# FE modeling and experimental verification of a CFRP strengthened steel section subjected to transverse end bearing force

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ABSTRACT: This paper reports improved web crippling behavior of steel Rectangular Hollow Section (RHS) strengthened by Carbon Fibre Reinforced Polymer (CFRP). A Finite Element model is presented for RHS externally reinforced with CFRP. Strengthening is achieved by applying CFRP plates outside the RHS. The finite element models are developed using three dimensional shell elements for the FRP composites. Contact elements were used to provide appropriate bonding between steel and FRP. Results obtained from the finite element analysis are compared with experimental data from literature and are found to be in good agreement.

#### 1 INTRODUCTION

The use of CFRP (carbon-fibre-reinforced-polymers) bonded to steel beams as a method of strengthening has increased during the last few years. Several laboratory and full-scale tests have been conducted (Mertz and Gillespie,1996; Dawood *et al.*,2006; Al-Saidy *et al.*,2004; Liu *et al.*,2001; Miller *et al.*,2001; Phares *et al.*,2003 etc.)all of which demonstrated that the load-carrying capacity can be increased by using this streng-thening system. Additionally, analytical and numerical studies have been performed by Smith and Teng(2001), Sen *et al.*(2001) and Deng *et al.*(2004) to obtain tools for predicting the degree of strengthening and the magnitude of the interfacial stresses, which can be critical for the strength of the system.

Web crippling of thin-walled steel members is often observed at loading or reaction points where concentrated forces exist. Extensive research on web crippling of RHS (rectangular hollow section) was carried out in the past (Packer ,1984,1987 and Zhao and Hancock ,1992,1995). The external corner radius ( $r_{ext}$ ) in cold-formed RHS introduces load eccentricity to the webs, which reduces the web crippling capacity. It has been found in the previous studies that the most important parameter related to web crippling of cold-formed RHS is the web depth-to-thickness ratio.

Web crippling consists of two failure modes, namely web buckling and web yielding. Critical web depthto-thickness ratios beyond which web buckling occurs are given by Zhao, *et al.*(2005) and has been showed that another important parameter influencing web crippling behavior is the loading position, i.e. interior bearing where the distance between the edge of the section and the loading point is larger than 1.5d or otherwise end bearing.

In general the web crippling capacity of an end bearing is lower than that for an interior bearing. This paper deals with the end bearing which is the most severe loading condition. In the case of I-section members, it is common to provide welded transverse stiffeners to prevent web crippling. For cold-formed members such as C and Z purlins, the cleats that attach the members to support structures provide web stiffening (Han-cock,1994; Young and Hancock ,2001).However, it is difficult to provide load-bearing stiffeners at loading points or supports for RHS sections.

Attempts were made before to increase the web crippling capacity of RHS especially for the end bearing load case. The techniques used include (i) partially filling the RHS with wood plus a bolt through the web (Zhao, 1999) and (ii) partially filling the RHS with concrete (Zhao, 1999; Packer and Fear, 1999). The carbon fibre reinforced polymer (CFRP) has high strength to weight ratio, resistance to corrosion and environmental degradation (Alsayed *et al.*, 2000). CFRP has been widely used in strengthening concrete structures with extensive research being conducted (Teng *et al.*, 2001; Neale, 2000; Nanni, 2003; Rizkalla *et al.*, 2003; Sen, 2003). There is an increasing trend of CFRP to strengthen steel structures. Here the possibility of using the CFRP strengthening technique to improve the web crippling capacity of cold-formed RHS is further encouraged.

It was found in previous literature that the CFRP strengthening significantly increases the web crippling capacity especially for those with large web depth-to-thickness ratios. The main reasons are: (i) change of

failure mode from web buckling to web yielding, (ii) increased restraints against web rotation and (iii) achievement of material strain hardening.

The FE analyses conducted in the current study are based on a series of laboratory tests conducted at Monash University by Zhao *et al.*(2006). The test results are verified with FE software so that in future applicability of CFRP can be increased and optimized by modeling the entire section following the analysis options used here.

