IABSE-JSCE Joint Conference on Advances in Bridge Engineering-III, August 21-22, 2015, Dhaka, Bangladesh. ISBN: 978-984-33-9313-5
Amin, Okui, Bhuiyan, Ueda (eds.) www.iabse-bd.org

# Structural retrofitting and renovation for sustainable infrastructures

T. Ueda
*Faculty of Engineering, Hokkaido University, Sapporo 060-8628, Japan*

ABSTRACT: This paper explains the definition and role of strengthening as a type of intervention, which would make structures sustainable. Despite the fact that there are many studies on strengthening, practical strengthening methods have not been well developed. For strengthening there is no standard method, no rational design and execution method for usage of new material as reinforcement, or no prediction method of service life of structures after strengthening. Some available strengthening methods imply that new concept, high deformability rather than high strength/stiffness, could be applied to reinforcing material. This paper briefly introduces those important issues for strengthening for development of rational guidelines.

## 1 INTRODUCTION

### 1.1 *What are Structural Retrofitting and Renovation?*

There are various ways for intervention of existing structures. There are primarily two types: one for enhancing durability (slowing down deterioration) or restoring degraded durability, and one for enhancing mechanical property or restoring degraded mechanical property. Structural retrofitting is enhancing mechanical property, while structural renovation is restoring degraded mechanical property. For both cases mechanical property is to be enhanced (improved) from the present condition. Thus, in this paper, “strengthening” is used to represent both structural retrofitting and renovation. For your information, however, the recently published ISO standard (ISO 16311) defines “strengthening” as enhancing mechanical property only, while restoring degraded mechanical property is a kind of “repair”. The common definition of terminology related to maintenance and repair has not been established through the world.

### 1.2 *Why Do We Need Structural Retrofitting and Renovation?*

Why do we need strengthening? One reason is to make structures satisfy the performance requirements, such as safety and serviceability against foreseen events, such as natural hazards and long-term mechanical actions (fatigue). Structures to be strengthened may be intact presently but are not safe or serviceable under the effects of foreseen events. In case where structures show some degradation in terms of strength and/or stiffness due to natural hazards as well as mechanical and/or environmental actions, the structures need to be intervened to restore the degraded mechanical property.

The second reason is to contribute the sustainability of the world. In order to make structures to satisfy the performance requirement, there are other options, such as demolition and reconstruction. However, this option would cost more not only money but also energy and resources. And it would emit more $CO_2$. Thus, the extension of service life of the structures by strengthening would make the structures sustainable in many cases.

Whether strengthening is a better option or not? Which strengthening method is the best? In order to answer those questions, “life cycle management (LCM)” of structures is necessary. LCM is taken for optimizing cost and impact-to-environment during service life of the structures (see Figure 1).

### 1.3 *What are the Issues for Structural Retrofitting and Renovation?*

The first ISO standard for maintenance and repair just came out in 2014 (ISO 2014), meaning that the technology of intervention, including strengthening has not been well developed. The followings are the main issues for strengthening:

i. Development of standard method

ii. Application of new material
iii. Development of design method
iv. Development of execution method
v. Prediction of service life after being strengthened

