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論文の内容の要旨

Prestressed concrete (PC) structures can generally be categorized into the three classes according to cracking criteria defined by ACI-ACSE Committee 423 (1999). The first class is defined as fully prestressed concrete members since no tensile stresses are permitted in the concrete under full service loading. Fully prestressed concrete girders have widely been used in bridge spans exceeding about 60 m. However, one of the drawbacks of using fully prestressed concrete beams is that the high-strength materials required for prestressing are relatively expensive. In the second class of PC members, an allowable level of tensile stress is permitted in the concrete under full service loading, while cracks are not permitted. The third class is partially prestressed concrete (PPC). PPC is made by introducing a low amount of non-prestressed steel into a fully prestressed concrete member. On the other hand, if a certain amount of prestressing force is introduced into reinforced concrete (RC), it results in an alternative member called prestressed reinforced concrete (PRC). In Japan, PRC beams have widely been used in bridge spans with lengths ranging from around 40 m to 60 m for the reason of economical point of view.

In PRC, cracks are permitted within allowable limits of crack width under full service loading. PRC members incorporate non-prestressed reinforcements as well as prestressed steels, and both contribute to member resistance. PRC members demonstrate that there are solutions intermediate between fully prestressed concrete and ordinary reinforced concrete and it offers numerous advantages. The small amount of prestressing steel used to provide this crack control is insufficient to ensure the required strength, so additional non-prestressed reinforcement is used. PRC members results in more economical design with smaller cross sections and a reduced amount of prestressing steel. The non-prestressed reinforcement used in PRC members enhances strength and also controls the formation of cracks and reduce crack width.

The cracking behavior of RC beams and PRC beams has been investigated in many studies over the last five decades. Most of these studies have focused on flexural cracking behavior, while very few have been concerned with shear cracking. Most existing design methodologies evaluate the flexural crack width in RC and PRC members, whereas there is a little mention of shear crack width in RC members. Indeed, there is no existing design methodology for evaluating shear crack width in PRC members. The equations stipulated in the ACI (2002), CEB-FIP Model Code (1978) and Japan Society of Civil Engineers (JSCE, 2002) codes provide very accurate determinations of flexural crack width in RC and PRC members. However, there are no specific prescribed design guidelines for evaluating shear crack width in PRC members. Further, there has yet been no clarification of the parameters that influence shear crack width in PRC members. As such, there is a need of an extensive experimental and analytical investigation on shear cracking behavior of prestressed reinforced concrete members.

In this research an attempt is made to investigate the shear cracking behavior of RC and PRC beams. The objectives of this research are; (a) to investigate the parameters affecting shear crack width of reinforced concrete and prestressed reinforced concrete beams subjected to four point symmetric-monotonic loading condition, (b) to develop an analytical methodology based on three dimensional finite element method and numerical programming that can accurately simulate the shear cracking behavior of reinforced concrete and prestressed reinforced concrete members and so that the more detailed behaviors hardly observable in the experiment can be inspected, (c) to propose a shear crack spacing model for reinforced concrete and prestressed reinforced concrete beams based on the Modified Compression Field Theory (MCFT) and crack spacing expression defined in CEB-FIP Model Code, and (d) to propose a rational and simplified design methodology to calculate shear crack width in reinforced concrete and prestressed reinforced concrete beams.

An experimental investigation was carried out on five I-shaped reinforced concrete beams and six I-shaped prestressed beams. This experimental study was focused on influence of prestressing force, stirrup ratio, side concrete cover, bond characteristics of stirrup, amount of longitudinal reinforcement and compressive strength of concrete on shear cracking behavior of RC and PRC beams. Experimental results showed that the prestressing force decreased shear crack width in PRC beams. Moreover, stirrup ratio and amount of longitudinal reinforcement showed insignificant effect on shear crack width in PRC specimens with higher prestressing force.

The high strength concrete specimens showed higher shear cracking load in RC and PRC specimens compared to normal strength concrete specimens. In addition, higher bond stiffness between steel and concrete was found in high strength concrete specimens compared to normal strength specimens. Due to the improved bonding, there was smaller shear crack width in high strength concrete PRC specimen compared to that in normal strength PRC specimen. A nonlinear numerical modeling was performed to simulate the shear cracking behavior of RC and PRC beams based on Modified Compression Field Theory (MCFT) and based on three dimensional finite element modeling. Using this analytical methodology, an extensive parametric evaluation was carried out to study the influence of various parameters on the shear crack width of RC and PRC beams. The comparison of the results obtained by the rigorous analytical methodology with the experimental observations showed that there is very good agreement of the load-displacement characteristics and the variation of steel strains. As such, it is concluded that by using this analytical methodology, the shear cracking behavior of reinforced concrete and prestressed reinforced concrete beams can be simulated with reasonable accuracy.

