Study on Shear Strengthening of RC Structures by Bonding Ultra High Strength Fiber Reinforced Concrete Panels

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論文内容の要旨

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論文題目（外国語の場合は，その和訳を併記すること。）

Study on Shear Strengthening of RC Structures by Bonding Ultra High Strength Fiber Reinforced Concrete Panels

(超高強度繊維補強コンクリートパネル接着による鉄筋コンクリート構造物のせん断補強に関する研究)

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Concrete as one of the most important construction materials was studied for centuries. Especially since Reinforced Concrete (RC) was patented by Joseph Monier in 1849, the development of concrete material has stepped into a new age. With the countries' tremendous economic growth and rapid development, a large amount of RC bridges have started to be built since 1960s. As time went on, those RC bridges have been aging or deteriorated, which leads to an increase of the accident risks. Now, how to deal with these aging or deteriorated RC bridges becomes a very urgent issue.

Today there exist a large number of aging RC bridges which have become huge potential safety hazards. Due to the poor design and/or construction, some of the aging RC bridges even do not meet the safety requirements, like the shear capacity. Here, a new shear strengthening technique, bonding the Ultra High Strength Fiber Reinforced Concrete (UFC) panels on the girder end of aging RC bridges, was proposed. This technique has many attractive characteristics, such as outstanding durability, workability, efficiency and reliability. The principle of the proposed shear strengthening method is to retard the opening and propagation of cracks around the ends of the RC beams by bonding UFC panels.

There exist amounts of causes to rise the loss of structural performance for RC structures, such as physical damage and chemical deterioration (due to carbonatation, chlorides, sulfates and distilled water). The strengthening effectiveness of bonding UFC panels on the RC structures with concrete degradation problem, such as the initial defect (low concrete strength), chloride attack (patch repair) and Alkali-Silica Reaction (ASR) damage will be discussed in this study.

Initial defect (low concrete strength)

In Chapter 2, a new shear strengthening technique, bonding the UFC panels on the girder end of aging RC bridges, was proposed. Two groups of specimens, Group 1 and Group 2, were used to evaluate the effects of the shear strengthening of UFC panels under different shear-span ratios (a/d = 2.5, 1.5). As there were many RC bridges reinforced with round rebars in 1960s, round rebars in tension were used and the influence of rebar type was investigated in this study. In addition, the aim of this experiment is to evaluate the shear strengthening performance for aging or damaged RC bridges. For this objective, RC beams were designed to break down in shear failure and few shear reinforcement stirrups were set. In Group 1 (a/d = 2.5), one control beam and five strengthened beams were included, and two strengthened schemes (B type and DB type) were designed. Experimental investigations were implemented in terms of the upgrading of shear capacity and the failure mode. In Group 2 (a/d = 1.5), two control beams and two strengthened beams were included, and the strengthening effect with low shear span ratio was explored.

The results showed that, when the shear-span ratio (a/d) is equal to 2.5, the shear capacity of RC beams was enhanced and the failure mode was ameliorated by bonding the UFC panels. Especially when the DB type strengthening (bonding RC beams with round tensile rebars) was applied, the improvement of the structural performance of RC beams was confirmed. Moreover, comparing different types of tensile rebars, the results showed a greater strengthening effectiveness and significant ductility were obtained in the beam with round tensile rebars. It is considered that a good performance can be expected when the DB type strengthening scheme is applied in the practical applications. When strengthening the RC beams with low shear span ratio, an un-predictable failure mode (anchorage splitting failure) was observed. Thus, an anchorage reinforcement method was proposed to extend the bonding region of UFC panel to the anchorage section. Based on the loading test results, the improvement on the shear strength (40%) and the destruction energy absorption were demonstrated, when the anchorage reinforcement method was applied. From the comparisons between the different shear-span ratios, it is inferred that the strengthening effect varies with the shear span ratios. It demonstrated that greater strengthening effects can be gained in RC beams with low shear span ratio.

Low shear-span ratio

In Chapter 3, to investigate the influence of UFC panel strengthening on the shear resisting mechanism and rebar bond-slip properties of RC beams with low shear-span ratio, experiments were conducted. To better understand the influence of UFC panel strengthening on the shear resisting mechanism in RC beams, the numerical analyses were also conducted. When analyzing the shear resisting mechanism of the strengthened RC beams, it is essential to investigate the material properties of UFC and the influence of UFC panel on the rebar bond-slip properties. So far, there are lots of investigations on the evaluation of the material properties of UFC. However, the influence of UFC panel on the rebar bond-slip properties has not been studied by now. According to the previous research results, the rebar bond-slip model affects the accuracy of analytical results. Thus, in the investigations in this study, the rebar bond-slip properties was studied by conducting the rebar bond-slip tests. Furthermore, two types of rebar bond-slip models were compared through numerical analyses.