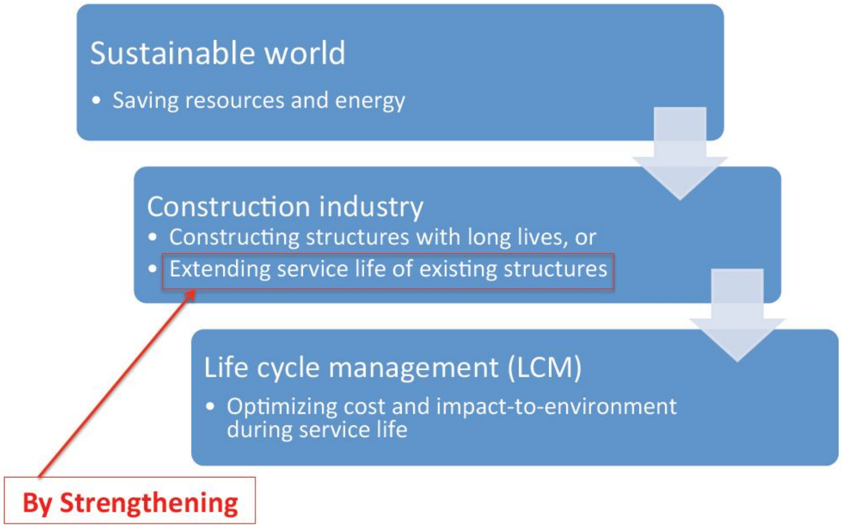



Figure 1. Life cycle management

## 2 DEVELOPMENT OF STANDARD METHOD

There have been many studies on development of strengthening method. The followings are typical methods for concrete structures (see Figure 2) (JSCE 2000):

i. Jacketing
ii. External bonding
iii. Overlaying
iv. External cable
v. Addition of element

For each method there are many available methods with different structural detailing and/or different material. External bonding can be done with steel and FRP. Steel is plate, however FRP can be sheet, plate and bar. Fiber of FRP can be carbon, aramid, glass and others. There is no specification for resin of FRP (adhesion and impregnation resin). Cementitious material for overlaying can be mortar, polymer cement mortar (PCM) and fiber reinforced mortar. Tension reinforcement in overlay can be steel and FRP.

Since there is no standard method, there are various problems: (1) higher cost, (2) difficulty to achieve high quality, and (3) difficulty to develop rational design and construction method.

## 3 APPLICATION OF NEW MATERIAL

Structural detailing of strengthened member is different from that of new structure. Bonding interface in external bonding and overlaying does not exist in new concrete structures. Construction space and time constraints for intervention are quite different from those for new structures, since the structures to be intervened are in service.

Because of those facts, various types of materials other than ordinary steel have been applied to strengthening, such as FRP. Steel strength can be different depending on types of steel, however elastic modulus is almost the same. Strength and elastic modulus of FRP are all different among FRPs with different fiber types. Steel shows yielding, but FRP does not. Figure 3 compares steel and various fiber materials. Materials with high strength generally have high stiffness but small fracturing strain. Materials with low strength show high fracturing strain. Price of high strength material is high, while that of low strength material is low.

