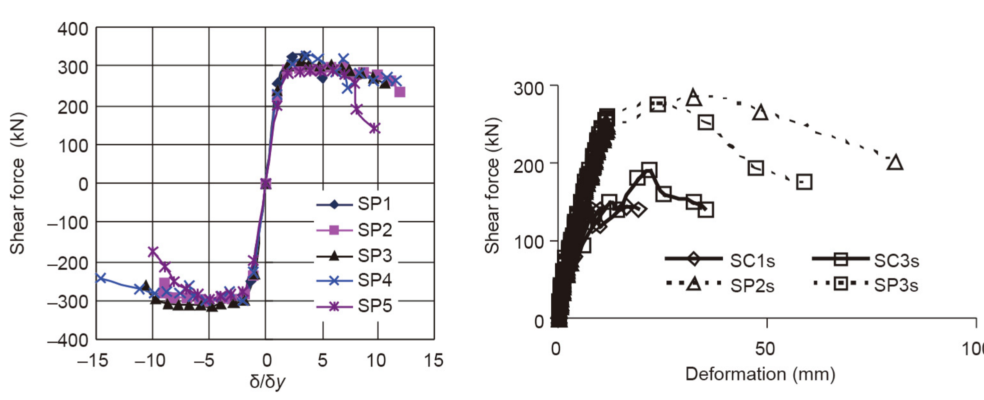

Fig. 3. Strength and ductility enhancement by PET fiber sheet jacketing. (a) Load-envelope curve in flexure-dominant case. SP1–SP4: column specimens with PET fiber sheet jacketing; SP5: without PET fiber sheet jacketing (δ: deformation, δy: yield deformation). (b) Load-envelope curve in shear-dominant case. SP2s and SP3s: column specimens with PET fiber sheet jacketing; SC1s: without jacketing; SC3s: with carbon fiber sheet jacketing.

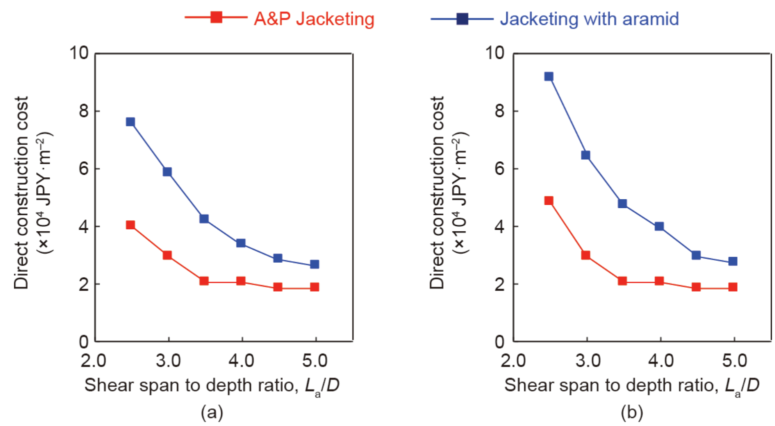

Fig. 4. Cost comparison of FRP sheet jacketing. (a) 800 mm × 800 mm section (longitudinal reinforcement ratio, p_t = 1.00%, transverse reinforcement ratio, p_w = 0.21%, axial stress, σ_N = 1.0 MPa); (b) 1000 mm × 1000 mm section (p_t = 0.86%, p_w = 0.17%, σ_N = 1.0 MPa).

