Behaviour of in Plane and out of Plane Curved Steel Beams Strengthened with Carbon Fiber Reinforced Polymers

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Degree of Doctor of Philosophy in Civil Engineering

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A thesis submitted in Partial fulfilment of the Requirements for the Degree of Doctor of Philosophy in Civil Engineering

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Declaration

I declare that this is my own 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.

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The above candidate has carried out research for the PhD thesis under my supervision.

Name of the supervisor: Prof J C P H Gamage

Signature of the supervisor: Date: 23.05.2023

Abstract

Application of curved steel members in constructions have shown an increasing demand during last few decades not only due to the aesthetic appearance, but also some structural advances. The curved steel beams used in structures may be either curve on a vertical plane or curved in a horizontal plane. A considerable number of steel structures contained vertically curved steel tubular members such as in bridges and curved roofs. Horizontally curved steel members are mostly made with steel I beams which can be seen in bridges and floor beams. These curved steel beams (either tubular or I beams) need retrofitting due to many reasons; errors in design stage, loss of original material properties due to material degradation, exposure to severe environments, or load increments in service stage. Though many methods available to retrofit steel structures, CFRP becoming popular within industry due to many of its favourable properties; comparatively higher durability when considering with other materials, superior fatigue performances, higher strength-to-weight ratio, less labour requirement, and easy applicability for any sectional shape. This study focussed on the behaviour of CFRP strengthened vertically curved circular hollow sectioned beams and the behaviour of I beams curved in a horizontal plane strengthened with CFRP. The study was conducted in several stages as explained below.

In phase one, Coupon tests were conducted in order to obtained the properties of steel tubes, steel I beams, CFRP and adhesives. All the specimens were prepared referring to ASTM standards and the tests were conducted according to same standard. Three samples from steel tubes, three samples from steel I beams, five samples from CFRP and Five samples from adhesive were prepared for testing. Tensile tests were conducted on all the samples and required properties for experimental studies and numerical studies were recorded. Some properties of the considered materials were calculated using empirical relationships found in the literature.

In phase two, experimental and analytical study for vertically curved circular hollow sectioned beams were conducted. Total sixteen samples bent in to four radii 0 mm, 2000 mm, 4000 mm and 6000 mm were prepared. Three specimens from each set of beams were strengthened with 500 mm, 750 mm and 1000 mm long CFRP patches. All the beams were tested under flexure until the failure occurs. It was noted that the curvature of the beams and the CFRP wrapping length have showed a major effect on the maximum load carrying capacity of the strengthened beams compared to control

beams. The proposed analytical method based on the equations found in literature to calculate the load deflection relationship of CFRP strengthened vertically curved steel hollow sectioned beams. The analytical model was verified using experimental results.

In phase three, a numerical analysis was performed to identify the effect of sensitive bond parameters such as number of CFRP layers, elastic modulus of CFRP, aspect ratio of steel sections, CFRP layer orientation. 3D finite element models were created and validated compared experimental results prior to conduct the parametric study. With the parametric study results, it was found that the rise in number of CFRP layers increases the ultimate load and this ultimate strength gain does not proportional to number of CFRP layers (percentage increment in ultimate loads reduced with successive increase in number of CFRP layers). It was also noted that the increase in CFRPs elastic modulus drastically increase the ultimate load of CFRP strengthened vertically curved beams while CFRP wrapping configuration showed a significant effect too. It was also noted that there is no significant effect of aspect ratio of beams on the strength gain, however, for beams having same dimeter the ultimate strength gain reduced with the increased thickness.

In fourth phase of the study, an experimental and analytical study was conducted on the CFRP strengthened horizontally curved steel I beams. The experimental study was conducted on twelve samples, consisted of beams bent in to three radii 0 mm, 4000 mm and 6000 mm. Three beams from each category was strengthened with three CFRP application profiles having 750 mm long CFRP patches while keeping one beam as a control beams. All the beams were tested under flexure until the failure with fixed end conditions at the either ends of the beams. The load-deflection responses and the failure modes were recorded. It was noted that the curvature of beams and CFRP application profile has significant effect on load-deflection behaviour and failure modes of CFRP strengthened horizontally curved steel I beams. An analytical model was developed base on the available literature to analyse the load deflection behaviour of CFRP strengthened horizontally curved steel I beams. The results obtained through experimental study and analytical method showed a good agreement which enable the use of analytical method for practical applications.

On the final stage of this research, a numerical study was performed in order to evaluate the effect of various bond parameters on the ultimate strength gain of the

CFRP strengthened horizontally curved steel I beams. 3D finite element models were developed using commercial available finite element modelling software and the results of numerical models were calibrated prior to conduct the parametric study. Influence of CFRP bond length, elastic modulus of CFRP, number of CFRP layers and elastic modulus of steel were studied. It was found that for both straight and horizontally curved beams strengthened with CFRP, ultimate strength increases until CFRP length increased to 750 mm. But, increase in CFRP length greater than 750 mm reduces the ultimate strength, and hence the optimum economical length of CFRP may be taken when CFRP length to span ratio become 0.75. Increase in elastic modulus of CFRP enhance the ultimate load for straight beams. However, this effect is not significant in beams curved to 4000 mm radius. The increase in CFRP layer count drastically increase the ultimate load for both straight and horizontally curved I beams. It was also noted that the percentage strength gain reduces with the increase in elastic modulus of steel.

Key words: Curved Beams, Circular Hollow Sections, Carbon Fibre Reinforced Polymer, Retrofit, Numerical Modelling, Debonding, Cohesive Zone Modelling

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2. Weerasinghe, K.A.B., Gamage, J.C.P.H., Thambirathnam, D.P., and Sabrina Fawzia, "Experimental and Numerical Investigation of Carbon Fibre Reinforce Polymer Strengthened In-plane Curved Beams with Circular Hollow Sections Subjected to Flexure", Thin Walled Structures– **Under Review**

3. Weerasinghe, K.A.B., Gamage, J.C.P.H., Thambirathnam, D.P., and Sabrina Fawzia, "Effect of Beam Curvature on the Strength Gain of Carbon Fibre Reinforced Polymer Strengthened Vertically Curved Beams With Circular Hollow Sections", Australian Journal of Civil Engineering – **Under Review**

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5. Weerasinghe, K.A.B., Gamage, J.C.P.H., Thambirathnam, D.P., and Sabrina Fawzia," Experimental and Theoretical Investigation of the Behaviour of Carbon Fibre Reinforced Polymer Strengthened Out of Plane Curved Steel I Beams", **(On Preparation)**

6. Weerasinghe, K.A.B., Gamage, J.C.P.H., Thambirathnam, D.P., and Sabrina Fawzia, "Experimental and Numerical Investigation of Carbon Fibre

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