博 士(工 学) カーリッド モハメッド アハメッド ファラー

学 位 論 文 題 名

Analytical Investigation on Non-linear Behavior of RC Members Strengthened with Externally Bonded FRP

(FRP により接着補強された RC 部材の非線形挙動に関する解析的検討)

学位論文内容の要旨

Extending the service life of the existing reinforced concrete (RC) structures is one of the major tasks of the civil engineering. Strengthening or retrofitting is one of the remedial actions to perform this task. There exist many different ways of strengthening an existing concrete structure, A strengthen method that was used quite extensively during the mid 1970s is steel plate bonding, this method has gained renaissance the last decade, but now composite materials made of fibers in a polymeric resin, also known as fiber-reinforced polymers (FRPs), have emerged as an alternative to traditional materials for repair and rehabilitation.

Extensive research and laboratory testing on the externally bonded FRP systems has been carried out all over the world and at many different locations. As a result, the performance of FRP-strengthened members is now relatively well understood from the experimental point of view. It is obvious that much less attention has been paid to numerical studies of debonding in comparison to the wealth of experimental investigation. In the same time the use of externally bonded FRP materials to improve performance of RC elements in bending, shear, or confinement requires detailed modeling of the structural behavior of the strengthened elements. Therefore there is a demand for further study specially the numerical study on the behavior of RC elements strengthened with externally bonded FRP sheets and plates under various loading cases.

This study presents analytical investigations of the behavior of RC members strengthened with externally bonded FRP under uni-axial tension loading and flexural-shear loading.

In this study, a two dimensional non-linear numerical code was built to simulate the behavior of the strengthened members under uni-axial tension loading and flexural-shear loading. The developed code has continuum element for concrete based on the rigid body spring method (RBSM), since cracks initiate and propagate along boundaries between elements, mesh arrangements may affect fracture directions. To avoid formulation of cracks with un-arbitrary direction, fine and random shape element is introduced using a Voronoi diagram. Discrete beam element was introduced for the internal and external reinforcement materials plus special linkage element to model the interface behavior between the different reinforcement materials and concrete.

The non-linear constitutive laws for different materials with un-loading and re-loading paths were included, in addition to the appropriate non-linear bond stress-slip models for different interfaces. The bond deterioration for steel-concrete and FRP-concrete interfaces were considered by proposing and applying different bond deterioration models.

Using the developed code uni-axial tension behavior of RC members strengthened with externally

bonded Carbon FRP sheets (CFS) was investigated. Group of RC members strengthened with externally bonded FRP under tension loading were examined to validate the proposed analysis method. The rules of the bond deterioration models were examined and the validity of the proposed bond deterioration models was confirmed by comparing the numerical output with the relevant experimental data. The proposed model and method of analysis were able to predict the experimental observation with accepted accuracy in terms of both for overall and local behavior.

The influence of the amount of CFS strengthening on the axial deformability was examined. Small amount of the external reinforcement provides a significance reduction on the axial deformability in the cracked range as well as reduction in the average crack width and average crack spacing. The average steel bond stress decrease by attaching the CFS and increasing the CFS stiffness. While, the average CFS bond stress increase by increasing the CFS number of layers. The average steel stress increase by increasing the CFS stiffness and the apparent yield stress become much closer the yield strength of the bare bar. The influence of CFS on the tension stiffening is much complicated where by applying small amount of CFS the tension stiffening increase greater than the un-strengthened one , by increasing the CFS amount the tension stiffening start to decrease below the un-strengthened one.

Based on this analytical study, average stress and strain relationships, for concrete, steel bars and CFS, which are function of the internal and external reinforcement ratios in addition to the internal and external reinforcement modular ratios were proposed. The calculated results were compared with the relevant experimental outputs. These models appear to match the experimental results very well.

The last part of this study covers the behaviour of RC beams flexurally strengthened with externally bonded FRP. Analyses of twelve beam specimens consisting of un-strengthened and FRP sheet/plate strengthened reinforced concrete beams were carried out. In the analysis, the FRP sheet-concrete interface behavior was simulated by adopting the local bond stress-slip model and the proposed bond deterioration model to take into consideration the bond deterioration and stress concentration at the cracks. It was found that the developed code was able to predict the behavior of the CFS strengthened members in terms of ultimate load carrying capacity, failure mode, and distribution of the strain and bond stress for the internal and external reinforcement with accepted accuracy. In other hand, in case of FRP plate-concrete interface the interfacial bond strength needed to be modified by adopting appropriate interfacial bond strength by considering the effect the higher plate stiffness. Finally the debonding process and mechanism were examined based on the numerical investigation.