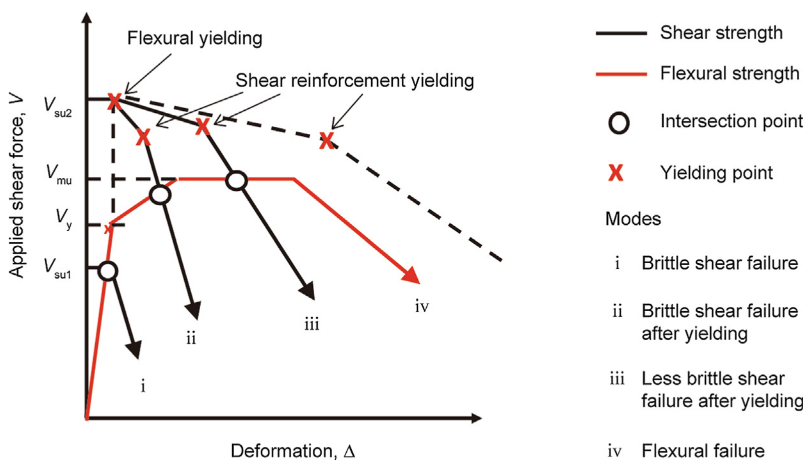

Fig. 5. Reduction in remaining shear strength with increase in deformation. V_{su2} and V_{su1}: the initial remaining shear strength which is greater and less than flexural strength V_{mu}, respectively; V_y: flexural yielding strength.

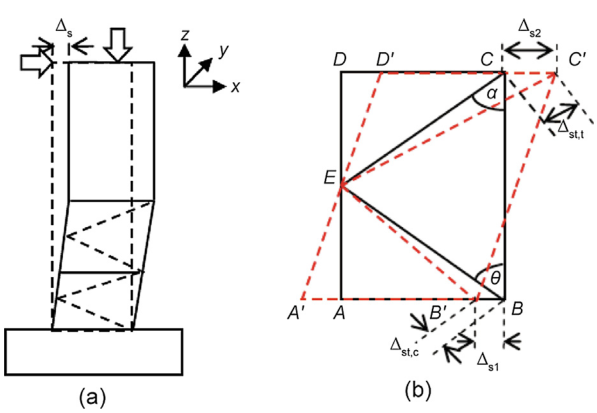

Fig. 6. Shear deformation model. (a) Total shear deformation; (b) a unit truss. *A, B, C, D, E* are the points before deformation, and *A′, B′, C′, D′* are the points after deformation.

where $\Delta l_{st,c}$ is the contraction of concrete diagonal strut, $\Delta l_{st,t}$ is the elongation of shear reinforcement, E_{ce} is the modulus of the surrounding effective concrete, S is the spacing of the shear reinforcement, t_f is the thickness of FRP reinforcement, A_w is the cross-sectional area of the steel shear reinforcement, A_{ce} is the cross-sectional area of the surrounding effective concrete in tension $(= A_{ceo}(V_{crack}/V)^3)$, A_{ceo} is the cross-sectional area of the surrounding effective concrete in tension immediately after shear cracking $(= (A_w f_{wy})/f_t)$, f_{wy} is the yield strength of the steel shear reinforcement, f_t is the concrete tensile strength, V_{crack} is the shear force at diagonal cracking, V is the applied shear force, θ is the strut angle, and α is the angle of steel shear reinforcement.

The generic model can predict the load-deformation relationships with good accuracy, as shown in Fig. 7 [1]. It can also predict the fracture of reinforcement, which makes it possible to know the fracturing strain required to achieve target ductility.

3. Material properties necessary for the adhesion layer

Debonding at the interface between the reinforcing material and the substrate concrete is a typical failure mode for structural intervention. Debonding is caused by failure of the adhesion layer, which includes: ① the surface layer of the substrate concrete, ② the adhesion interface between the substrate concrete and the adhesion material, ③ the layer of the adhesion material, ④ the adhesion interface between the adhesion material and the reinforcing (strengthening) material, and ⑤ the surface layer of the reinforcing (strengthening) material (Fig. 8). In a case where there is no adhesion material to bond the reinforcing material to the

