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論文の内容の要旨

High-strength concrete (HSC) with a strength (f'_c) exceeding 80 MPa is being increasingly used in buildings and prestressed concrete bridges in Japan. This is because it enables the use of smaller cross-sections, longer spans, and reduced girder height while improving durability. According to JSCE (2002) and ACI (2005) design equations, the shear strength of reinforced concrete (RC) beams without web reinforcement increases as concrete strength increases. However, the shear capacity of reinforced high-strength concrete (RHSC) beams does not increase as expected with the concrete compressive strength. Further, increasing the compressive strength of concrete results in greater early-age shrinkage (autogenous shrinkage) due to self-desiccation, brittleness, and smoothness of crack fracture surfaces. These limitations have led to some concerns about the shear strength of RHSC beams.

For slender RC beams without web reinforcement, where shear span to depth ratio (*a/d*) is greater than 2.5, the shear force is carried by: 1) the shear resistance of uncracked concrete in the compression zone; 2) the interlocking action of aggregate along the rough concrete surfaces on each side of a crack; 3) the dowel action of the longitudinal reinforcement; and, 4) the residual tensile stresses across cracks. In rectangular beams, the proportions of the shear force carried by these mechanisms are approximately as follows: 20-40% is carried by the uncracked concrete of compression zone, 33-50% by aggregate interlocking, and 15-25% by dowel action. The residual tensile stresses across inclined cracks can also provide a significant percentage of shear resistance up to crack widths in the range of 0.05-0.15 mm although the percentage is unknown.

According to past studies, the shear resistance of uncracked concrete in the compression zone is lower with HSC as a result of its brittleness. The crack surface of HSC beams is relatively smoother than that of normal strength concrete (NSC) because cracks penetrate through the aggregate. The smooth crack surface reduces aggregate interlock and lowers the shear strength of RHSC beams. Until now, no research has attempted to quantitatively evaluate the roughness of concrete fracture surfaces. In addition, early-age shrinkage causes deterioration in shear strength at diagonal cracking of RHSC beams. It has been observed that cracking around reinforcing bars due to early-age shrinkage of HSC and such cracking degrades the bond stiffness. This means that the dowel action of the longitudinal reinforcement is affected by early-age shrinkage. Previous studies have also shown that the use of admixtures such as expansive additives and shrinkage-reducing agents is effective in reducing early age shrinkage. Although concrete is assumed to carry no tension at crack locations, it is still able to develop residual tensile stresses between the cracks through the transfer of bond forces from the reinforcement to the concrete. Tension stiffening arises from this ability of concrete to carry tension between cracks in an RC member which helps improve member shear strength and, therefore, satisfies serviceability requirements. To date, the relationship between concrete strength and tension stiffness of concrete has not been clarified. It has also been shown that an increase in the *a/d* ratio results in a reduction in shear strength. However, most studies have been carried out using concrete with a strength of less than 80 MPa due to design limitations.

Against this background, the objectives of this study are: 1) to quantitatively explain the effect of concrete compressive strength, brittleness, fracture surface roughness, aggregate strength, and a/d ratio on the shear behavior of RHSC beams where the concrete strength exceeds 100 MPa; 2) to experimentally evaluate the tension stiffness of axially loaded tension members of HSC; and, 3) to accurately predict the shear capacity of RHSC beams using a two-dimensional frame method(2D-Frame) and a two dimensional finite element method (2D-FEM) based on the modified compression field theory (MCFT) and a smeared crack model respectively.

In order to investigate the influence of concrete compressive strength, early-age shrinkage, brittleness, fracture surface roughness, aggregate strength, and *a/d* ratio on the shear behavior of RHSC beams, twelve beams without web reinforcement were fabricated for study. All beams were 200 mm wide and had an effective depth of 250 mm. The value of f'_c was varied from 38 to 194 MPa. The value of *a/d* was varied from 3.0 to 4.0.

The test beams were simply supported and loaded symmetrically with two equal concentrated loads. For the entire test program, the distance between the two point loads was kept constant at 300 mm. At each load increment, the vertical deflection and the strains at the top and bottom of the beams were measured. The interlocking action of aggregate along a crack can be described using post-failure evidence from the fracture surface. For the surface roughness test, fractured splitting-tensile-strength test specimens were tested as they were used to measure the tensile capacity of concrete. A laser-light confocal microscope was used to scan the fractured surface three dimensionally. Concrete shrinkage was measured immediately after placement. A strain gauge with a reference length of 100 mm was embedded at mid-height in the center of the 100 x 100 x 400 mm prisms. A fracture energy test of the concrete was carried out at almost the same age as when the beams were subjected to loading tests. To determine the aggregate strengths, uniaxial compressive strength (σ_c) and tensile strength (σ_t) tests of rock cylinders were measured. Cylinder specimens measuring 50 mm in diameter and 100 mm in height were prepared for uniaxial compressive strength tests and others measuring 50mm in diameter and 50 mm in height were prepared for tensile strength tests (measured using the Brazilian test).

Test results indicated that the ratio of uniaxial compressive strength to tensile strength (the ductility number) of the concrete relative to that of the aggregate governs the shear capacity of HSC. When the ductility number of concrete was lower than that of the aggregate, the shear strength increased with the increase of concrete strength due to rough fracture surface and increased tensile strength. When the ductility numbers of the concrete and aggregate were equal, shear strength stayed constant at the maximum value. However, when concrete had a higher ductility number than the aggregate, shear strength decreased due the smooth fracture surface and high brittleness of the concrete. However, in this study, the maximum coarse aggregate size was 19 mm and the rock type was crushed granite. Therefore, further studies on different aggregate sizes and rock types are essential.

The ductility number of the aggregate (crushed granite) used in this study ranged from 18 to 22. The ductility number of the NSC was between 11 and 13. Therefore, shear capacity increased by about 9-14% as concrete strength increased from 36 to 114 MPa. Concrete with a strength between 114 and 155 MPa had the same ductility number as the aggregate. Therefore, in this strength region, shear strength is not dependent on concrete strength. The ductility number of concrete with a strength over 155 MPa was more than 22. Hence, shear strength started to decrease due to the smooth fracture surface and high brittleness of the concrete. The change in the fracture surface roughness index of beams with a concrete strength between 155 and 183 MPa was minimal, while concrete strength 155 MPa was about 4% lower than the beam with concrete strength 114 MPa. At concrete strength 114 MPa fracture surface roughness index was about 14% lower than concrete strength 36 MPa. The present JSCE code and ACI equations for evaluating the shear strength of HSC beams need to be modified according to the suggestions made in this paper.

All of the tension stiffness test specimens had a length of 1200 mm. A single deformed steel bar, with a minimum concrete cover of 40 mm, was provided. Tension stiffening was evaluated for NSC (40 to 60 MPa) and HSC (100 to 150 MPa) using reinforcement ratios (ρ) of 1.99 and 2.252% respectively.

The relationship between concrete strength and tension stiffness of concrete has not yet been clarified. In fact, in numerical methods such as the MCFT, tension stiffness is not dependent on concrete strength. However, a previous numerical study found that the tension stiffness of HSC is lower than that of NSC. Other variables such as the percentage and distribution of reinforcing steel, bar size, bond properties, and shrinkage of concrete are also reported to have an effect on tension stiffening.

Specimens were loaded vertically through one-axial tension rods. Two linear variable displacement transducers (LVDT) were clamped to the steel reinforcing bar just outside of the concrete to measure the total elongation of the reinforced concrete specimen. At each loading stage, the cracks were measured using pi-gauges. The complete response of each specimen was described by plotting the applied tension against the average member strain.

It was observed that the tension stiffening effect was highly dependent on concrete strength when it is greater than 100 MPa. As the concrete strength increased from 40 MPa to 145 MPa, the tension stiffening effect became smaller for members with a c/d_b ratio of 2.5. The crack spacing between the adjacent transverse cracks narrowed as higher concrete strength was used. Furthermore, a reduction in crack spacing of 10-50% was observed when the compressive strength of concrete varied from 40 MPa to 145 MPa. Based on results, a more accurate tension stiffening prediction equation is suggested in the paper for the design of HSC members.

In this study, the analytical methodology is based on the MCFT and a smeared crack model. Experimental data are compared with these methods to assess their accuracy. The MCFT is capable of predicting the load-deflection behaviour of RC elements subjected to in-plane shear and normal stresses. In this model, cracked concrete is treated as a new material with its own stress-strain relationships formulated in terms of average stresses and average strains. In this analysis, the numerical method proposed by Bentz (2000) was used. The 2D-FEM used by Maekawa et al. (2003) was also used to predict shear behaviour of the beams. In 2D-FEM, a smeared crack model based on average stress-strain was used to model concrete after cracking. For post cracking behaviour, the compression and tension model proposed by Maekawa et al. (2003) was used.

According to this study, the surface roughness of NSC beams was about 16% and 20% greater than that of 100 and 176 MPa beams respectively. Therefore, during the analysis, a_g and α were reduced proportionately from a_g =19 mm and α = 1.0 to zero and 0.1 respectively as f'_c increased from 38 MPa to 176 MPa. Additionally, compressive peak strain was taken as 2.55 x 10^{-3}, 2.40 x 10^{-3} and 2.33 x 10^{-3} with NSC40, HSC80, and HSC160 respectively. In 2D-FEM, the tension stiffening behaviour was modelled as proposed in the paper. That is, near the centre of RHSC beams, the tension stiffening factor was taken to be 1.0, while for NSC beams it was 0.4.

