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FINITE ELEMENT ANALYSIS OF CONCRETE-FILLED STEEL TUBE BEAMS PARTIALLY WRAPPED WITH CFRP SHEET

Ahmed W. Al-Zand[1], Wan Hamidon Wan Badaruzzaman, Azrul A. Mutalib and Salam Jasim Hilo
Department of Civil and Structural Engineering
Universiti Kebangsaan Malaysia (UKM)
Bangi, Selangor, Malaysia
ahmedzand70@gmail.com

Abstract— **The behaviour of Concrete-Filled Steel Tube (CFST) beam strengthened with Carbon Fibre Reinforced Polymer (CFRP) sheet was investigated numerically in this paper. Nonlinear analysis using ABAQUS Finite Element (FE) software to assess the behaviour of square and circular CFST beams wrapped from bottom side with U-shaped of CFRP sheet using different length and multi layers. The FE models were verified accurately through successful comparison with existing experimental study done by others. The results obtained from the study show that various lengths and multiple layers of CFRP sheets directly affect the ultimate moment capacity of CFST beams; where the ultimate moment capacity of the CFST beams was improved by increasing the layers of CFRP sheets - specifically for beams - wrapped along 75% or more of their length. Meanwhile, CFRP delamination failure has been observed for beams wrapped along 50% of their length, where delamination failure occurred earlier with an increasing number of CFRP layers. Moreover, by increasing the wrapping length of CFRP sheet to more than 75% of the beam's length did not lead to further improvement in the beam's moment capacity for each specific number of CFRP layers.**

Keywords- **Finite element analysis, Concrete-filled steel tube beam, Composite beam, CFRP sheet, Strengthening**

I. INTRODUCTION

Concrete-Filled Steel Tube (CFST) members have become most interesting composite members recommended by engineers for several modern structural projects. Unlike conventional hollow steel/concrete members, this type of composite member has high ductility and strength capacity. However, the CFST members are similar to other structural members that may need strengthening for different reasons, such as degradation due to the environment, ageing, fire, fatigue, and upgrades to carry extra loads. The conventional methods for strengthening the existing steel members, by replacing and/or adding new steel parts by bolting or welding, leads to extra project costs, because it's needs heavy tools and more time for repair work. Therefore, Fibre-Reinforced Polymer (FRP) composite material has recently become an adequate solution for strengthening and upgrading structural members. This material has shown perfect performance in strengthening concrete structures over the past 20 years [1]. However, recently the researchers and engineers are more intent on using Carbon Fibre-Reinforced Polymer (CFRP) materials for strengthening steel members specifically, because it has a higher modulus of elasticity and tensile strength to weight ratio than steel, add to that it's is very flexibility to be applied easily to any shape of structural members.

Several theoretical and experimental studies have been conducted on adopting CFRP to strengthen steel members, where some of these studies are summarized in review papers presented by Shaat et al., [2] and Zhao and Zhang [3]. However, some researchers have studied the effect of surface preparation, different types of CFRP, adhesive materials and length of interactions between steel and CFRP material, such as in [4-9].

A limited number of studies have generally investigated the behaviour of steel hollow tube/CFST members strengthened by CFRP material, subjected to pure flexural/combined loads, such as in [10-14]. Consequently, Tao et al., [10] performed a series of experiments on square and circular concrete-filled tube members. The specimens were loaded by axial and bending loads, subjected to fire damage, and then repaired by multiple layers of unidirectional CFRP sheets with full confinement around the columns (using varies directions of CFRP confinement). The tests confirmed that both the longitudinal stiffness and the load carrying capacity of repaired members increased with the increasing number of CFRP layers. Sundarraja and Ganesh [13] performed experiments for square CFST beams strengthened from the bottom flange by flat strip of CFRP fabric sheet. The beams were all subjected to four point loads, distributed equally along the beam's lengths (pure flexural loading). However, the CFRP sheets applied either along the full beam's length (full wrapping length) or along the distance between the two loading points (partial wrapping length) with multiple CFRP layers (i.e., 1, 2, and 3 layers). The tests showed limited improvements in deflection with no improvement in ultimate load capacity when the beams were strengthened with partial wrapping length because of the CFRP patch delamination failure; which occurred earlier due to increasing the CFRP layers. Meanwhile, the beams with full wrapping length showed better performance, where the ultimate loads of their beams increased from 10 to 35% more than the capacity of control beam when using 1 & 3 CFRP layers, respectively.