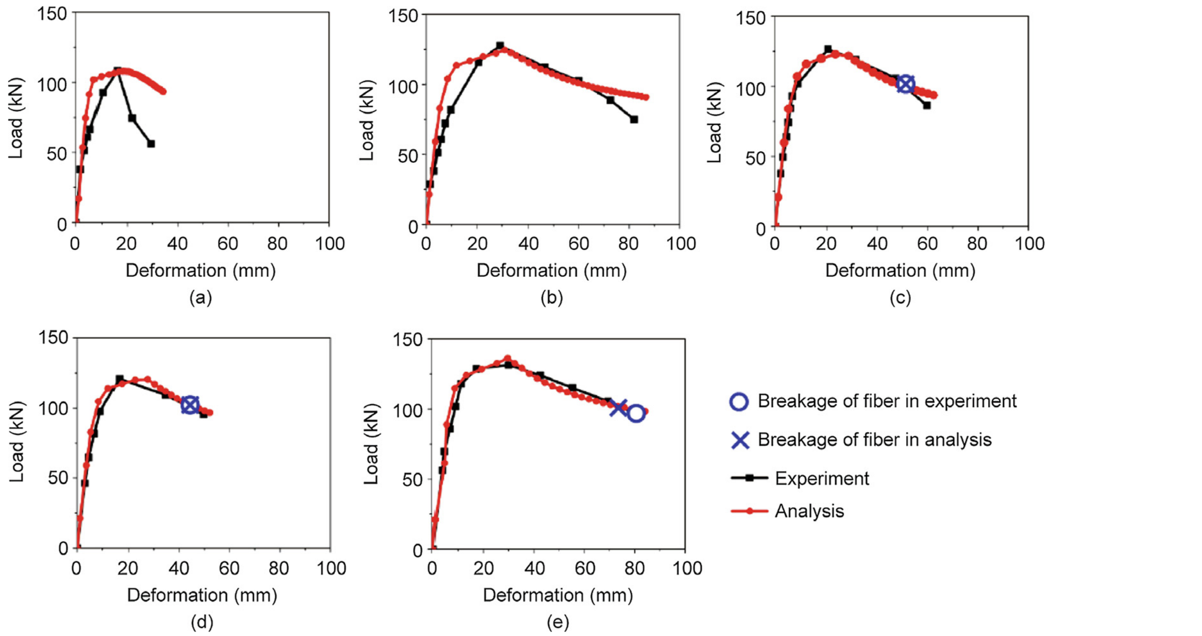

Fig. 7. Load–deformation relationship predicted by the generic model. (a) Specimen AS-N1; (b) specimen ASC-NS2; (c) specimen ACS-NS3; (d) specimen AS-NS4; (e) specimen ASC-NS5 [1].

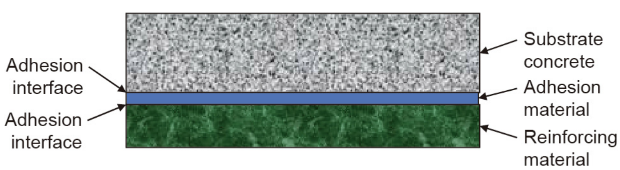

Fig. 8. An adhesion layer consisting of five components.

substrate concrete, there are only three components: ① the surface layer of the substrate concrete, ② the adhesion interface between the substrate concrete and the reinforcing material, and ③ the surface layer of the reinforcing material. The minimum strength among five (or three) components determines the debonding strength. In fact, the material properties that enhance each of the five components are different.

In a case with external bonding with steel and FRP, the weakest component is usually the surface layer of the substrate concrete. This fact indicates that the local stress/strain acting in the surface layer of the substrate concrete is likely to determine the debonding. Experimental facts show that the softer the layer of adhesion material is, the higher the debonding strength is [3] (Fig. 9). This is because a softer adhesion material layer needs a longer effective bond length, which reduces the interface bond stress and, subsequently, the stress/strain in the concrete surface layer [4]. Given this fact, a bond model for the bond stress (τ) and slip (s) relationship and a model for the interfacial fracture energy, G_f, were proposed, as shown below [5].