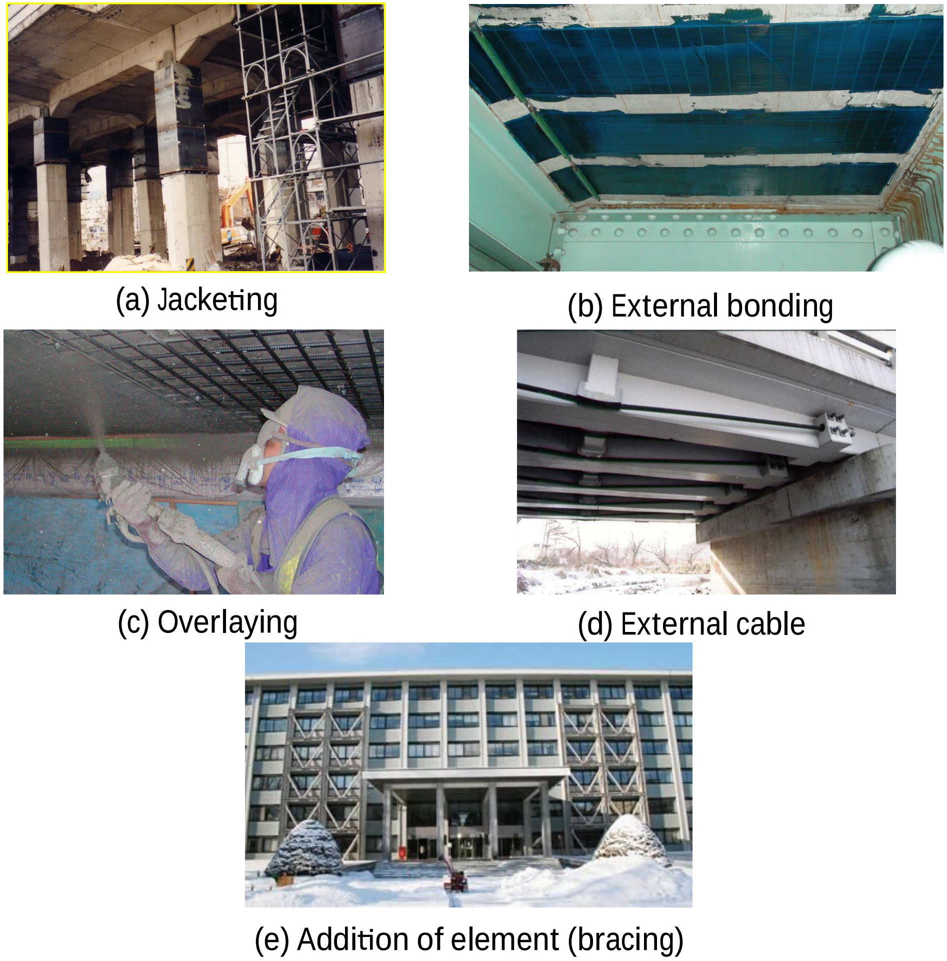



Figure 2. Types of strengthening

Structures that need high deformability often need to develop high strain in the material in the structures. Therefore, we need material with high fracturing strain. On the other hand the required strength and stiffness for material can be achieved by providing necessary amount no matter how the material strength and/of elastic modulus is. Thus, a material with a high fracturing strain can be a better option for structures, which need high deformability. Shear reinforcement of concrete structures, especially under seismic effects, need high stiffness and fracturing strain (Jirawattanasomkul, et al. 2013). Steel shear reinforcement thus become less effective after its yielding. Considering those facts, the better material property can be sought. PET and natural fiber, which are with large fracturing strain and inexpensive, can be a good material for jacketing and external bonding (see Figure 4) (Anggawidjaja, et al. 2006, Lunn, et al. 2013, Takasaki, et al. 2014, Rahman and Ueda 2015).

## 4 DEVELOPMENT OF DESIGN METHOD

Since structural detailing and material are different from those of new concrete structures, new design method needs to be developed. For this purpose many studies have been conducted in not only developed countries but also developing countries (for example, CUET 2014). The followings are the main issues for development of design method:

i. Axial, flexure and shear strength with reinforcing material rather than steel
ii. Identification of potential debonding failure modes
iii. Strength for each debonding failure mode
iv. Effect of interface roughness on debonding
v. Crack spacing