Numerical analysis by FE methods has become a frequently used tool by researchers to represent several case studies. The FE studies showed perfect comparisons with experimental works of steel sections wrapped by CFRP sheets and subjected to dynamic and static tests, such as done in [13, 15-17].

In this study, 3D-FE models were used to investigate the behaviour of CFST beams wrapped partially with CFRP sheet. The study aimed to evaluate the effects of various wrapping lengths and layers of CFRP sheet applied partially on square and circular tube cross-sections, in order to optimize the best economical solution when strengthened such kind of composite members. All models of CFST beams had fixed values of length, concrete compressive strength, and steel yielding strength. The validity of the FE models was examined with the existing experimental works [13].

II. FINITE ELEMENT ANALYSIS

Nonlinear 3D-FE models were prepared by ABAQUS software in order to investigate the structural behaviour of simply supported CFST beams strengthened with CFRP sheet. Material modelling, convergence study, and verification of the FE models, are presented as follows:

A. Modelling of the CFST beams

This research studied specifically the square and circular cross-sections of the CFST beams, with 1.5m length, partially wrapped with U-shaped of CFRP sheet for the bottom half of the beam's section, with boundary conditions shown in Figure 1. Each FE model consist mainly from three different materials; steel, concrete, and CFRP sheet. The steel tube, modelled with the element type C3D8R (3D solid element with an 8-node linear). Element type C3D8RH was chosen for concrete material, which is also a 3D solid element with an 8-node linear-hybrid. Meanwhile, shell element type S4R was used for the CFRP patch (4-node linear).

A typical quarter FE mesh models were used for the square and circular CFST beams are shown in Figure 2. Support conditions were appropriately modelled by restraining the nodes corresponding to the support points. A displacement load option was adopted in the FE model at the loading points, which was increased gradually with smooth rate until satisfy the ultimate capacity of selected beams.

The assumed uniaxial stress–strain curves for steel and concrete are shown in Figure 3. Material properties for steel tubes, concrete, CFRP sheet and adhesive material are shown in Table I. The CFRP fabric sheet material type MBrace 240, with 0.234mm thickness, was selected in this study. MBrace saturant material was used as adhesive material. The cohesive behaviour technique available in ABAQUS was used to implement the surface interaction between the steel tube and CFRP patch.