$$\tau = 2BG_f[\exp(-Bs) - \exp(-2Bs)] \tag{7}$$

$$B = 6.846(E_f t_f)^{0.108}(G_a/t_a)^{0.833} \tag{8}$$

$$G_f = 0.446(G_a/t_a)^{-0.352} f_c'^{0.236}(E_f t_f)^{0.023} \tag{9}$$

where B is the experimental parameter, which can be regarded as the ductility index, E_f is the elastic modulus of the FRP reinforcement, t_f is the thickness of the FRP reinforcement, G_a is the shear

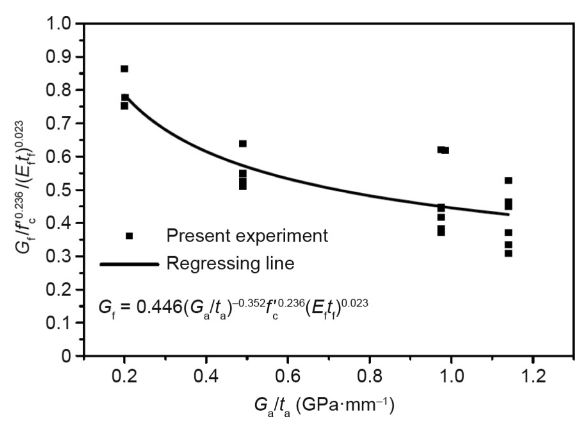

Fig. 9. Relationship between the shear stiffness (G_a/t_a) of the adhesion material layer and the debonding strength in terms of the fracture energy (G_f), which is a function of concrete strength (f_c') and FRP stiffness ($E_f t_f$).

modulus of the adhesive, t_a is the thickness of the adhesive layer, and f_c' is the concrete compressive strength.

This bond model predicts the difference in the relationship between the local bond stress and the slip among different cases of shear stiffness of the adhesing material layer, as shown in Fig. 10. A lower shear stiffness results in a lower peak bond stress, but makes the bond behavior more ductile. A softer adhesion material layer is softer in shear. The way to make an adhesion material layer softer is not only to make the adhesion material softer, but also to make the adhesion material layer thicker. As shown in Fig. 9, a greater debonding strength (i.e., greater interfacial fracture energy) with a softer adhesive layer (i.e., smaller G_a/t_a) can be predicted by Eq. (9) [5]. The advantage of a softer adhesion material layer is only true for a case in which the bond length is longer than the effective bond length. For a case in which the bond length is limited, a harder adhesion material layer may provide a higher debonding strength.

When the substrate concrete is a material of high strength, such as ultra-high-strength fiber-reinforced concrete (UFC), the weakest component is no longer the surface layer of the substrate concrete.

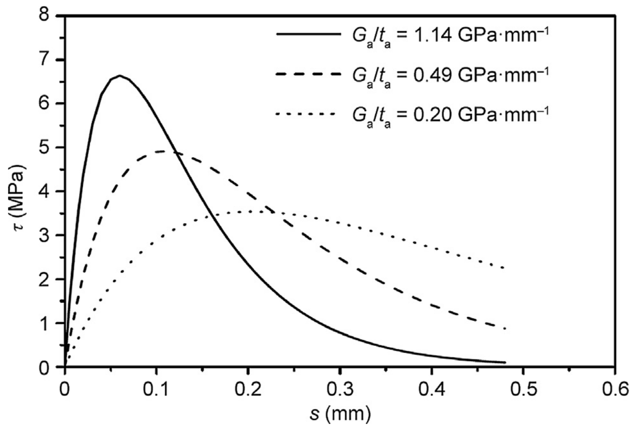

Fig. 10. Local bond stress–slip relationships (τ–s) among different shear stiffnesses of the adhesion material layer (G_a/t_a) for a case with a substrate concrete strength (f') of 35 MPa and an FRP stiffness ($E_f t_f$) of 50.6 kN·mm^{-1}.