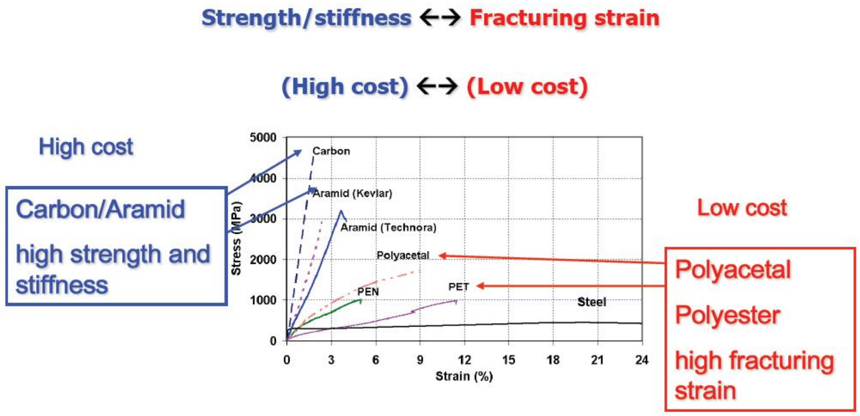



Figure 3. Stress – strain relationships of various materials

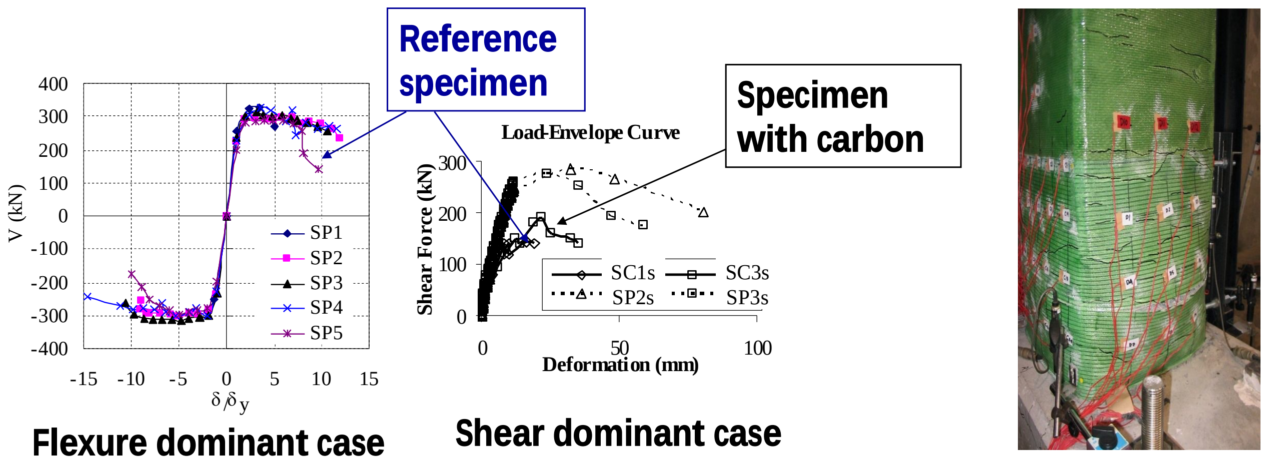



Figure 4. Jacketing with PET FRP sheet

Shear strength formula is generally experimental one for the cases with steel reinforcement. Shear strength with FRP needs new generic model which can predict stress in FRP shear reinforcement (see Figure 5) (Jirawattanasomkul, et al. 2013). Axial, flexure and shear strength can be increased efficiently by confining substrate concrete including cover even for the case of low quality concrete with brick and recycled aggregates (Hasnat, et al. 2015, Islam, et al. 2015).

There are three debonding failure modes besides ordinary failure modes (see Figure 6). We need to develop strength prediction model for each failure mode. For intermediate crack debonding various factors affect debonding strength. One of them is shear stiffness of adhesive resin layer. The lower stiffness would give the larger debonding strength (see Figure 7) (Dai, et al. 2005). Tooth model can be applied to predict concrete cover separation (see Figure 8) (Zhang, et al. 2012).

Roughness of interface between substrate concrete and bonded material affects the debonding strength. The rougher interface is, the higher the debonding strength is. However, there is an optimum roughness beyond which the debonding strength does not increase or could be decrease (see Figure 9) (Zhang, et al. 2013).

Crack spacing in members after being strengthened with external bonding or overlaying is different from that in members before being strengthened. Thus, we need a separate method for predicting crack spacing. Crack spacing would affect debonding strength.