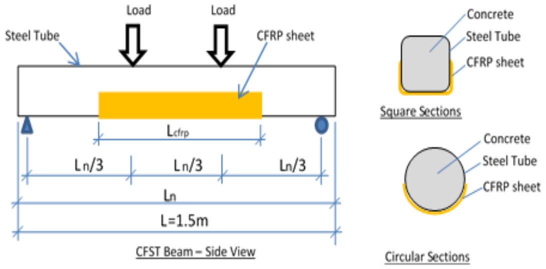


Fig. 1. Boundary Conditions of a CFST Beam wrapped with CFRP sheet

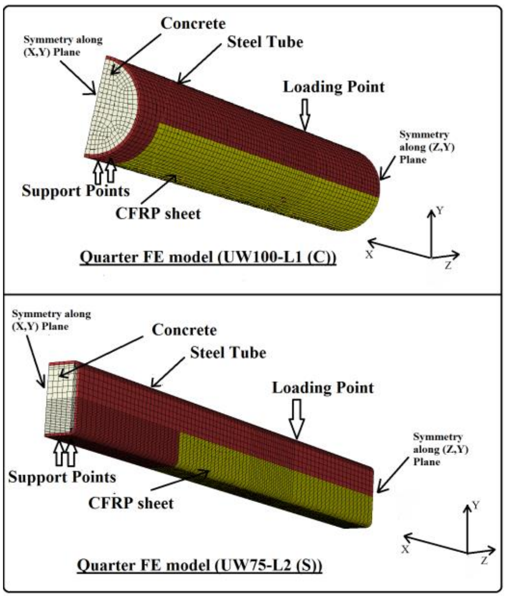
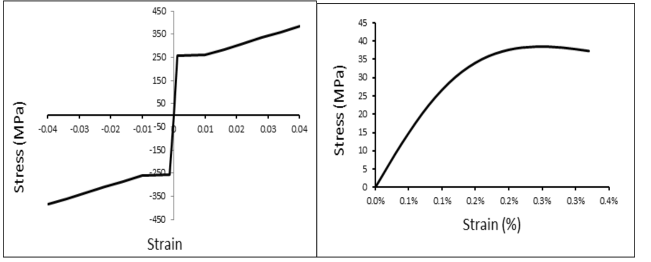


Fig. 2. Typical FE mesh of the CFST beam used in this study



a- Steel **b- Concrete**

Fig. 2. Typical stress–strain curves for steel tubes and concrete

Table I-Material Properties for FE models of CFST beams

Material	Poisson's Ratio	Elastic Modulus	Yield Stress	Compressive Strengt	Ultimate Tensile Strength
Steel	0.3	203	258	-	380
Concret	0.2	31.02	-	38.5	-
CFRP	0.4	240	-	-	3800
Adhesiv	-	1.138	-	-	17

B. Meshing convergence study

A convergence study was conducted for the CFST beam numerical model to verify the suggested FE model. Several numbers of elements were selected by changing the meshing size of the beam's elements. The ultimate load capacities of these models were obtained and compared with the ultimate load (109kN) of control beam (CB2) experiments in [13]. Figure 4 shows that the models with total elements equal to 1596 and more having very close ultimate load values.

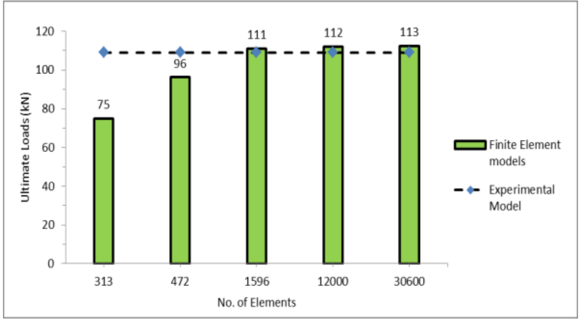


Fig. 4. Results from the convergence study

However, the model with the 12000 elements was selected to represent the FE models in this study, because this model took a reasonable amount of program running time (on a normal PC), shows better curve's behaviour when compared to the experimental model and also it's satisfied the failure load with deviation equal to +2.7% higher than the experimental value.

C. Verification of the Finite Element Model

Three square CFST beams wrapped from bottom flange only with flat CFRP sheet, which were studied experimentally by Sundarraja and Ganesh [13] (with properties given earlier), were selected to verify the FE modelling used in this study. As shown in Figure 5, the results obtained from the FE analysis were very close to the ones obtained from the experiment. According to the figure, the ultimate moment capacity from the FE analysis of the CFST control beam (CB, beam without CFRP sheet) was 26.15 kN.m compared to 25.44 kN.m from the experimental study (CB2); giving a +2.7% overestimation by FE analysis. The ultimate moment capacity of the FE model (FW100-L3) for the CFST beam wrapped along its full length by three layers of CFRP sheet, was 36.27 kN.m compared to 34.54 kN.m for the experimental model

(FWB-L3(2)); giving a +2.0% overestimation. Meanwhile, the ultimate moment capacity of the FE model (PW33-L2) for the beam's partially wrapped by two layers of CFRP sheet was 24.6 kN.m compared to 26.6 kN.m from the experimental study (PWB-L2(1)); giving a -7.5% lower estimation by FE analysis. Therefore, this verification study concluded that the proposed FE modelling is capable of implementing the behaviour of CFST beam strengthened by CFRP sheet in this study.