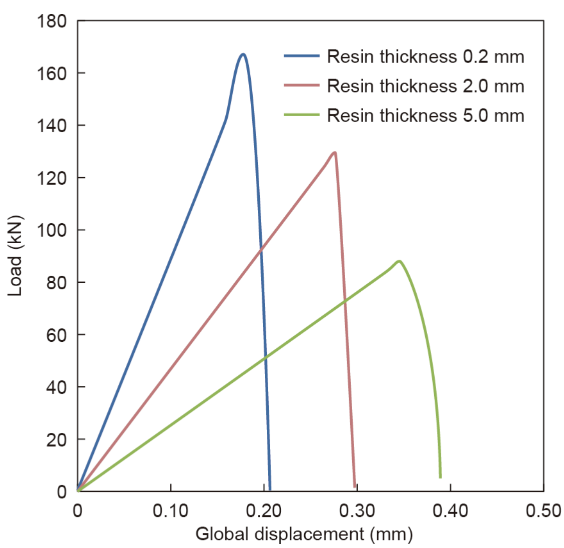

Fig. 11. Effect of adhesion material layer thickness on debonding strength.

In this case, failure of the adhesion material layer is a typical failure mode and the effects of the thickness of the adhesion material layer are different. A thicker adhesion material layer causes higher principal tensile stress in the adhesion material, resulting in a lower debonding strength [6]. Fig. 11 presents the prediction results by FEM, which show that the debonding strength decreases by half when the adhesion material layer thickness increases from 0.2 to 5.0 mm. Therefore, an adhesion material with higher strength results in a higher debonding strength. One point requires consideration: If the adhesion material shows shrinkage during curing and/or under environmental conditions, internal tension stress/strain will be induced due to the constraint established by the substrate concrete and reinforcing material. This tensile stress/strain can cause earlier failure of the adhesion material. Therefore, another necessary material property is small shrinkage under curing and environmental conditions for debonding with adhesion material failure.

As mentioned earlier, the material properties required to enhance the debonding strength of the five different components of the adhesive layer can be different for each component. Higher strength of the substrate concrete and reinforcing material usually result in higher debonding strengths of the surface layer of the substrate concrete and of the reinforcing material, respectively. However, a higher strength of the substrate concrete does not necessarily result in a higher debonding strength at the adhesion interface between the substrate concrete and the adhesion material. Similarly, a higher strength of the reinforcing material and adhesion material may not result in a higher debonding strength at the interface of these materials. An experimental study found an interesting result of debonding strength (i.e., tensile interfacial bond strength) at the adhesion layer between substrate concretes and polymer cementitious mortar (PCM) [7]. All debonding failure for the interface between the concrete and PCM occurred through failure at the adhesion interface between the concrete and PCM. The debonding strength was less than the tensile strength of the constituent materials and decreased with freeze thaw cycles (FTC) for substrate concrete both with and without an air-entraining agent (Fig. 12). The tensile strength of the concrete with the air-entraining agent and PCM did not show degradation with FTC, whereas that of the concrete without an air-entraining agent did. This finding may be explained by the fact that the observed surface of the PCM showed some deterioration after FTC; such