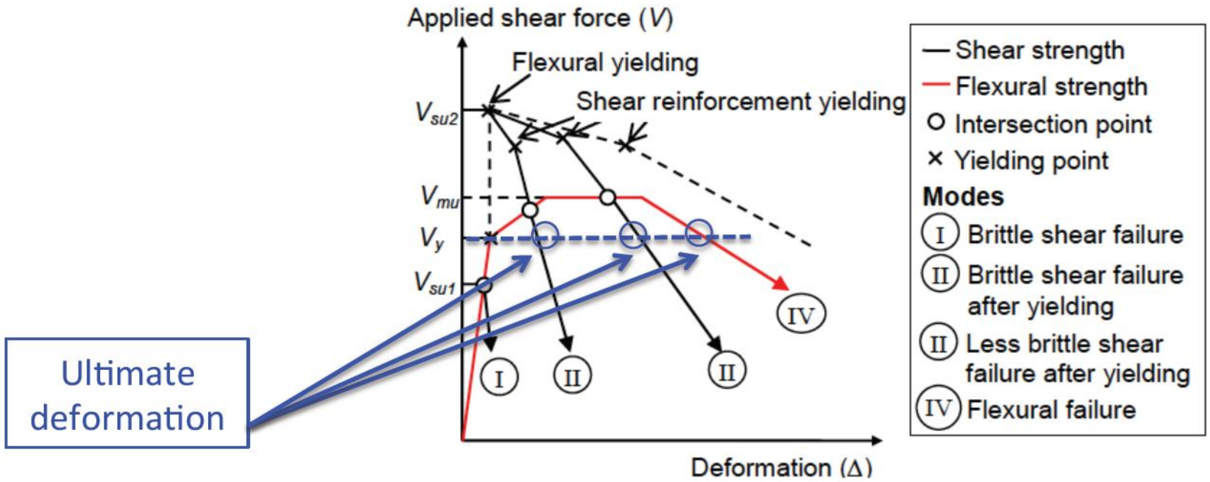



Figure 5. Shear strength prediction by generic model

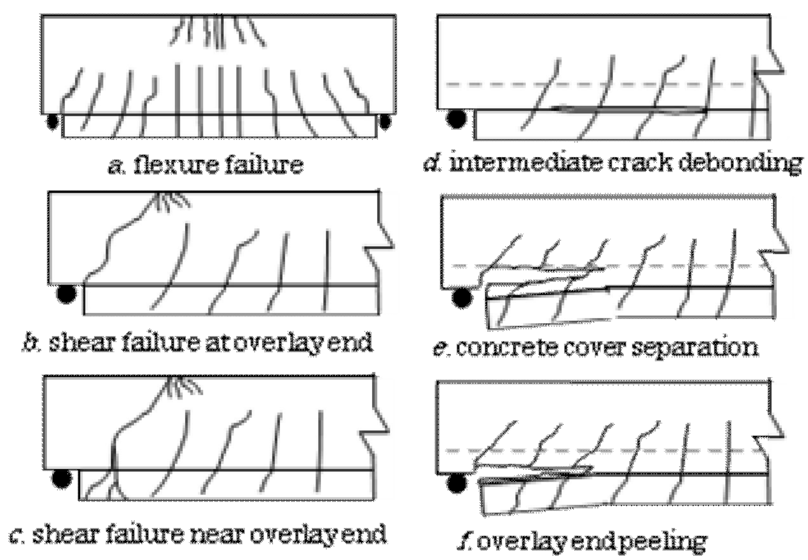
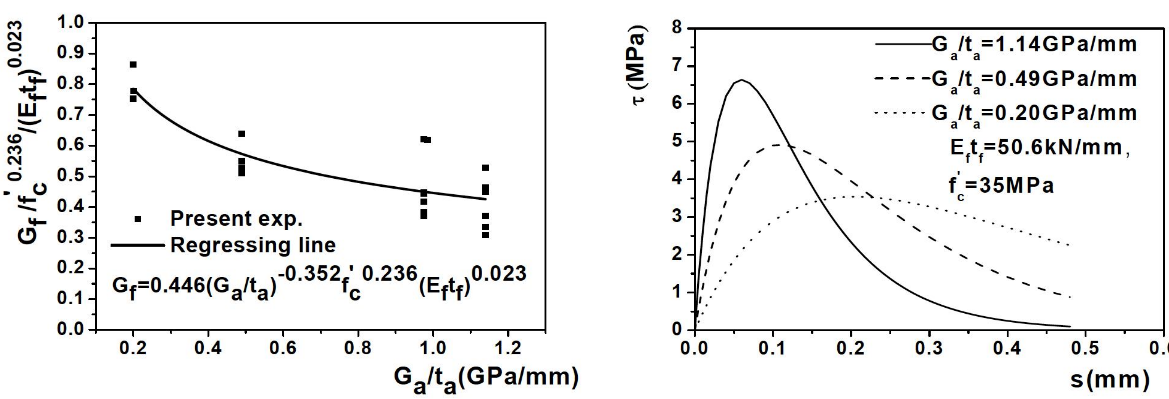