A rational model was proposed to calculate diagonal crack spacing in RC and PRC beams. In this model, crack control characteristics of both the longitudinal reinforcements and transverse reinforcements were incorporated by introducing two orthogonal (horizontal and vertical) crack spacing expressions. In addition, presence of prestressing tendon in PRC specimens was incorporated into the vertical crack spacing expression. These two crack spacing expressions were used to calculate diagonal crack spacing. The calculated crack spacing values showed good correlation with experimentally measured crack spacing values in RC and PRC specimens.

A rational simplified design methodology to calculate shear crack width in RC and PRC beams was proposed. From the experiment results it was revealed that the relationship between the shear crack width and the stirrup strain was linear relationship. As such, it was assumed that the shear crack width is equal to a product of shear crack spacing and the stirrup strain. The proposed shear crack spacing model was included into the proposed design equation which predicts shear crack width. A comparison of calculated values with experimental data shows that the proposed design methodology predicts shear crack width in RC and PRC beams with better accuracy, than the accuracy of the existing equations.

論文の審査結果の要旨

当論文の審査委員会は，平成 20 年 2 月 4 日に論文発表会を公開で開催した。その発表を含む論文審査結果を以下に要約する。

近年，コンクリート橋梁の中で，スパンが 40 ～ 50m のものでは，プレストレストコンクリート（PC）と鉄筋コンクリート（RC）の両方の特性を兼ね備えたプレストレスト鉄筋コンクリート（PRC）が経済性に優れており，我が国において建設されている。PRC は供用時において，ひび割れを許容するため，設計時においてひび割れ幅を数値的に求めておく必要がある。ひび割れには一般に，曲げひび割れとせん断ひび割れがあるが，曲げひび割れについては，ほぼ明らかにされており，既往の設計法で概ね計算できることが明らかにされている。一方，せん断ひび割れについては，PRC はもちろん，RC についても明らかにされておらず，設計法も十分に確立されていない。本研究は，PRC はりのせん断ひび割れに着目して，実験および解析的に明らかにするとともに，新しい設計法を開発したものである。本論文の概要と成果を示すと以下のようである。

第 1 章は，本研究の動機，背景，既往の研究，目的などが述べられている。

第 2 章は，RC および PRC はりの載荷実験とその結果について述べている。すなわち，11 体の I 型 RC および PRC はりを，スターラップの間隔，プレストレス量，コンクリート強度を変化させて製作して静的一方向載荷を行い，せん断ひび割れのメカニズムを実験的に明らかにしている。その結果，1) プレストレスの増加に伴い，せん断ひび割れ幅が小さくなるとともに，せん断ひび割れ荷重が増大すること，2) PC 鋼材の存在がせん断耐力を増大させること，3) せん断補強筋のひずみとせん断ひび割れ幅と大きな相関があること，4) 高強度コンクリートを用いた場合には，最大せん断ひび割れ幅が大きくなるとともにひび割れ幅のばらつきが大きくなることが明らかとなった。第 3 章では，上記実験結果を解析的に検討したものである。解析には，修正圧縮場理論を用いた RESPONSE-2000 および 3 次元有限要素解析法が用いられた。ここでは, 材料モデル, 解析モデルの詳細が述べられている。第 4 章では, 解析と実験結果の比較が述べられている。その結果，1) 修正圧縮場理論を用いた RESPONSE-2000 により，RC から PRC に至るせん断ひび割れ挙動を概ね解析的に表現できること，2) 一方，3 次元有限要素法では，最大耐力を 3 割程度過大評価すること，その理由として，コンクリートと鉄筋において完全付着を仮定していることが主な原因であることを述べている。第 5 章では，これまで行った実験及び解析結果からせん断ひび割れ幅の定式化を行った。すなわち，*fib* で提案されている考え方に修正を加え，独自のアイデアによってせん断ひび割れ幅を求める手法を提案している。本手法の提案が本研究の中で最も重要でかつオリジナルな部分でもある。すなわち，水平方向と垂直方向のひび割れ幅を各種要因を用いて求め，せん断ひび割れ幅を最終的に求めている。本手法により求めたせん断ひび割れ幅と実験値と比較した結果，他のどの式よりも精度よく求められることが明らかとなった。第 6 章は本研究成果を取りまとめた結論が述べられている。

本研究は，PRC のせん断ひび割れのメカニズムを実験及び解析的に明らかにするとともに，さらに実設計上必要となるせん断ひび割れ幅を計算できる独創的な設計式を開発し，その精度が高いことを明らかにしている。コンクリート構造において，せん断の問題は現在でも不明な点が多く，実験に依存しているのが現状である。本研究では，最も複雑で難しいひび割れをとりあげ，研究成果をまとめたもので，コンクリート工学上大きな貢献をしており，研究成果は高く評価される。また，本研究成果は既に多くの学術論文集に掲載されている。

以上より，当審査委員会は本論文が博士の学位授与に十分値するものであると判断した。