The results showed that, by using the proposed shear strengthening method (bonding the UFC panels), a very positive effect on the load bearing capacity was obtained. Comparing to Group 1 (concrete strength is 18.5 MPa), a higher increase of the ultimate load (56%) and the initial stiffness (24%) were gained in Group 2 (concrete strength is 13.4 MPa) because of the lower concrete strength. And the brittle failure mode (shear failure) was also changed to the ductile mode (UFC

panels blocking) in Group 2. Furthermore, from the experimental results, the shear capacity shared by UFC panels does not rely on the concrete matrix configuration, which can be evaluated separately from the matrix. The evaluation result shows the shear capacity shared by UFC panels can be estimated within an acceptable error range. Furthermore, more effort is still needed to verify and improve the design method of UFC panel strengthening on more specimens. According to the bond-slip testing results, it was found that the proposed UFC panel strengthening method affects the bond-slip properties of rebars. The maximum bond stress and softening behavior were both enhanced in case of small cover. Moreover, from the comparison of experimental and analytical results, the validity of the modified bond model (modified according to the bond-slip tests) was verified. The original model underestimated the stiffness, while the modified model well captured the shear resisting behavior in the experimental results.

Chloride attack (patch repair)

In Chapter 4, the patch repair which is widely used to locally replace the deteriorated concrete and corroded reinforcement bars, and to rehabilitate the pervious functions of repairing objects was considered. The patch repair method was carried out on the RC beams to study its effects on the shear resisting mechanism. The strengthening effectiveness of bonding UFC panels on the patch repaired RC beams is evaluated. And the factors of shear-span ratio, patch repair and the strengthening of UFC panels are also discussed in this chapter. RC beams were designed to break down in shear failure and few shear reinforcement stirrups were set. Two groups of specimens, Group 1 and Group 2 (with different shear-span ratio), were used to evaluate the effects of the shear strengthening of UFC panels under different shear-span ratios (a/d = 2.5, 1.5).

The results showed that, when a/d was equal to 2.5, the load bearing capacity and stiffness were enhanced by applying the patch repair. The concrete splitting around tensile rebars was delayed due to the relatively good bonding of PCM and rebars. However, the beam broke down in the interfacial debonding, which showed the integrality between the matrix concrete and PCM was hard to be secured. When repairing the RC beams with low shear-span ratio (a/d = 1.5) using PCM, an un-predictable brittle failure occurred. Besides, the decrease in load bearing capacity was observed. The side effect of applying patch repair on the structural performance should be paid attention especially for the RC beams with low a/d. Due to the strengthening effect of bonding UFC panels, the shear capacity and stiffness of RC beams were enhanced and the failure mode was ameliorated. Especially the problems such as the interfacial debonding, the decrease in shear capacity and the brittle failure observed in the repaired RC beams were all restricted. It can be said that the integrality and safety of repaired RC beams can be secured by bonding UFC panels.

Alkali-Silica Reaction (ASR) damage

In Chapter 5, it presented how to evaluate the degradation states of RC members which were deteriorated by Alkali Silica Reaction (ASR) for 1 year and 3 years exposure tests, and investigated the influence of the strengthening measures on the load-bearing capacity and failure mode. Two series of RC beams were cast to simulate the bridge girder (Series A) and T-shaped RC pier beam (Series B), respectively. The non-destructive inspections, loading tests, and strengthening evaluations were conducted to evaluate the influence of the ASR damage and the strengthening effects on the degradation states and load-bearing mechanism. In addition, to represent the experimental results, different analytical models were investigated in the numerical analyses.

The experimental results showed that the rebar restraint ratio and the exposure condition affected the degradation state in RC structures with ASR damage, which leaded to the different failures in loading tests. Due to the influence of preceding cracks and pre-stress, the load bearing mechanism changed from the diagonal tensile resisting mechanism to the arch mechanism, and the bearing capacity was enhanced consequently. In addition, even though some specimens were cast and exposed in the same conditions, different maximum load and stiffness were obtained in the loading tests. The uncertainty and complexity of ASR damage were confirmed. Comparing the experimental and FE analytical results, the validity of analysis method proposed for ASR was verified. For ASR affected specimen, the no expansion model significantly underestimated the stiffness and load-bearing capacity. Conversely, the chemical pre-stress model showed a good agreement with the experimental results, in which the chemical pre-stress due to ASR was considered. Based on the different failure modes in Series A and Series B, different strengthening schemes were proposed to restrain the diagonal cracks or bond-split cracks. Using the proposed shear strengthening method (bonding the UFC panels) leaded to a very positive effect on the load bearing capacity in both Series A and Series B. Furthermore, the brittle failure mode was also changed to the ductile mode.