Figure 6. Failure modes in strengthened member




Bond strength – adhesion layer stiffness relationship

Bond stress – slip relationship

Figure 7. Effect of shear stiffness of adhesive resin on bonding property

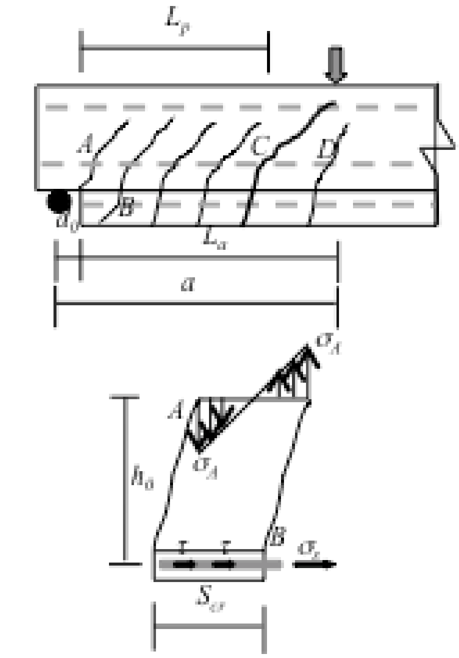



Figure 8. Tooth model for concrete cover separation

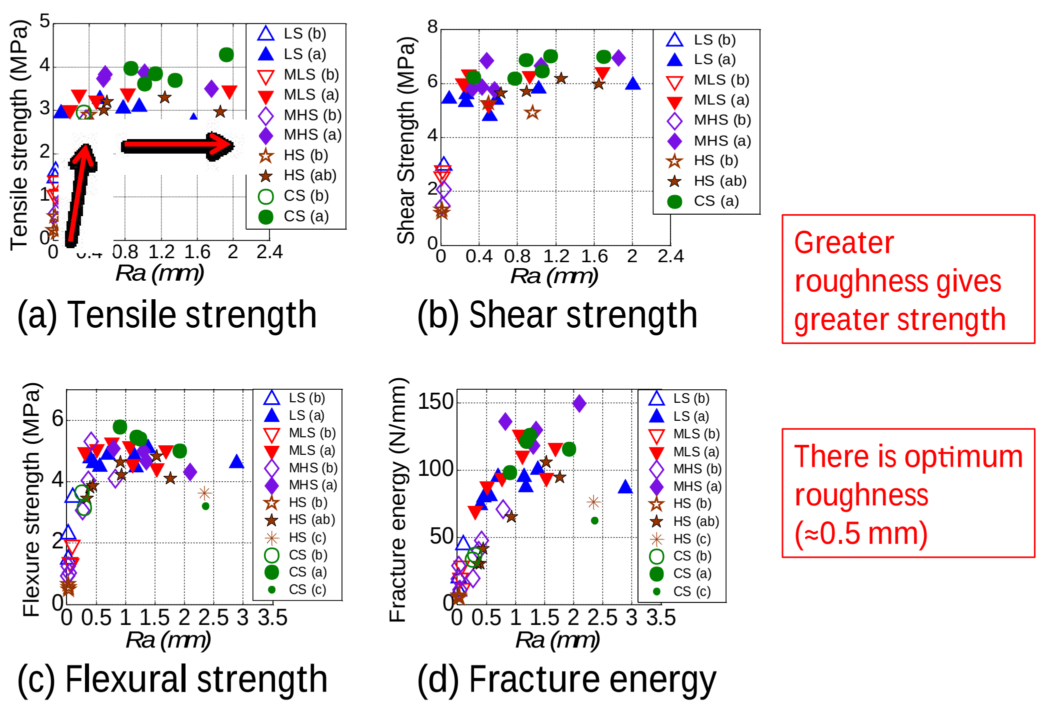



Figure 9. Effects of roughness on interface bonding properties

## 5 DEVELOPMENT OF EXECUTION METHOD

There are many cases in which external bonded layer or overlay is deteriorated, especially with deteriorated interface. This fact is partly because the execution of external bonding or overlaying was not conducted properly. Guidelines for proper pretreatment of substrate concrete surface and placement of strengthening material are needed. Since the effects of interface roughness have not been properly considered in design, the proper execution to create roughness has not been well developed yet.

