BEHAVIOUR OF REINFORCED CONCRETE FLEXURAL MEMBERS STRENGTHENED WITH EXTERNALLY BONDED CARBON FIBER REINFORCED POLYMERS

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Degree of Master of Philosophy

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DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

Reinforced concrete structures often have to face modification and improvement of their performance during their service life. The main contributing factors are change in their use, new design standards, design errors, deterioration due to corrosion in the steel caused by exposure to an aggressive environment and accident events such as earthquakes. In such circumstances there are two possible solutions: replacement or retrofitting. It is desirable to repair and reuse reinforced concrete structures from the point of view of sustainability. Strengthening may also be needed to prolong the life of deteriorated members. Use of Fiber reinforced polymers (FRP) can be considered as one of efficient technique for such strengthening of reinforced concrete elements.

The previous research studies show the lack of field scale experimental studies and analytical studies such as finite element models (FEM) have been carried out to complete understanding of strengthening reinforced concrete structural element using FRP with respect to failure behaviour, strength enhancement, ductility assessment and deflection behaviour. Further, no studies have been carried out in Sri Lankan context to understand behaviour of FRP strengthening reinforced concrete systems and no technical data is available. This has led to less confidence of using this technique by practicing engineers in Sri Lanka. Various design guidelines shows the different approaches to design FRP strengthening system, especially the prediction of failure strains. This has led to poor understanding of safety against ultimate failure and confidence of using the existing guidelines for the designs. This study covers the above aspects with respect to strengthening of reinforced concrete flexural elements using carbon fiber reinforced polymers (CFRP).

A comprehensive experimental program has been carried out using field scale flexural strengthened reinforced concrete elements (beams and slabs) to understand failure behaviour, flexural strength enhancement, ductility assessment and deflection behaviour. A nonlinear finite element model has been developed to simulate complete experimental behaviour of CFRP strengthened reinforced concrete flexural system till failure. ACI and Japanese method of designing flexural system have been evaluated and checked with the experimental results.

It was observed that CFRP strengthened beams with u-wrapping showed about 60% load carrying capacity improvement with respect to control specimens It was about 140% load carrying capacity increment for normal strengthened R6 slabs (reinforced with 6mm diameter mild steel) with CFRP at soffits. The load carrying capacity increment for T10 slabs (reinforced with 10 mm diameter tor steel) with CFRP was about 70% with normal wrap of CFRP. It was clear that gain in flexural enhancement has highly depend on the reinforcement ratio and the wrapping method of CFRP.

It was observed from the experimental study, a reduction in ductility of both beams and slabs strengthened with CFRP. This reduction has considerably depended on the reinforcement ratio of the elements. However, the elements still have sufficient ductility against failure.

The only failure mode observed in beam failure can be classified as cover separation with simultaneous deboning of CFRP laminates. The failure has initiated by cracks formed in the reinforced concrete elements during loading. The failure mode in the slabs is due to peeling of CFRP laminates from the slab soffit known as debonding failure. The measured strain values of CFRP for beams specimen are almost constant at failure. It was about 3570 $\mu\varepsilon$. The slabs are also constant with 2540$\mu\varepsilon$ which is independent on the reinforcement ratio. This

indicates the failure is governed by the FRP strain at failure. The difference in FRP strain at failure in beams and slabs are due to wrapping method of the laminates.

It was observed that tested specimen with flexural enhancement still satisfied the serviceability deflection criterion (span/300) for reinforced concrete elements. Hence, these flexural enhancement designs for beams and slabs are governed by the ultimate limit state failure.

ANSYS based non-linear finite element model has been developed to simulate experimental behaviour of FRP strengthened flexural system. It has good agreement with experimental results. The calibrated material parameters has presented in this dissertation.

ACI and Japanese method of designs of flexural system are governed by the prediction of debonding strain values by empirical based formulae. It was observed that prediction of debonding strain by ACI method overestimate the value compared to Japanese method. On the other hand, it was observed that Japanese method prediction is more close to experimental CFRP strain observed at the failure in this experimental program. However, ultimate moment of resistant calculation using conventional section analysis (this method is used in both codes) indicates that both ACI and Japanese method have adequate safety margin against ultimate failure of beams whereas ACI method does not show the adequate safety margin for the slabs but Japanese method does. However, Japanese method has high safety margin against beams and less value of the slabs. This difference in strains, highly depending on the failure behaviour which is directly related to the wrapping method, has to be accounted in the prediction of the debonding strain values.

Proposed Japanese method of debonding prediction formula has been modified based experimental results. This modification has led to prediction of ultimate design moment for flexural enhanced elements (both slabs and beams) with reasonable factor of safety against ultimate failure.

This study has led Sri Lankan engineers to understand complete behaviour of CFRP strengthened flexural systems. Proposed methodology can be used for the design with higher confidence.

Keywords: flexural strengthening, CFRP, debonding failure, nonlinear FEM, Design criterion

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