#### 2 MATERIALS

The RHS sections used in the tests were conducted by "in-line" galvanizing cold-formed rectangular hollow sections. A section identification number is assigned to each RHS section as shown in Table 1. The average measured dimensions are given in Table 1. Tensile coupon tests were conducted according to Standards Australia (1991) to determine the tensile yield stress (0.2 % proof stress) and the ultimate tensile strength. Average measured values are presented in Table 1. The 0.2% proof stress is used later on in the paper as the yield stress of RHS. This is a common practice in dealing with cold-formed RHS (Zhao *et al.*,2005). The CFRP sheeting used in the tests is MBrace fibre CF130 which has a nominal modulus of elasticity of 240 GPa, a nominal ultimate tensile strength of 3800 MPa and a nominal thickness of 0.18 mm. The CFRP plates used in the tests were MBrace S&K laminate 150/2000 with a nominal modulus of elasticity of 165 GPa, a nominal ultimate tensile strength of 2700 MPa and a nominal thickness of 1.2 mm. The adhesive adopted was Araldite 420 as used in previous research by Jiao H and Zhao XL(2004). The thickness of adhesive for CFRP sheets was about 0.3 mm whereas the thickness of adhesive for CFRP plates is about 1 mm. This gives a reinforcement thickness for Type 2 about 1 mm ( $\approx 2 \times (0.18 + 0.3)$ ).

#### **3 TEST SPECIMEN**

A schematic view of various types of strengthening techniques is shown in Figure 1. Type 1 has no CFRP strengthening and acts as reference tests. Two layers of CFRP sheets are wrapped outside the RHS in Type 2. In all the specimens the direction of CFRP fibre is always perpendicular to the longitudinal axis indicated by an arrow in Figure 1(a) of RHS.



Figure 1.Types of CFRP strengthening — a schematic view (not to scale).

ruble 1.1(11) dimension and material properties												
Section	Nominal	Average measured dimensions			Young's	Yield stress	Ultimate					
Identification	dimensions	<u>d(mm)</u>	<u>b(mm)</u>	<u>t(mm)</u>	Modulus	$f_{y}$ (MPa)	tensile					
no.	(d x b x t)				(MPa)		strength					
							$f_u$ (MPa)					
S1	100 x 50 x 2	99.86	50.38	1.99	199	458	541					
S2	100 x 50 x 3	99.65	49.82	2.99	202	472	541					
S3	100 x 50 x 5	100.07	50.42	4.83	211	478	542					

Table 1.RHS dimension and material properties

#### 4 FINITE ELEMENT ANALYSES

The section of RHS without FRP is modeled with shell elements. The elements were merged together by sharing common nodes at the interfaces. Full interaction was therefore assumed between the different elements. Figure 2. shows the geometrical model used in the FE analyses. The analyzed RHSs are same in length but the loading length varied in different models. The load was given at the end of the section within a strip and the loading was given uniformly with a rectangular Solid block.



Figure 2. FE Model of the RHS without FRP

The analyses were carried out considering the non-linear material behavior of steel. . Stress-strain behavior of the steel material used in the FE model is shown in Figure 3. No initial imperfections or residual stresses, caused by the manufacturing process, were included in the model. The loading was given at the end section with varying strip length and varying load. Ultimately the max deflection in the loaded region was observed and was compared with the laboratory test results



Figure 3. Stress-strain behavior of the steel material used in the FE model.

## 4.1. RHS without CFRP (type-1)

At first analysis was conducted for type-1. The section shows web buckling mode (Figure 4 to 6) which is quite visible from the laboratory test also(Figure 7). The results obtained from the analysis were collected and compared with the laboratory test data and agreement was found between results.





Figure 4. Deformation along the Y-axis (type-1)

Figure 5. Deformation along the X-axis (type-1)





Figure 6. Deformation along the Z-axis (type-1)

Figure 7. Web buckling in Lab test (type-1) (Zhao et al., 2006)

Here contact element is used to get the actual contact surface between the block and the RHS. Target element is also used here to achieve the appropriate contact. Surface-to-surface contact is used instead of node-to-node contact. For establishing the contact parameters Augmented Lagrange method was followed, separation between the surfaces was allowed, shell thickness was considered, initial penetration was excluded and change in contact predictions made to achieve the minimum time/load increment whenever a change in contact status occurs was used.