## 6 PREDICTION OF SERVICE LIFE AFTER BEING STRENGTHENED

Another reason for deterioration of strengthened parts is effects of environmental actions. The prediction of long-term performance of members after strengthening is important for LCM. The past studies show quite different results on moisture effects on debonding strength for FRP-concrete interface (Shrestha, et al. 2014). One of the reasons of the different results is the difference in interface roughness. The less rough the interface is, the greater reduction in the debonding strength is. PCM-concrete interface is weaker than PCM and concrete and sensitively affected by temperature since polymer in PCM is temperature-sensitive (see Figure 10) (Rashid, et al. 2015). The moisture condition does not change much the effects of temperature.

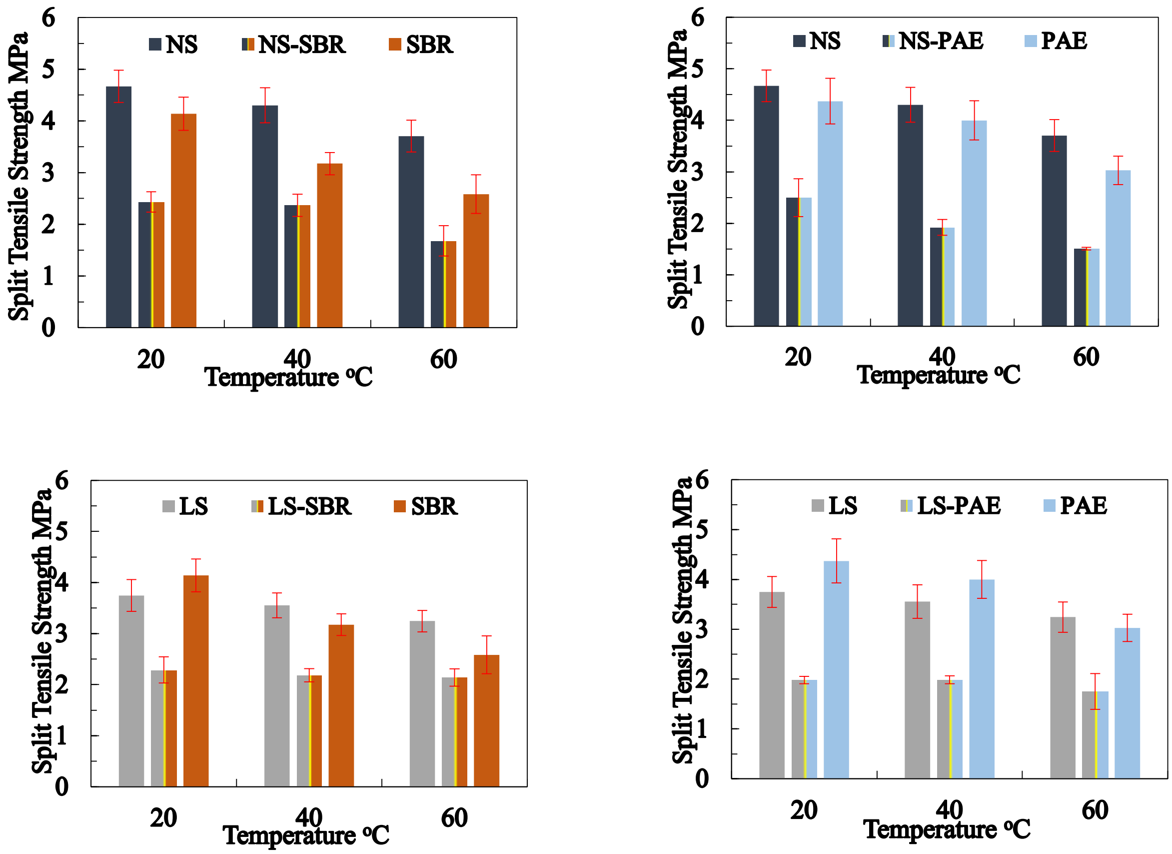



Figure 10. Effects of temperature on bonding properties at PCM-concrete interface

## 7 CONCLUDING REMARKS

Development of rational guidelines for strengthening, which covers design, construction and maintenance of strengthened structures, is necessary. International community, such as ISO TC71 and *fib*, and some countries such as Japan have been putting efforts towards this development. Standard and inexpensive method for strengthening is necessary, especially for developing countries.