学位論文審査の要旨

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(FRPにより接着補強されたRC部材の非線形挙動に関する解析的検討)

既設コンクリート構造物の延命化は,土木工学における最重要課題のひとつである.そして補強は,既設構造物の延命化を図るための重要な手段のひとつである.これまでに,数多くの補強方法が開発されているが,その中にあって,1970年代半ばに広まった鋼板接着工法は,鉄筋コンクリート構造物の延命化に大きな役割を果たしてきた.その後,耐食性に優れるポリマー樹脂と繊維からなる複合材料,すなわちFRPによる接着工法が開発され,現在,その適用が増えつつある.

これまでに,FRPにより接着補強された鉄筋コンクリート部材(以下「FRP補強RC部材」)の構造性能に関する研究が世界中で精力的に行われて,FRP補強RC部材の基本的な性能が明らかにされてきた.しかし,FRPのはく離破壊機構は未だ解明されておらず,補強部材の耐力と破壊形式を精度良く予測することができない.実験的な検討のみではその機構の解明と予測は難しく,信頼性の高い数値解析手法の開発が望まれている.

本研究は,一軸引張力もしくは曲げモーメントとせん断力を受ける,FRP補強RC部材の非線形挙動を解析的に検討したものである.すなわち,剛体バネモデル解析法に基づく2次元非線形解析コードを開発し,解析コードによるFRP補強RC部材の耐力,剛性,変形,応力,はく離の進展に関する検討が行われている.解析コードの大きな特徴は,補強材(鉄筋およびFRP)がはり要素によりモデル化され,コンクリート要素とはり要素間に,精緻な付着構成モデルが導入されているところにある.

この論文では,まず始めに,一軸引張力を受けるFRPシート補強鉄筋コンクリート部材の解析が行われた.既往の実験結果との比較を通じて,解析コードに導入されたFRPシートおよび鉄筋の付着応力すべりモデルおよび付着劣化モデルの妥当性が示された.すなわち,本解析コードは,荷重変位曲線などの全体的な挙動とひび割れ近傍のひずみ分布などの局所的な挙動を精度良く予測できるとともに,実験的検討により指摘されていた,FRPシートで補強することによりひび割れ幅とひび割れ間隔が小さくなるという事実,FRPシートの補強量が増すと鉄筋の平均付着応力が減少するという事実,鉄筋の平均応力と平均ひずみ関係における降伏強度がFRPシートの補強量が増すほど裸鉄筋の降伏強度に近づくという事実,そして,コンクリートの平均応力と平均ひずみ関係が補強を施さ

ない場合よりも小さくなる場合があるという事実, を解析的に再現することに成功した. さらには, 解析コードを用いたパラメトリックな検討を通じて,FRP シートで補強した RC 部材のコンクリートの平均応力と平均ひずみとの関係, 鉄筋の平均応力と平均ひずみとの関係の定式化を図った.

続いてこの論文では,FRP が引張面に接着補強された RC はりの曲げ挙動のシミュレーションが行われた. その結果,FRP シートで補強した RC はり部材の耐力, 破壊形式, 補強材のひずみおよび付着応力を精度良く予測できること, また,FRP プレートで補強した RC はりの挙動を予測するためには,FRP シートに対する既往の付着強度式の修正が必要であることを明らかにした. さらに, 実験結果に基づき既往の付着強度式の修正を施し, その修正式を用いれば,FRP プレート補強 RC 部材の非線形挙動を的確に予測できることを示した. 加えて,FRP シートと FRP プレートのはり部材中のはく離の発生・進展過程に関する検討を行い, 最大荷重時のはく離破壊領域の大きさを見出した.

これを要するに, 著者は,FRP 接着補強 RC 部材の非線形挙動を予測できる新しい解析手法を開発するとともに,FRP シートおよびプレートのはく離破壊機構についての新しい知見を得たものであり, コンクリート構造学ならびに維持管理工学に貢献するところ大なるものがある. よって, 著者は, 北海道大学博士 (工学) の学位を授与される資格あるものと認める.