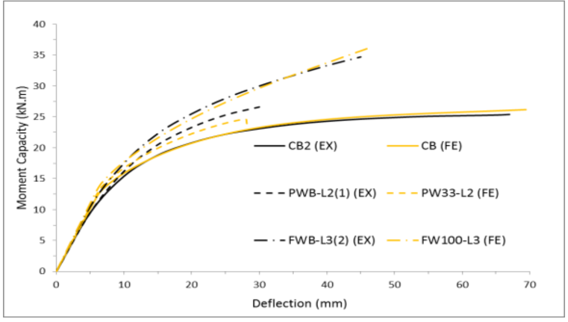


Fig. 5. Comparison of the moment-deflection curves between the FE models and Experimental tests [13]

III. NUMERICAL ANALYSIS OF CFST BEAMS STRENGTHENED BY CFRP SHEET

In view of the accuracy of the proposed FE model, this method was used to analyse the concrete-filled steel tube beam strengthened by CFRP fabric sheet. However, the selected sizes and cross-sections of the CFST beams were wrapped partially from below with U-shaped CFRP sheet. The study investigated the effects of various CFRP wrapping lengths (Lcfrp = 50, 75, and 100% of the beam's length), as well as multiple layers of CFRP sheet (1, 2, and 3 layers) applied to CFST beams. Two types of tube cross-sections (square and circle) were investigated in this study. The square tube's cross-section was 91.5 x 91.5 x 3.6mm (same as the section tested in [13]) and 107.4 x 3.5mm for the circular tube's cross-section (as suggested in the present study). Table II shows the numbering system and the strengthening scenario for the twenty FE models adopted in this study. Each beam was modelled as per the mesh, materials and boundary conditions mentioned previously.

Table II- FE models of CFST beams strengthened by CFRP sheet

No.	Beam's ID	Tube's cross section (C) / (S)	CFRP U-wrapping length as % Ln (UW)	CFRP layers (L)
1	CB (C)	Circle	-	-
2	UW50-L1 (C)	Circle	50%	1
3	UW50-L2 (C)	Circle	50%	2
4	UW50-L3 (C)	Circle	50%	3
5	UW75-L1 (C)	Circle	75%	1
6	UW75-L2 (C)	Circle	75%	2
7	UW75-L3 (C)	Circle	75%	3
8	UW100-L1 (C)	Circle	100%	1
9	UW100-L2 (C)	Circle	100%	2
10	UW100-L3 (C)	Circle	100%	3
11	CB (S)	Square	-	-
12	UW50-L1 (S)	Square	50%	1
13	UW50-L2 (S)	Square	50%	2
14	UW50-L3 (S)	Square	50%	3
15	UW75-L1 (S)	Square	75%	1
16	UW75-L2 (S)	Square	75%	2
17	UW75-L3 (S)	Square	75%	3
18	UW100-L1 (S)	Square	100%	1
19	UW100-L2 (S)	Square	100%	2
20	UW100-L3 (S)	Square	100%	3

IV. RESULTS AND DISCUSSION

The results obtained from the FE analysis are presented in the form of moment-mid span deflection relationship curves for each FE model. Figures 6-8 show the moment–deflection curves for square CFST beams wrapped by multiple layers of CFRP sheet along 50, 75, and100% of the beam's length, respectively. Figure 9 shows the bar charts of the ultimate moment capacity for the same square beams, with reference to the number of CFRP layers. Meanwhile, Figures 10-12 show the moment-deflection curves for circular CFST beams wrapped also with multiple layers of CFRP sheet along 50, 75, and100% of the beam's length, respectively, and Figure 13 presents their ultimate moment capacity with reference to the number CFRP layers.

