# INVESTIGATION ON CARBON FIBRE REINFORCED POLYMER (CFRP) STRENGTHENED, OUT OF PLANE CURVED CONCRETE BEAM SUBJECTED TO COMBINED EFFECTS OF SHEAR AND TORSION

Warnakulasuriya Chinthana Vimukthi Fernando

198096T

Degree of Master of Science

Department of Civil Engineering

University of Moratuwa

Sri Lanka

January 2021

# INVESTIGATION ON CARBON FIBRE REINFORCED POLYMER (CFRP) STRENGTHENED, OUT OF PLANE CURVED CONCRETE BEAM SUBJECTED TO COMBINED EFFECTS OF SHEAR AND TORSION

Warnakulasuriya Chinthana Vimukthi Fernando

198096T

A thesis submitted in partial fulfilment of the requirements for the degree Master of Science in Civil Engineering

Department of Civil Engineering

University of Moratuwa

Sri Lanka

January 2021

## DECLARATION

I declare that this is my work and this thesis 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.

Also, I hereby grant to the University of Moratuwa the non-exclusive right to reproduce and distribute the thesis, in whole or in part in print, electronic or other media. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: *UOM Verified Signature* Date: 28/02/2022

The above candidate has carried out research for the Masters under my supervision

Name of the supervisor: Dr. (Mrs.) J.C.P.H. Gamage

Signature of the supervisor: Date:

## ACKNOWLEDGEMENT

Under the Research Project, I had the opportunity of gaining very valuable experience of how to apply the theoretical knowledge gathered throughout the four years as an undergraduate to produce important findings for the well-being and development of the community. There are a number of persons whom I must pay my gratitude for their help towards the successful completion of the research project and report.

First, I am very grateful for the valuable guidance and encouragement were given by my research supervisor, **Dr. (Mrs.) J.C.P.H. Gamage**, Senior lecturer in the Department of Civil Engineering, University of Moratuwa. Without her support and guidance none of this would be possible. Further, I am thankful to, **Prof. A.A.D.J. Perera and Prof. C. Jayasinghe**, Senior Professors in the Department of Civil Engineering, University of Moratuwa, for the progress evaluation and for providing valuable instructions to move forward in my research direction.

Next, I would like to express my gratitude to **Mr. D.M.N.L. Dissanayaka**, technical officer and the non-academic staff in the structural Testing, building material, rock mechanics and computer laboratories in the Department of Civil Engineering, University of Moratuwa.

W. C. V. Fernando
Department of Civil Engineering
University of Moratuwa
06.11.2020

## ABSTRACT

Carbon Fibre Reinforced Polymer (CFRP) strengthening technique had been shown excellent performance in externally strengthening Reinforced Concrete (RC) elements due to their superior properties compared to the alternatives. A substantial amount of studies had been done to study the behaviour of externally CFRP strengthened RC elements. However, as per the authors' knowledge, while most of the studies have been focused on the external strengthening of straight RC beams using CFRP, none of the studies had been focused on strengthening horizontally curved RC beams. Curved beams innately respond with flexure, shear and especially torsion under out-of-plane loads due to its curvature. Hence, it is important to study the effect of the additional torsional stress on the CFRP external reinforcement.

A detailed experimental program, a theoretical analysis and a numerical analysis were conducted in order to reduce the aforementioned research gap. A series of testing was conducted on beam specimens with 2 m and 4 m radii and externally strengthened with normal modulus CFRP fabrics to enhance the effects; shear, torsion and their combination.

From series one experimental results, it was found that the wrapping CFRP fabrics have enhanced the shear capacity of the curved RC beams by at least 30 % and the enhancement is higher for beams with lower curvatures. It showed that CFRP wrapping is a very effective method to enhance the shear capacity of horizontally curved beams.

The series two experimental results showed that U-socketing of CFRP fabrics for shear has increased the shear strength by 15.61 kN (16.7 %) and 17.41 kN (18.2 %) respectively for 2 m and 4 m radius specimens. The main failure mode was crack induced intermediate debonding of CFRP U-sockets. However, the predicted shear enhancements according to theoretical investigation are 23.64 kN and 24.51 kN for 2 m and 4 m radius beams respectively. It can be observed that for 2 m and 4 m specimens recorded respectively 33.97 % and 28.97 % less than the predicted enhancement by the theoretical study. This can be explained by the additional

torsional stresses contributing to the direct shear stresses which cause to reduce the shear capacities of RC beams.

The results from numerical models showed excellent agreement with experimental results which was used to carry out a parametric study. Subsequently, a capacity reduction factor was defined as the ratio between numerical shear gain and theoretically predicted shear gain to quantify the effect of torsional stresses on the shear enhancement of U-socketed CFRP on RC beams with a 1.4 m support distance which can be used to modify the currently existing analytical model adopted by ACI 440.2R-17 guide to design of FRP as external reinforcement for RC beams.

# LIST OF PUBLICATIONS

## International Conferences (Published)

1. Fernando, W. C. V., Chandrathilaka, E. R. K. & Gamage, J. C. P. H., (2019). "Experimental Study on Shear Behaviour of CFRP Strengthened Curved RC Beams". 10th International Conference on Structural Engineering and Construction Management (ICSECM2019), Kandy, Sri Lanka.
2. Kulendran. S., Fernando, W. C. V. & Gamage, J. C. P. H., (2020). "Strengthening of Damaged Out of Plane Curved Reinforced Concrete Beam Using Carbon Fiber Reinforced Polymer". 6th Moratuwa Engineering Research Conference (MERcon 2020), Moratuwa, Sri Lanka.

## Journal papers (in preparation)

1. Himasha, M. W. C., Fernando, W. C. V. & Gamage, J. C. P. H., 2020. Study on Shear Behaviour of CFRP Strengthened Horizontally Curved RC Beams. *Case Studies in Construction Materials*. (In preparation)
2. Fernando, W. C. V. and Gamage, J. C. P. H., 2020. Bond characteristics of Carbon Fibre Reinforced Polymer Strengthened, Out of Plane Curved Reinforced Concrete Beam Subjected to Combined Effects of Shear and Torsion. (In preparation)
3. Fernando, W. C. V. and Gamage, J. C. P. H., 2020. A theoretical approach to quantify the combined effects of shear and torsion in Carbon Fiber Reinforced Polymer (CFRP) strengthened out of plane curved Reinforced Concrete Beams. (In preparation )

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES