Reinforcement of Corroded Steel Structures with CFRP Panels

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Abstract
Carbon Fibre Reinforced Polymer composites are a proven method of providing structural strengthening that is lighter, non-corrosive, and less labour intensive than the application of steel plate or exterior post-tensioning. Corrosion of steel structures in bridges and other civil engineering applications induces a serious structural damage that could lead to the failure during operating conditions. Instead of replacing the damaged structures there is the current approach of repairing the corroded steel structures by strengthening the damaged steel beams or gridges using Carbon Fibre Reinforced Polymer (CFRP). The focus in this work is on tension angle members in truss type of steel structures. The loss of sectional area due to corrosion effect was represented by creating notches of different sizes (3 mm – 12 mm) in the angles. The results revealed that CFRP reinforcement is able to rehabilitate the corroded steel to the point that the tensile strength reached a value within 20% of the original value of the undamaged steel truss for artificial notch length lower than 9 mm. The effect of moisture on the corroded and rehabilitated steel structures was also investigated and the results revealed a decrease of 7% in the ultimate tensile strength of the steel truss after 2000 hours of continue immersion in water.

Keywords : CFRP composites, corrosion of steel, tensile strength, moisture effect.

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Introduction
Carbon fibre reinforced polymer (CFRP) laminates is a modern technology that provides a solution for strengthening problems of different types of structures such as concrete and steel. It provides high strength, high modulus of elasticity, and outstanding fatigue resistance. It is a very lightweight non-corrosive material, which requires minimal preparation of laminates, and is alkali resistant. These lightweight carbon fibre strips can provide ten times the tensile strength of steel. This capability of the fibre to carry loads in tension can be used to strengthen against flexure, shear, or compression, depending on how the carbon fibre strips are oriented to the longitudinal reinforcing steel. CFRP strips have been on use for over twenty years, on bridges, parking garages, manufacturing facilities, schools, libraries and public utility structures.

Corrosion can reduce the total sectional area of a steel member in a structure which in turn increases the stress in the corroded area leading to a catastrophic failure of the structure.

See in Figure 1 the physical deterioration of steel in a bridge due to corrosion. In Europe, about 50% of the existing bridges need to be retrofitted due to the corrosion effect but the situation differs from one country to another (Radomski, 2002).

Figure 1. Typical corrosion observed in the steel structure of a low level bridge.

The traditional method of repairing corroded steel structures is by cutting out the damaged sections and replacing them with new steel plates. Such method is costly, time-consuming, and needs heavy lifting equipment. In addition to that, the new plates add more dead load to the structure and they are prone to corrosion, as well as, stress concentration resulting from welding or drilling (Tavakkolizadeh and Saadatmanesh, 2003; Colombi and Poggi, 2006). Also, welding introduces additional problems such as quality control of welding, welding difficulties in poorly accessible locations, unknown residual stresses introduced by welding, weld cracking in the zones affected by welding heat and dramatic reduction in fatigue life cycles (El-Tawil et al., 2011).

Also important is the fact that repairing by welding of a steel structure in a highly explosive environment can be only done under strict safety precautions, while this can cause significant interruptions to traffic in a bridge and production cost for storage and offloading vessels in ports it is used widely in offshore oil and gas mining. All these procedures due to safety and resulting in production interruption mean dramatic increase in the repairing cost (Tsouvalis et al., 2009; Mcgeorge et al., 2009).

As a result of these factors in recent years the use of carbon fibre reinforced polymer (CFRP) laminates for the rehabilitation of steel structures is gaining popularity among engineers and the construction industry. CFRPs have superior characteristics such as high strength to weight ratio and very good durability for ambient conditions, anti-corrosive properties and high resistance to severe environments. These characteristics make CFRP a good candidate for retrofitting of old steel structures. Besides that, the weight of CFRP laminates is less than one fifth of the weight of similar size steel plates (Shaat et al., 2003). The use of CFRP also avoids the welding problems mentioned previously. Along with the reduction in cost and time of rehabilitation of corroded steel components, the Young modulus of CFRP composite is close to or higher than that of steel (Nguyen et al., 2011) which adds another reason for choosing it to rehabilitate steel structures.