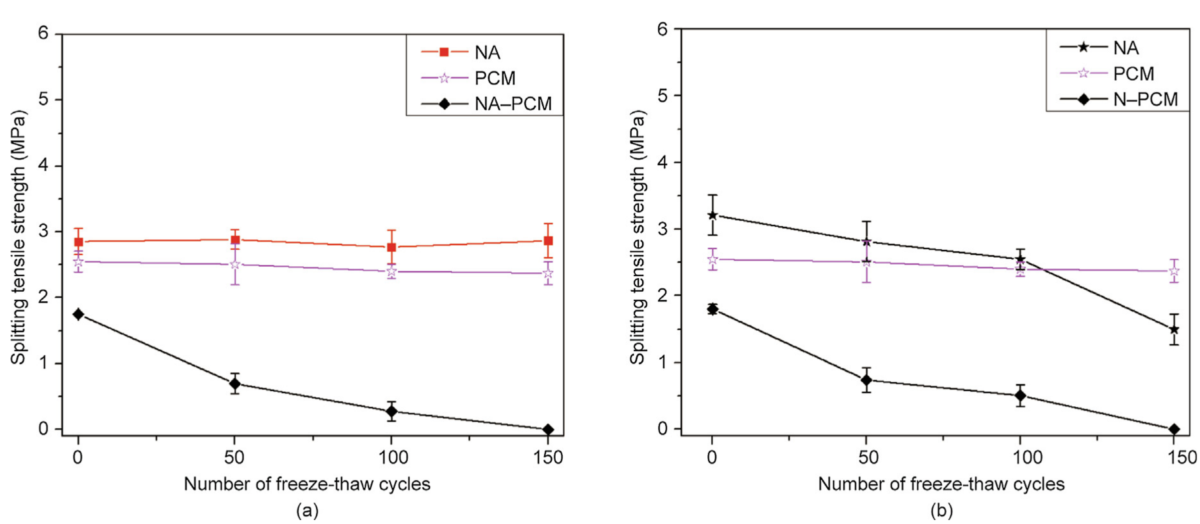

Fig. 12. Debonding strength (splitting tensile strength) of the adhesive layer between concrete and PCM. (a) Interface between concrete with air-entraining agent and PCM; (b) interface between concrete without air-entraining agent and PCM. NA: concrete with air-entraining agent; N: concrete without air-entraining agent; NA–PCM: interface between NA and PCM; N–PCM: interface between N and PCM.

deterioration might occur at the interface as a result of some moisture ingress into the interface during FTC—although the rest of the PCM (other than the surface) did not show deterioration. In the same study, the interface between concrete and ordinary mortar was tested for comparison purposes. The results showed that the debonding strength of the interface with the mortar with an air-entraining agent did not show strength reduction after FTC, whereas the debonding strength of the interface with the mortar without an air-entraining agent did show strength reduction for both cases (i.e., the substrate concrete with and without an air-entraining agent). This experimental evidence reveals that the material property necessary to enhance the debonding strength with adhesion interface failure can be different from the property necessary to enhance the debonding strength with failure of constituent materials. The debonding strength of the adhesion interface should be investigated directly through experiments on adhesion interface failure.

The roughness at the interface is naturally an influential factor. Interface roughness helps to enhance the debonding strength with adhesion interface failure. In a case involving the interface between the substrate concrete and FRP, the strength of the concrete should be high in order to take advantage of interface roughness. Otherwise, debonding strength with surface concrete failure will occur. In an experiment in which the strength of the substrate concrete was 90 MPa, the debonding strength increased by 110% as the roughness (R_a) increased from 0.11 to 0.54 mm, as shown in Fig. 13 [8]. The observed failure mode was a mixed failure mode of adhesion interface failure and concrete surface failure. In the case of sand blasting (R_a = 0.54 mm), FRP sheet fracture and adhesion interface failure were observed for one and two layers of FRP sheet cases, respectively. In order to compare two cases of adhesion interface failure with small and large roughness (R_a of 0.11 and 0.54 mm), the debonding strength in the case of two FRP layers should be adjusted to that of a case with one layer. After one year of exposure to moisture, the debonding strength with adhesion interface failure decreased more (28%) in the case of smaller roughness (0.11 mm), and decreased less (7%) in the case of greater roughness (0.54 mm) (Fig. 14). This difference can be explained by the difference in moisture effects between mechanical and chemical bonds. The contribution of the mechanical bond increases with greater roughness, while the contribution of the chemical bond increases with lower roughness. The chemical bond is more affected by moisture than the mechanical bond. For a case involving the interface between the substrate concrete and a cementitious material as the reinforcing material, it is not necessary for the strengths of both constituent materials to be high in order to result in debonding with adhesion interface failure. In an experiment investigating the interface between concrete and PCM, the debonding strength increased as the roughness increased up to 0.5 mm, and then scarcely increased for roughnesses greater than 0.5 mm [9]. In some cases, the debonding strength slightly decreased because a coarse aggregate came out, indicating that the interface roughness itself broke. In summary, a rougher interface is necessary to enhance the debonding strength with adhesion interface failure; however, there is a threshold value for roughness beyond which the interface itself may break.