It can be observed from all figures that the use of multiple layers of CFRP sheet along various wrapping lengths leads to an improved bema's moment capacity for both cross-sections (square and circular). However, the square CFST beams with 50% CFRP wrapping recorded limited improvement to their ultimate moment capacity when 1 CFRP layer was applied; equal to 29.5 kN.m, compared to the control beam value of 25.6 kN.m (an increase equal to +15.2%). An increasing number of CFRP layers (up to 3) for the same wrapping scenario (Lcfrp=50%) led to a decreasing moment capacity up to 27.3 kN.m. The circular CFST beams showed the same behaviour for beams wrapped along 50% of the beam's length when 1 CFRP layer was applied; equal to an ultimate moment capacity of 30.5 kN.m, compared to the control beam value of 29.0 kN.m (an increase equal to +5.1%), then this value dropped to 29.5 kN.m for the same beam wrapped by 3 CFRP layers. These dropping values occurred due to the delamination failure that occurred for the ends of CFRP sheet, where delamination failure occurred earlier with an increasing number of CFRP layers; only for beams with a short wrapping length (50% of the beam's length).

CFST beams wrapped along 75 and 100% of the beam's lengths showed better responses in their ultimate moment capacities with increasing numbers of CFRP layers. No delamination failure was observed for these wrapping lengths, because all beams failed due to reaching the CFRP sheet their ultimate strength. For example, the square CFST beams with 1 CFRP layer recorded an ultimate moment capacity equal to 30.4 kN.m (for both beams wrapped along 75 and 100% of the beam's length); an increase equal to +18.7% compared to the control beam value of 25.6 kN.m. Using 3 CFRP layers increased the ultimate moment capacity up to 41.1 and 42.1 kN.m for beams with the same wrapping lengths (75 and 100%), respectively; an increase equal to 60.5-64.4% compared to the same control beam value. A better performance was observed for circular CFST beams with the same wrapping scenarios (Lcfrp=75 and 100% of the beam's length), where the ultimate moment capacity was equal to 48.0 kN.m for beams wrapped by 1 CFRP layer; an increase equal to +65.5% compared to the control beam ultimate moment capacity of 29.0 kN.m. Meanwhile, the ultimate moment capacity increased up to 57.8 and 58.5 kN.m for both beams wrapped along 75 and 100% of the beam's length, respectively, when wrapped by 3 CFRP layers with approximately 100% increasing higher than the control beam value.

In general, both beams with different cross-sections (square and circular) had very little difference in their recorded ultimate moment capacities, when the wrapping length increased from 75% to 100% of the beam's length. In the other words, the ultimate moment capacity for beams wrapped by CFRP sheet along 75% and 100% of the beam's length, are very close in their values for each number of CFRP layers.

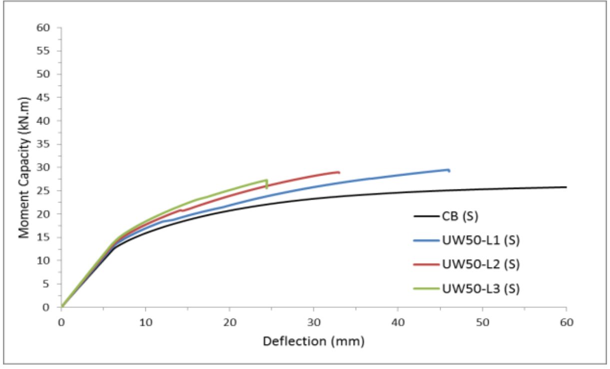


Fig. 6. Moment-deflection relationship for square CFST beams wrapped partially with CFRP sheet along 50% of beam's length