The predicted results showed a good correlation with the experimental results. Furthermore, 2D-FEM was found to be able to predict not only the diagonal cracking shear strength but also the failure mode. The average ratio of tested to predicted diagonal cracking shear strength of RC beams using both 2D-Frame and 2D-FEM was 0.95 and 0.98, respectively. Both 2D-Frame and 2D-FEM can predict the effect of fracture surface on shear strength, but should be improved to include concrete brittleness.

論文の審査結果の要旨

当論文の審査委員会は、平成 23 年 7 月 29 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。

我が国における土木・建築分野において、高強度コンクリートの発展はめざましく、建築の分野では設計基準強度が 100N/mm^2 程度の高強度コンクリートの適用例が増えている。一方、橋梁などの土木分野においても、各方面での技術開発の成果により、近年実用化のレベルに達しており、実構造物への適用例が増えてきている。高強度コンクリートを橋梁等のＰＣ構造物に適用することにより、部材の軽量化、地震時の慣性力の低減、長スパン化、低桁高化および耐久性の向上などが可能となり、付加価値の高い構造物や経済的な構造物が実現でき、今後ますますニーズが高まっていくものと考えられる。しかし、高強度コンクリートを鉄筋コンクリート（RC）はりに用いた場合、せん断耐力は頭打ちとなり増加しないことが実験で確かめられているが、何故増加しないのかは解明されていない。本研究は高強度コンクリートを RC 部材に用いた場合のせん断性状を実験および解析により明らかにしたものである。

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、目的などが述べられている。

第２章は高強度コンクリートの材料組成から硬化したコンクリートの力学的特性を詳細に記述している。さらに、RC 部材のせん断性状、耐力について既往の研究、設計法をとりあげ、特に斜め引張せん断耐力に及ぼす要因を逐一とりあげ、詳細にレビューしている。

第３章は本論文の中核となるところで、高強度コンクリートを用いた供試体を製作して、時間経過による収縮量を測定し、実験的に明らかにした。また、引張試験（割裂試験）を実施し、破壊面の祖度をレーザーマイクロスコープによって測定し、roughness index を定義した。これを用いて、高強度コンクリートと普通強度コンクリートの破面を定量的に明らかにした。このような手法は初めてのものであり、きわめて独創的であるといえる。さらに、せん断補強筋を有しない RC はり 15 体製作して、４点載荷によりせん断試験を行った。実験要因は、コンクリート強度（40 － 160MPa）、収縮量の大小、粗骨材の種類、せん断スパン比（3.0 － 4.0）である。これらの試験より、破壊モード、せん断耐力を実験的に明らかにした。せん断耐力はコンクリート強度が増大しても大きくならないことが再度確認された。このような現象を ductility number により説明できることを明らかにした。また、高強度コンクリートを用いた場合、せん断ひび割れの破面は普通強度コンクリートを用いた場合と比較して､ひび割れが骨材を貫通することから滑らかになる。これにより、骨材のかみ合わせによるせん断力伝達効果が減少するため、せん断耐力が増加しないことを明らかにした。

第４章は高強度コンクリートを用いた部材の tension stiffening について実験を行い、ピーク以降の下降域の性状を明らかにし、解析に用いるためのモデル化を行った。

第５章はこれまでの実験結果に基づいて、高強度コンクリートの構成則、tension stiffening factor を独自にモデル化して、解析により高強度コンクリート RC 部材のせん断性状を解析的に明らかにした。解析手法は、圧縮場理論に基づく方法と、２次元有限要素解析による２種類の方法を用いている。この結果、高強度コンクリート部材のせん断性状を解析的に精度よく表すことが可能となった。さらに、高強度コンクリートを用いた RC はり部材のせん断耐力算定式を新たに提案した。提案式は既往のコード、あるいは他研究者のによって提案されたものより精度よいことが確かめられた。

第６章は結論が述べられている。

本論文は、これまでほとんど明らかにされていなかった、高強度コンクリート RC 部材のせん断性状を実

験および解析に解明したもので、破面の祖度を roughness index を定義し、これにより、破壊モードの解明を行った。また、せん断耐力については ductility number を定義して定量的解明を行った。これらはこれまで行われていない独創的な手法の提案であり、これらを駆使して難解な高強度コンクリート RC 部材のせん断性状を明らかにした。本研究の成果は土木・建築分野において大きな成果をもたらしたもので、その意義は極めて大きいと考えられる。本研究成果は既に多くの学術論文集（ACI Structural Journal、Proceedings of Japan Concrete Institute 等）に掲載予定あるいは掲載されている。

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