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THESIS OUTLINE

TITLE: "BEHVIOR OF PRETENTIONED PC BEAMS STRENGTHENED IN FLEXURE AND SHEAR USING EXTERNALLY BONDED CFRP SHEETS"

Prestressed concrete (PC), which was invented in 1950s, with the advantages of high strength to weight ratio, high ductility and small section, has been used widely for infrastructures, especially, for long span girders. There was a huge number of bridges constructed by PC during the period of 1960s to 1990s in Japan and worldwide. Recently, the deterioration of PC girders has been reported and raised a concern in many countries. The causes of the deterioration of PC bridges include corrosion, aging, traffic overload, external impact, environmental condition or lack of maintenance. The deterioration of the PC girders leads to a severe reduction in the member strength and stiffness. In addition, as a result of the urbanization, many bridges have been required to increase the capacity due to the increase in transportation demands. In order to enhance the structural performance of the existing PC structures for the prolonged use and avoid an unfavorable failure, an effectively practical strengthening technique is required.

Carbon fiber reinforced polymer (CFRP) sheet is one of fiber matrix polymer materials, reinforced by carbon fiber. The CFRP sheet has the advantages of high tensile strength to weight ratio and excellent corrosion resistance, which gains strength by impregnating carbon fibers sheets with a polymer matrix composite material. The implement of this strengthening methods does not require a large space and heavy equipment. It can be carried out within a short time in comparison to the conventional strengthening methods. Furthermore, since carbon fibers are non-corrosion materials, the cost for future maintenance can be reduced. Owing to the advantages of the material and simple technique, the application of this strengthening method is expected to be highly efficient not only in improvement of the structural performance but also in economical effectiveness. Up to now, the externally bonded CFRP sheets has been used widely for strengthening existing RC structures. Nevertheless, due to the lack of experimental data on strengthening PC beams using this method, the behavior of PC beams, especially the damaged ones, strengthened by externally bonded CFRP sheets has not been well understood. Therefore, the adoption of the equations in the existing design guidelines has been found conservative.

In this regards, the main objective of this study is to investigate the behavior of damaged PC beams strengthened in flexure and shear using externally bonded CFRP sheets. Two experimental programs were carried out. The first experimental program aimed to investigate the behavior of the pretensioned PC beams having ruptured strands strengthened in flexure by CFRP sheets. The different parameters of CFRP sheet lengths, number of layers and presence of U-shaped anchorages or transverse wrapping sheets were studied. The second one examined the strengthening effects of various parameters (strip spacing, stiffness and thickness of sheets, prestressing levels in the strands) on the shear strength enhancement and shear resisting mechanism of pretensioned PC beams without shear reinforcement strengthened by CFRP sheets.

The thesis contains 7 chapters.

In **Chapter 1**, the general background of the requirement in strengthening PC beams and the proposed strengthening method using externally bonded CFRP sheets are introduced. Subsequently, the aims and methodology of the study are shortly described.

Chapter 2 provides the basic knowledge on the structural behaviors of PC beams in flexure and shear. The properties and the advantages of CFRP sheets are reviewed. Furthermore, the existing studies on strengthening PC beams using externally bonded CFRP sheets are summarized.

In **Chapter 3**, the experimental program of PC beams having ruptured strands strengthened in flexure by CFRP sheets are presented. The ruptures of strands were simulated by cutting prestressing strands at the middle of the span. When the strands are ruptured, the flexural capacity and stiffness of damaged beams decreased significantly. The damaged PC beams, then, were strengthened by externally bonded CFRP sheets. The experimental parameters included the length of CFRP sheets, number of layers, presence of U-shaped anchorages and wrapping sheets. The experimental results revealed that the flexural capacity and the stiffness of the PC beams having ruptured strands could be increased significantly by bonding CFRP sheets. The increase in the thickness of bonded sheets results in a reduction of the tensile stress resisted by the remaining prestressing strands.

Chapter 4 explains the various failure modes occurred in the PC beams having ruptured strands strengthened in flexure by CFRP sheets. The failure behaviors depend on the length and the total thickness of the bonded sheets. When the thickness of bonded sheets increases, the failure tends to change from debonding induced by flexural cracks to debonding from the sheet ends due to the stress concentration and loss of prestress at the sheet ends. Thus, the increase in the total thickness of the bonded sheets needs to be considered with a sufficient sheet length. The increase in the length of the longitudinal sheets or the presence of the wrapping sheets is able to enhance the stiffness of the strengthened beams due to the effect on restraining the opening of cracks along the span. In addition, the comparison between the calculation based on the equations in the recent guidelines of ACI and JSCE and the experimental results was performed.

Chapter 5 presents the details of the experiment of pretensioned PC beams without shear reinforcement strengthened in shear using the externally bonded CFRP sheets. The effects of CFRP ratio, thickness and stiffness of the sheets, wrapping type and effective prestress in the strands on the strength, stiffness of the strengthened PC beams are investigated. The higher effectiveness of strengthening can be obtained in the beams strengthened with higher amount of CFRP sheets or PC beams having higher effective prestress. However, the increase in the sheet thickness may not improve the shear capacity compared to the use of the thinner sheets. Furthermore, the insufficient anchorage bond length in case of U-shaped strips may lead to an abrupt failure by debonding of the sheets.

Based on the experimental results in Chapter 5, the shear resisting mechanisms and failure behaviors of the strengthened beams are presented in **Chapter 6**. The outcomes imply that the shear force in PC beams without shear reinforcement strengthened by externally bonded CFRP sheets is resisted by beam action, arch action and bonded CFRP sheets. The increase in the amount of CFRP and higher prestressing level in the strands maintain the performance of these actions. As a result, the higher effectiveness of strengthening can be obtained. Nevertheless, when the beams are over-reinforced, the increment of shear capacity is limited by either strength of concrete in compression or tensile strength of the bonded sheets. The sheet with high elastic modulus effectively restrains the diagonal crack, hence, remains the stiffness of the beam. Moreover, the predictions of the increment of shear capacity of the strengthened beams based on the recent design guidelines of ACI and JSCE showed highly inconsistent with the experimental results. It is apparent that the effect of prestressing and the inverse effect of sheet thickness have not been considered in the equations of the design guidelines.

Finally, the conclusions of the study are summarized and the recommendations for further research are given in **Chapter 7**.

This thesis provides a deep understanding on the behavior of damaged pretensioned PC beams strengthened in flexure and shear with the externally bonded CFRP sheets. Importantly, the resisting and failure mechanisms of the damaged PC beams strengthened by externally bonded CFRP sheets have been clarified. Nevertheless, further research on experiment and numerical analysis are necessary to develop rational design equations for predicting capacity of PC beams strengthened by externally bonded CFRP sheets.