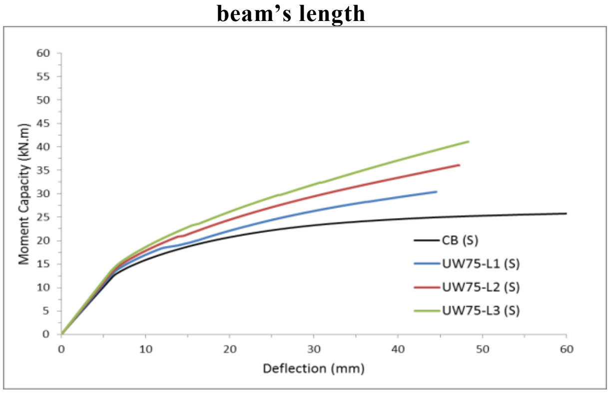


Fig. 7. Moment-deflection relationship for square CFST beams wrapped partially with CFRP sheet along 75% of beam's length

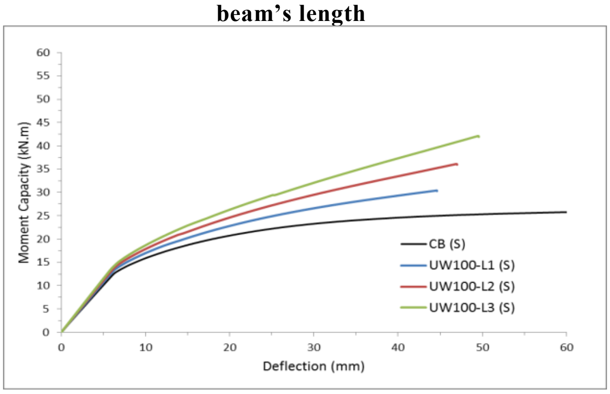


Fig. 8. Moment-deflection relationship for square CFST beams wrapped partially with CFRP sheet along 100% of beam's length

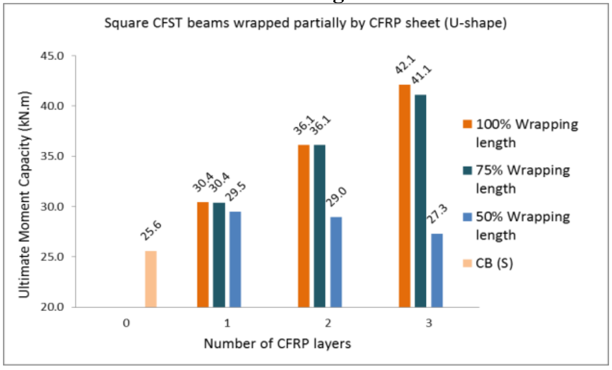


Fig. 9. Ultimate moment capacity for square CFST beams wrapped partially with CFRP sheet along varies of beam's length

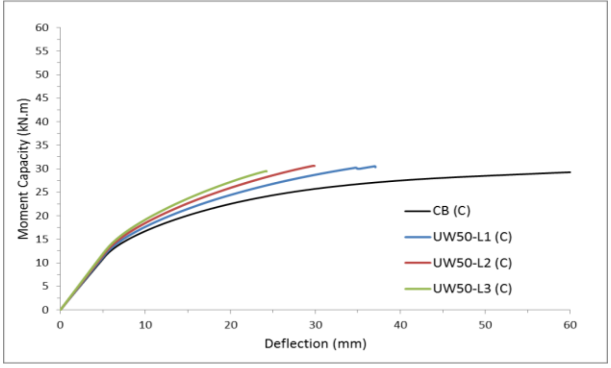


Fig. 10. Moment-deflection relationship for circle CFST beams wrapped partially with CFRP sheet along 50% of beam's length

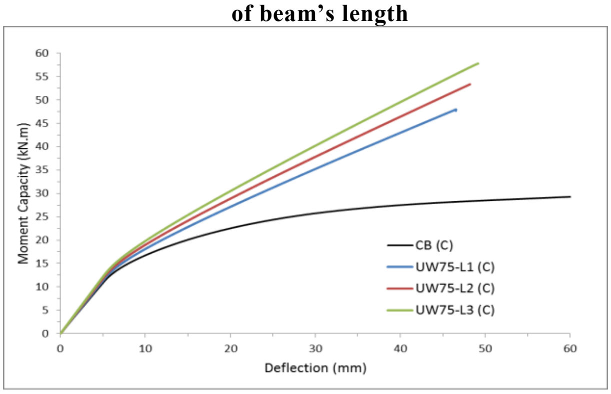


Fig. 11. Moment-deflection relationship for circle CFST beams wrapped partially with CFRP sheet along 75% of beam's length