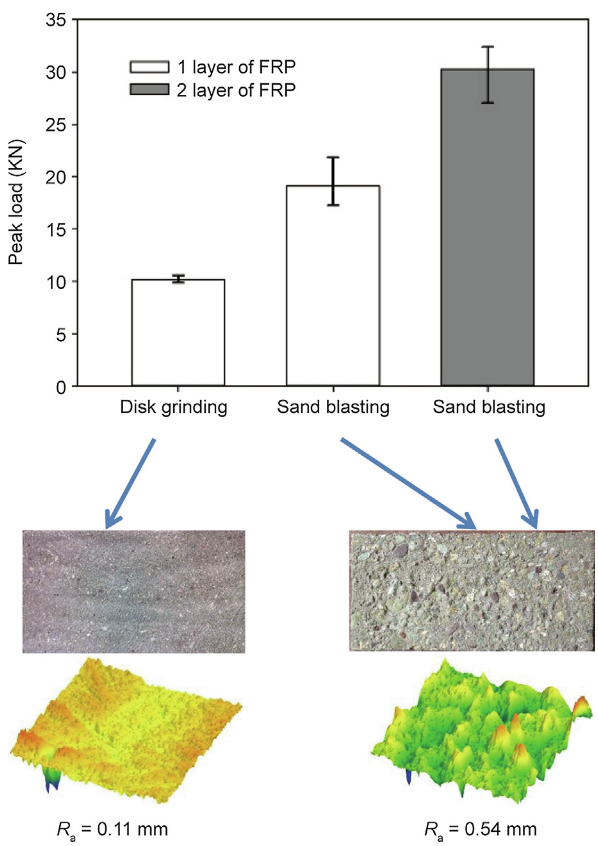

Fig. 13. Effects of interfacial roughness on debonding strength.