## 4.2. RHS with CFRP (type-2)

After the verification of the loading test results of the RHS without CFRP, another section with CFRP is modeled and was simulated to verify with laboratory results. The FRP lamina was modeled using shell element. The contact between the FRP and the plate was established by the contact element and the target element. The Augmented Lagrange method was followed to establish the parameters. Shell thickness was considered during the deformation. Aggressive contact stiffness was avoided to get a real life contact situation. The FRP lamina was meshed with the same size as that of the RHS to get the proper contact. In case of CFRP the material properties were given as were used in the laboratory test. Surface-to-surface contact between the RHS and the CFRP were used. FE models of the section are shown in Figure.8 to 11.



Figure 8. Deformed shape of the RHS after loading (type-2)



Figure 9. Deformation along the X-axis (type-2)



Figure 10. Deformation along the Y-axis (type-2)



Figure 11. Deformation along the Z-axis (type-2)



Figure 12. CFRP delaminating and web yielding in Lab test (type-2) (Zhao et al., 2006)

Web yielding failure was observed in the FE analysis which can also be observed from the laboratory test (Figure 12). At the same time CFRP delaminating was also found to take place. It was quite a distinct fact that after implementing the CFRP, the section was able to take more loading and less deformation.

## 5 RESULTS AND VERIFICATION WITH THE LAB TEST

The results obtained from the type-1 & type-2 sections FE analysis was compared with the actual test results found in the lab tests. The comparison of the two approaches is presented in Table.2 and Table.3.

Table 2.Specimen details of type-1 and test results										
Section ID	Bearing length (bs) mm	Experimental Ulti- mate load <i>Pmax</i> (KN)	Load simulated with ANSYS (KN)	Deformation at Ul- timate load ∆max (mm)	Deformation ob- tained from FE with ANSYS (mm)					
S1	50	26.1	26.7	3.02	4.4					
S1	50	27.53	28	3.56	4.65					
S1	25	21.86	22	3.6	6.1					
S1	25	21.53	22.4	3.69	6.3					
Table 3.Specimen details of type-2 and test results										
Section ID	Bearing length (bs) mm	Experimental Ulti- mate load <i>Pmax</i> (KN)	Load simulated with ANSYS (KN)	Deformation at Ultimate load Amax (mm)	Deformation ob- tained from FE with ANSYS (mm)					
S1	25	31.36	31.25	36.29	32.54					

It is quite visible from the provided data that the test results and the FE results are very close. The deformation at the ultimate load capacity gives an idea about the ductility of the material. Another findings of the FE analysis is that it is easily visible that the sections behave more ductile when the CFRP were implemented. The predicted ultimate load and the deformation found from the FE analysis were in good agreement with the actual test data.

#### 6 CONCLUSIONS

FE analyses can be regarded as a very useful tool for modeling and analyzing the behavior of steel beams strengthened with bonded CFRP laminates. The following conclusions can be put forward, based on the results of the present study.

CFRP strengthening significantly increased the web crippling capacity especially for those with large web depth to-thickness ratios. The main reasons are: (i) change of failure mode from web buckling to web yielding, (ii) increased restraints against web rotation and (iii) achievement of material strain hardening. In case of type-2 it can be seen that the section is taking higher loading due to the implementation of the CFRP along its surface.

This paper highlights comparison between FE analysis results with a single laboratory test results but it encourages the other researches on FRP strengthened steel beams. These areas have received only small coverage, but which have developed rapidly: the bond between steel and FRP, the strengthening of steel hollow section members, and fatigue crack propagation in the FRP–Steel system. Future research topics have been identified as: the bond–slip relationship, the stability of CFRP strengthened steel members, and fatigue crack propagation modeling.

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