学 位 論 文 内 容 の 要 旨

DISSERTATION ABSTRACT

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Ultimate Shear Behavior and Modeling of Reinforced Concrete Members Jacketed by Fiber Reinforced Polymer and Steel

(連続繊維もしくは鋼板巻立て補強鉄筋コンクリート部材の終局せん断挙動とモデル)

Many existing reinforced concrete (RC) members built using old design codes are susceptible to catastrophic collapse during a major earthquake due to their insufficient shear strength and member ductility. Use of fiber-reinforced polymer (FRP) composites as the external bonding/jacketing material of RC members to improve their shear strength and ductility has been a widely used because of the high strength-to-weight ratio and corrosion resistance of FRP composites. The most often used FRP composites include carbon-fiber reinforced polymer (CFRP) and aramid-fiber-reinforced polymer (AFRP) composites, termed conventional FRPs. In recent years, a new category of FRP composites, which are made of polyethylene naphthalate (PEN) and polyethylene terephthalate (PET) fibers, have emerged as an alternative to conventional FRPs as the strengthening materials of RC members. These FRPs have a much larger rupture strain (LRS) compared to conventional FRPs. Although their elastic modulus and strength are relatively low, they are much cheaper than conventional FRPs. It should be noted that the relatively low strength and modulus of LRS FRP can be compensated by the use of a greater amount of the fiber material, whereas the small rupture strain of conventional FRP cannot be compensated in this way. Up till now, it has remained unclear how to predict the shear strength of LRS FRP-strengthened RC members, which in turn influence their overall behaviors. Moreover, the efficiency of LRS FRP composites for the shear strengthening of RC members remains a concern because concrete degradation may occur before the full activation of the strain capacity of LRS FRP composites.

This research program aims to conduct an experimental study for the first time on the shear strength and deformation behavior of RC members strengthened with LRS FRP composites. Tests on ten RC beams strengthened in shear with fully wrapped PET FRP sheets have been conducted considering the following test parameters: the strengthening ratio, the longitudinal reinforcement ratio and the shear-span to effective-depth ratio. The increase in the amount of PET FRP sheets led to an increase of the shear strength and shear ductility, whereas a lower longitudinal reinforcement ratio and a smaller shear-span to effective-depth ratio corresponded to improved shear ductility. PET FRP sheets developed very high strains, namely the maximum strains of 1.4-6% at the peak shear loads and as high as 14.0% at the defined ultimate state (i.e., the load dropped by 20% compared to its peak load). Consequently, PET FRP can be used to enhance the shear strength of RC beams while substantially increasing the member ductility. In particular, PET FRP did not rupture at the peak load, and led to a ductile shear failure of the strengthened RC members. This failure mode also enabled us to clearly observe the behavior of shear strength degradation of concrete with increase in shear deformation even before the peak strength was developed. The shear contribution of concrete was found to degrade by 0-54.6% depending on the volumetric ratio of the FRP sheets, the shear-span to effective-depth ratio and the member depth.

Owing to the close relationships among the concrete shear deterioration, the member shear deformation and the strain levels in both FRP sheets and transverse steel reinforcement as observed in the current study, further research work was carried out to build up a comprehensive model to explain the above relationships.

The development of a comprehensive shear strength model is proposed to precisely predict not only the concrete shear deterioration but also the overall load-deformation responses of RC members. The proposed model, based on the work of Sato et al., is extended to account for the stiffness of both flexural and shear reinforcements, enabling us to connect interaction between flexural and shear strength behaviors. To address this interaction, a flexure-shear interaction (FSI) analytical method is presented and verified using existing experimental results, and demonstrate shear strength and ductility enhancement of RC columns confined with several alternative jacketing materials, including CFRP, AFRP, PEN, and PET FRPs. As part of the overall analytical process, in specimens failing in shear, the reduction in load-carrying capacity with increase in deformation can be considered as a reduction of the contribution of the shear strength behavior caused by the reduction in secant stiffness of both shear and flexural reinforcements and residual concrete strength. However, in specimens failing in flexure, the load-carrying capacity decreases due to concrete crushing along with the buckling of the compression reinforcement. The influence of the shear strength behavior on the flexural deformation is introduced through the tension shift phenomenon which increases the flexural deformation. Meanwhile, the flexural strength behavior affects the shear deformation through the yielding of flexural reinforcement, which decreases the shear strength of concrete and also increases the shear reinforcement strain, causing an increase of the shear deformation. The FSI analytical method can precisely predict the strain response of shear reinforcement, including the rupture of the FRP jackets. It is proven that FRP with high fracture strain (PEN and PET) is less likely to fracture than conventional fiber (AFRP and CFRP) at ultimate deformation.

The final goal of this research program is to extend the FSI analytical method to the cases of steel-jacketed RC members with different jacketing shapes (i.e., elliptical and rectangular shapes). Comparing FRP and steel jacketing, FRP jacket can resist the shear crack opening only in the fiber alignment whereas steel jacket can resist the opening in both vertical and lateral, leading to different in the concrete shear strength and its degradation. Namely, concrete shear strength in steel jacketing is larger than that in FRP jacketing since shear crack opening restrained by a steel jacket causes the aggregate interlock of concrete, which results in it contributing to the shear resistance. In the FSI analytical method, the concrete contribution to the shear strength is therefore significantly affected by the steel jacket, and its contribution to shear strength is considered equivalent to that in a continuous steel shear reinforcement. Considering confinement shape, elliptical steel jackets provides better enhancement of the flexural performance of inadequately confined columns than that of rectangular jacket. Using these concepts, the FSI analytical method can successfully predict the load-deformation envelope responses of RC columns with steel-jacketing. It can be concluded that the FSI analytical method is expeditious and efficient for use in predicting structural response of RC members with and without various types of seismic jacketing, while maintaining a high degree of accuracy.