Practical Study

In Chapter 6, the practical study on shear strengthening of RC beams using UFC panels was conducted. By far, to evaluate the influence of concrete strength, tensile rebar type, shear-span

ratio and patching repair on the strengthening effects and the shear resisting mechanism, the experimental investigations of the UFC panels strengthening on RC beams with 1/4 scale depth of real bridge girder were conducted in previous chapters. However, whether the similar shear strengthening effects can be gained on the existing bridge girder, becomes an important problem. To realize the practical application, the influence of the factors in terms of size effect and UFC panel thickness has to be evaluated. In this chapter, the experimental investigations were conducted to evaluate the strengthening performance of bonding UFC panels on the large specimens and to evaluate the influence of the factors in terms of size effect and UFC panel thickness. JSCE recommendation equation was verified to evaluate the shear carried by UFC panels.

The results showed that, the investigation of the size effect influence in the strengthening method is an important step in the practical applications. In this chapter, the strengthening effects on two different sizes beams were discussed. Comparing the 1/2 size and 1/4 size beams, similar strengthening improvements on shear capacity and ductility were obtained in the experimental results. But for the stiffness, the upgrading effect was only observed in the 1/2 size beams. Moreover, the experimental results proved that the shear strengthening effects by bonding UFC panels could be expected in the real size bridge girder. The JSCE recommendation equation was used to evaluate the shear force carried by UFC panels. The evaluation results showed a good agreement with the experimental results. Based on the splitting tensile strength of UFC, the shear carried by UFC panels can be estimated within an acceptable error. This evaluation means of shear capacity of UFC panles can be expected to guide the design of the UFC panel strengthening. Moreover, adding a safety coefficient would be a practical means to involve the influence from the changes of the failure mode and shear resisting mechanism.

（別紙１）　　　　　　　　　論文審査の結果の要旨

氏名	王　健		
論文題目	Study on Shear Strengthening of RC Structures by Bonding Ultra High Strength Fiber Reinforced Concrete Panels (超高強度繊維補強コンクリートパネル接着による鉄筋コンクリート構造物のせん断補強に関する研究)		
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要　　旨

近年，多くの既設コンクリート構造物で様々な要因による劣化が発生しており，老朽化対策が喫緊の課題となっている．既往研究により，初期欠陥を有する鉄筋コンクリート（以下，RC）橋では，せん断破壊に対する安全性が低い場合も多くあることが分かっている．また，劣化したRC構造物の鉄筋が腐食した場合，鉄筋の力学的性能や付着性能が低下し，脆性的なせん断破壊が先行したり，付着破壊や定着破壊などの本来望ましくない破壊形態が発生する可能性があり，せん断破壊に対する合理的な補修・補強工法に関して検討することが必要である．このような背景の下，本論文は，超高強度繊維補強コンクリート（以下，UFC)パネル接着によるせん断補強に着目し，その補強のメカニズムと効果を明らかにするとともに，実用化のための検討を行うことにより，従来補強工法の欠点を補う新しいせん断補強工法の確立を目指したものである． 本論文の第１章から第７章までの概要は以下のとおりである．

第１章「Introduction（緒論）」：本章では，既設RC橋の劣化，初期欠陥，それに伴うせん断耐荷力不足の現状を述べた上で，本研究の目的を示している．また，UFC などの高性能コンクリート材料に関する従来の研究を概観し，本研究の位置づけを明確にしている．

第２章「Basic Investigations on Shear Strengthening Effects of Bonding UFC Panels on RC Beams with Low Concrete Strength（低強度RCはり部材に対するUFCパネル接着によるせん断補強についての基礎的検討）」：本章では，既往の工法の欠点を補う新しいせん断補強工法の確立するため，鉄筋種類（丸鋼，異形鋼棒），UFCパネル接着位置，せん断スパン比（1.5, 2.5），曲げ補強（CFRPシート接着）との併用といった要因を考慮し，UFCパネル接着によるせん断補強の基本特性と効果の評価を行った．