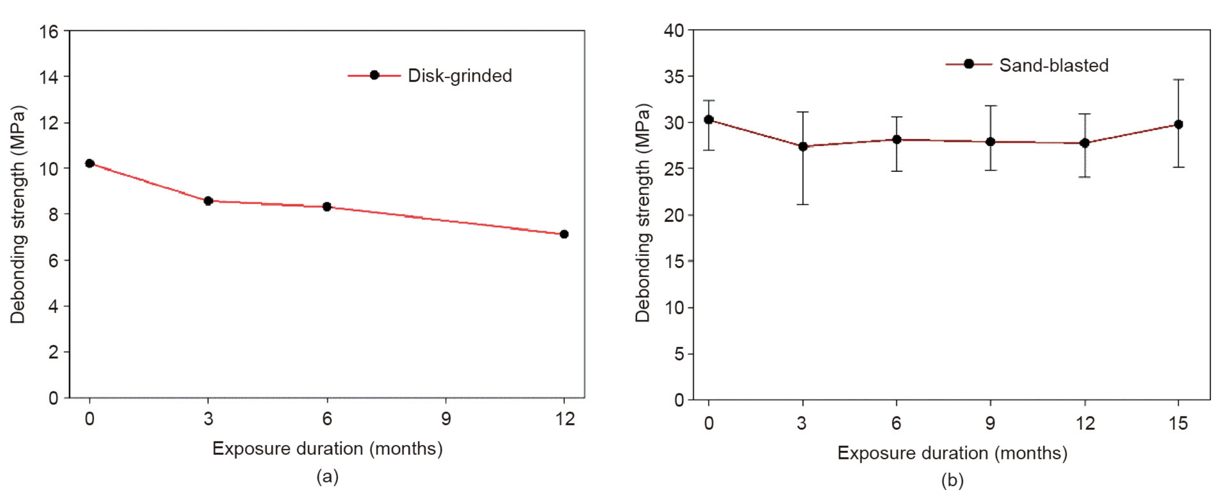

Fig. 14. Effects of interface roughness on debonding strength after moisture exposure. (a) Debonding strength change after moisture exposure for low roughness (R_a = 0.11 mm); (b) debonding strength change after moisture exposure for large roughness (R_a = 0.54 mm).

4. Concluding remarks

New materials such as FRP, PCM, and adhesive resin, and new structural detail such as external bonding, have been applied for structural intervention. The material properties necessary for shear reinforcement and for the enhancement of debonding strength are as follows:

(1) Necessary properties for shear reinforcement—which enhances shear strength and thereby member deformability—are high fracturing strain (5% or greater) and moderate stiffness without yielding.

(2) Necessary properties in addition to material strength for the enhancement of debonding strength are:

- Low shear stiffness for failure of the surface layer of the substrate concrete;
- Small shrinkage for failure of the adhesion material layer;
- Interface roughness for failure of the adhesion interface with the substrate concrete.

Necessary properties for the enhancement of the debonding strength for failure of the adhesion interface should be directly obtained from the adhesion interface's failure test, since the material property of the constituent materials of the interface may not reflect the adhesion interface strength.

Acknowledgements

The author would like to express his sincere gratitude to the research team involved in the research related to the contents of this paper, especially Mr. Hiroshi Nakai, Dr. Tidarut Wisuthseriwong (formerly Jirawattanasomkul), Prof. Jianguo Dai, Dr. Justin Shrestha, Dr. Ye Qian, and Dr. Dawei Zhang.

References

[1] Jirawattanasomkul T, Zhang D, Ueda T. Prediction of the post-peak behavior of reinforced concrete columns with and without FRP-jacketing. Eng Struct 2013;56:1511–26.
[2] Anggawidjaja D, Ueda T, Dai J, Nakai H. Deformation capacity of RC piers wrapped by new fiber-reinforced polymer with large fracture strain. Cem Concr Compos 2006;28(10):914–27.
[3] Ueda T, Dai J. Interface bond between FRP sheets and concrete substrates: properties, numerical modeling and roles in member behaviour. Prog Struct Eng Mater 2005;7(1):27–43.
[4] Dai J, Ueda T, Sato Y. Unified analytical approaches for determining shear bond characteristics of FRP-concrete interfaces through pullout tests. J Adv Concr Technol 2006;4(1):133–45.
[5] Dai J, Ueda T, Sato Y. Development of the nonlinear bond stress-slip model of fiber reinforced plastics sheet-concrete interfaces with a simple method. J Compos Constr 2005;9(1):52–62.
[6] Krintrakul N, Ueda T, Takahashi J, Fujima S, Furuuchi H. Improvement of debonding strength with consideration of adhesive layer property and its FEM analysis. J Struct Eng A 2016;62A:23–31. Japanese.
[7] Qian Y, Zhang D, Ueda T. Interfacial tensile bond between substrate concrete and repairing mortar under freeze-thaw cycles. J Adv Concr Technol 2016;14(8):421–32.
[8] Shrestha J, Ueda T, Zhang D. Effect of primer and surface preparation on the FRP-concrete bond. In: Proceedings of the 7th International Conference on FRP Composites in Civil Engineering; 2014 Aug 22–24; Vancouver, BC, Canada; 2014.
[9] Zhang D, Ueda T, Furuuchi H. Fracture mechanisms of polymer cement mortar: concrete interfaces. J Eng Mech 2013;139(2):167–76.