## ACKNOWLEDGEMENTS

The author is grateful to all the students and colleagues who have taken and are taking a part of the series of studies on strengthening among the author's group. A part of this study was conducted with the financial support, the Grant-in-Aid for Scientific Research (A) of Japan Society of Promotion of Science (No. 26249064).


## REFERENCES


Anggawidjaja, D., Ueda, T., Dai, J.G. and Nakai, H. 2006. Deformation capacity of RC piers wrapped by new fiber-reinforced polymer with large fracture strain, *Cement & Concrete Composites*, 28: 914-927.

Chittagong University of Engineering and Technology (CUET), 2014. Book of Abstract, 2nd International Conference on Advances in Civil Engineering, 26-28 December 2014, Chittagong.
Dai, J.G., Ueda, T. and Sato, Y. 2005. Development of the nonlinear bond stress-slip model of fiber reinforced plastics sheet-concrete interfaces with a simple method, *Journal of Composites for Construction*, 9 (1): 52-62.
Hasnat, A., Islam, M.M. and Amin, A.F.M.S. 2015. Enhancing the debonding strain limit for CFRP-strengthened RC beams using U-clamps: Identification of design parameters, *Journal of Composites in Construction*, 20.
Islam, M.M., Choudhury, M.S.I. and Amin, A.F.M.S. 2015. Dilation effects in FRP-confined square concrete columns using stone, brick and recycled coarse aggregates, *Journal of Composites in Construction*, 20: 04015017-1-11.
ISO TC71/SC 7, 2014. *ISO 16311 Maintenance and repair of concrete structures*. Geneva: ISO.
Jirawattanasomkul, T., Zhang D., Ueda, T. 2013a. Prediction of the post-peak behavior of reinforced concrete columns with and without FRP-jacketing, Engineering Structures, 56: 1511-1526.
JSCE Working Group on Retrofit Design of Concrete Structures in Specification Committee (Coordinator: UEDA Tamon), 2000. Guidelines for retrofit of concrete structures -Draft-. *Concrete Library International*, JSCE, 36: 61-112.
Lunn, D.S., Maeda, S., Rizkalla, S. H. and Ueda, T. 2013. Anchorage systems for FRP strengthening of infill masonry structures, *Int. J. Sustainable Materials and Structural Systems*, 1 (2), 2013: 142-160.
Rahman, A. and Ueda, T. 2015. Seismic rehabilitation of masonry structure strengthening by two distinct FRPs, *Proceedings of IABSE-JSCE Joint Conference on Advances in Bridge Engineering-III*, 21-22 August 2015, Dhaka: 10 pages.
Rashid, K., Ueda, T., Zhang, D., Miyaguchi, K. and Nakai, H. 2015. Experimental and analytical investigation on the behavior of interface between concrete and polymer cement mortar under hygrothermal conditions, *Construction and Building Materials*, 29: 12 pages.
Shrestha, J., Ueda, T. and Zhang, D. 2014. Durability of FRP concrete bonds and its constituent properties under the influence of moisture conditions, *Materials in Civil Engineering*, 26: A4014009-1-14.
Takasaki, K., Jirawattansomkul, T.,, Zhang, D. and Ueda, T. 2014. Experimental study on shear behavior of RC beams jacketed by flax fiber sheet, *Proceedings of Japan Concrete Institute*, 36 (2): 1189-1194.
Zhang, D., Ueda, T. and Furuuchi, H. 2012. Concrete cover separation failure of overlay-strengthened reinforced concrete beams, *Construction and Building Materials*, 26: 735-745.
Zhang, D., Ueda, T. and Furuuchi, H. 2013. Fracture mechanisms of polymer cement mortar - concrete interfaces, *Journal of Engineering Mechanics*, 139 (2): 167-176.