第３章「Investigations on Strengthening by Bonding UFC Panels on RC Beams with Low Shear-Span Ratio（低せん断スパン比を有するRCはり部材に対するUFCパネル接着せん断補強についての検討）」：本章においては過積載車両などによりRCはり部材端部に大きなせん断力が作用する場合や，低せん断スパン比の実構造部材を模擬するため，比較的低せん断スパン比（1.5）を有するRCはり部材を対象としてUFCパネル補強を行い，せん断耐荷機構に及ぼす影響について評価を行った．また，種々の実験からRCはり部材のせん断破壊形式は，鉄筋とコンクリートの付着性状により大きく変化することが明らかとなっている．そこで，鉄筋付着試験供試体を作製し，UFCパネル接着が鉄筋付着特性に及ぼす影響を評価した．さらに，これらの検討結果を考慮した弾塑性３次元FEM解析手法を検討し，実験結果との比較によりその妥当性を検証するとともに，各種要因によるUFCパネル補強効果への影響について評価した．

氏名	王　健

第４章「Investigations on Strengthening by UFC Panels and Patch Repair on RC Beams Affected by Chloride Attack（塩害劣化したRCはり部材の断面修復およびUFCパネル接着せん断補強に関する検討）」：塩害により鉄筋が腐食すると，RC構造物の安全性能，使用性能，第三者影響度などに顕著な悪影響を及ぼすことになる．このような塩害劣化を受けたRC構造物に対してせん断補強を行う場合には，まず，断面修復により塩害に対する処置を講じることになる．よって，UFCパネル接着によるせん断補強を適用するためには，断面修復を施したRCはり部材に対するUFCパネルの補強効果についての検討を行う必要がある．そこで，本章では，断面修復された実構造物を模擬したRCはり部材を作製し，断面修復部材に対するUFCパネルの補強効果の検討を行った．UFCパネル接着およびポリマーセメントモルタル（以下，PCM）断面修復が低強度RCはり部材の破壊形式およびせん断耐荷機構に及ぼす影響の評価を目的として，せん断スパン比（1.5, 2.5）の二つのシリーズの低強度RCはり部材に対してPCM断面修復とUFCパネル接着補強を行い，基本特性と補強効果を評価した．

第５章「Investigations on Shear Behavior and Strengthening by UFC Panels on RC beams affected by Alkali-Silica Reaction（ASR劣化したRCはり部材に対するUFCパネル接着せん断補強に関する研究）」：アルカリシリカ反応（以下，ASR）が生じたRC構造物に対する補強の検討が行われた事例がきわめて少なく，データ数が不足している．ASRの劣化機構は極めて複雑であり，現在のFEM解析手法で正確に追随することは困難であり，適切な解析方法が必要であると認識されている．そこで，本章では，ASR反応性骨材を用いて同条件で作製し，屋外暴露環境で劣化の促進を行ったASR劣化RCはり供試体の劣化状態を評価するとともに弾塑性FEM解析手法について検討し，提案した．さらにASRが生じたRCはり部材に対して，UFC接着せん断補強を行い，その基本特性と補強効果について評価した．

第６章「Size Effect on Shear Strengthening of RC Beams by Bonding UFC Panels for Practical Study（RCはり部材のUFCパネル接着せん断補強の実用化のための寸法効果）」：前章までにおいて，UFCパネル接着方法や鉄筋の種類など様々な条件の下でUFCパネルの補強効果を検討した．しかし，UFCパネル接着せん断補強の実用化に向けては，前章までの小型供試体のみならず実橋梁における検討が必要となる．本章では，UFCパネル接着による新たなせん断補強工法の実用化に向け，せん断スパン比1.5に設定した普通強度RCはり部材において実験的な検討を行った．さらに，実橋梁への展開を考慮した比較的大型RCはり供試体におけるUFCパネルのせん断補強効果について検討し，大型供試体においても小型供試体と同等の補強効果が得られることを確認した．また，土木学会指針式を用いてUFCパネルによる耐荷力補強の算定手法を検討し，UFCパネルがせん断抵抗に十分寄与した場合，実験値と計算値の差は小さく，妥当性のある算定結果となり，UFCパネル実用化にあたって耐荷力計算の有効性を示すことを確認した．

第７章「Conclusions（結論）」：以上の検討結果を総括し，本研究で得られた結論を示している．

以上，本論文は，初期欠陥や劣化を有するRC構造物に対する新しいせん断補強手法としてUFCパネル接着による補強に着目し，その基本特性や補強効果を明らかにするとともに，供試体寸法の影響や補強設計耐荷力算定手法を提示して実用化に関する知見をまとめたものであり，価値ある集積である．提出された論文は工学研究科学位論文評価基準を満たしており，学位申請者の王健は，博士（工学）の学位を得る資格があると認める．