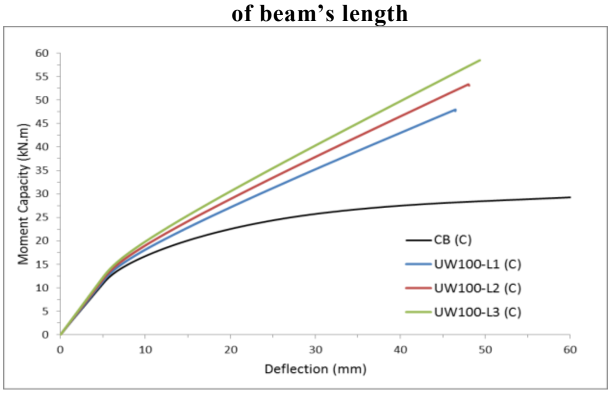


Fig. 12. Moment-deflection relationship for circle CFST beams wrapped partially with CFRP sheet along 100% of beam's length

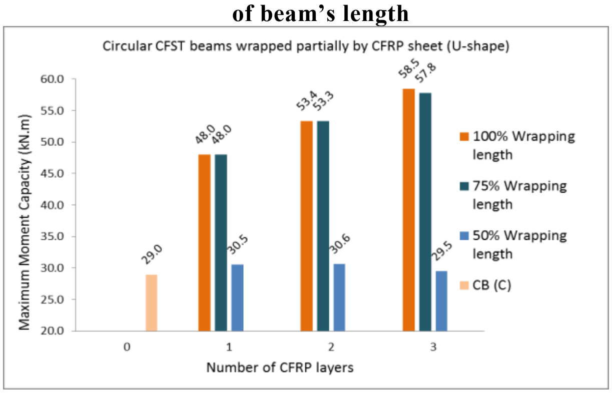


Fig. 13.Ultimate moment capacity for circle CFST beams wrapped partially with CFRP sheet along varies of beam's length

V. CONCLUSIONS

Ultimate moment capacity and behaviour for square and circular cross-sections of CFST beams strengthened partially by U-shape of CFRP sheets along varying wrapping lengths were studied in this paper using nonlinear FE analysis. The conclusion of this study can summarise as follows:

- The successful comparison between the models of FE analysis and existing experimental study confirm that, the proposed FE modelling is very sufficient to implement the behaviours of the CFST beams wrapped by CFRP sheet.
- Beams wrapped along 50% of its length by CFRP sheet showed very limited improvements of their ultimate moment capacities, then these capacities starts to decreasing with increasing numbers of CFRP layers. This was because delamination failure occurred for the ends of CFRP patch even before reaching its ultimate strength.
- Beams wrapped along 75 and 100% of its length by CFRP sheet showed increasing of their ultimate moment capacities with increasing number of CFRP layers. This was because the CFRP patch reached their ultimate strength, since no delamination failure has been observed.
- No significant improvement was observed in the ultimate moment capacity for square and circular beams when wrapped by CFRP sheet along the 100% of its length, than the values of the same beams wrapped along only 75% of its length.
- The circular CFST beams showed better response to the strengthening actions than the square CFST beams, specifically for beams wrapped along 75 & 100% of its length by CFRP sheet. Where the ultimate moment capacity of circular beams increased by approximately 65.5% to 100% when wrapped by 1 and 3 CFRP layers, respectively; while the ultimate moment only increased from 18.7% to 64% for the square beams wrapped by 1 and 3 CFRP layers, respectively.

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