Many experimental works and theoretical studies have been conducted on the performance of bonded CFRP composites on steel members. Patnaik and Bauer (2004) studied four I-sectioned undamaged beams. It was observed that the CFRP reinforcing resulted in 14% increase in the capacity of flexure strength and 26% increase in shear strength.

Vatovec et al. (2002) used 50 mm x1.2 mm CFRP strips to reinforce in tension and compression flanges of rectangular steel tubes. The results showed increase in the ultimate moment capacity from 6% for specimens with one strip bonded to the compression flange to 26% for specimens with two strips bonded to the tension flange. A theoretical study by Toutanji and Dempsey (2001) proved that using CFRP sheets around damaged steel pipe lines (circular hollow section) improve the internal pressure capacity of pipes better than other types of FRP sheets (glass or aramid fibres).

A three-point bending test on artificially notched steel beams and reinforced with bonded CFRP strips was conducted at the University of Missouri-rolla (Liu et al., 2001). The use of CFRP generated an increase of 60% in the plastic load capacity for the full length specimen and 45% for the one quarter length specimen.

Tavakkolizadeh and Saadatmanesh (2001) used four-point bending on two groups of S5 x 10 (American steel sections designation) steel beam, which were cut in the middle of tension flange to depths of 3.2mm for the first group and 6.4 mm for the second group. Both groups were reinforced by different lengths of CFRP sheets. Their results showed that ultimate load carrying capacity and stiffness of retrofitted specimens were close to their original values in the control specimen regardless of the length of the CFRP patch. The results of the deep cut group showed distinct loss of ductility in comparison with the shallow cut group. Zhao et al.(2006) used different styles of CFRP strengthening technique to improve the web crippling capacity of cold-formed rectangular hollow section. It was found that CFRP composite remarkably increased the web crippling capacity, especially when the ratio of web depth-to-thickness is large. However, one disadvantage of this technique is the possibility of causing further corrosion of the steel by galvanic corrosion. This risk can be eliminated by the application to the steel of an isolating epoxy film or a nonconductive layer of fabric between the two bonded materials (steel and carbon), or applying moisture barrier to the bonded area (Tavakkolizadeh and Saadatmanesh, 2001 and Shaat et al., 2003).

Most of the previous studies on rehabilitation of steel members using CFRP laminates were focused on the flexural properties of the steel structures. There is a clear gap in the research on the rehabilitation of truss type members in which the steel member is subjected to axial load mainly. This study investigates the possibility of strengthening corroded steel angles using CFRP laminates. The focus here is on tension angle members in truss type of steel structures. The loss of sectional area due to corrosion effect is represented by creating notches of different sizes on the steel truss specimens. Additionally, the effect of moisture on the mechanical properties of the notched steel structures after the rehabilitation with the bonded CPFRP laminates, is also investigated in this work.

Experimental Works

Material properties and dimensions

The steel truss specimens and the CFRP strips were purchased from Blue Scope Steel Company (SMORGON STEEL) in Australia, and H. E. Supplies Pty Ltd, Australia, respectively. The tensile tests were performed in accordance to AS 1391- 2007 Standard for steel specimens and with reference to ISO 527 – 5: 1997 for the CFRP specimens. The average modulus of elasticity for steel panels and CFRP laminates were approximately 272 and 125 GPa, respectively. The suggested dimensions for steel angle were 25 mm equal legs angle x 3 mm thickness x 350 mm length, while the dimensions for CFRP strip were 25.4 mm width x 0.8 mm thickness x 150 mm length.

Primer and Adhesive resin

It is recommended for bare steel to be pre-treated by and adhesion promoter or a primer which leaves a thin layer attached to the oxide surface of steel (Mays and Hutchinson et.al. 1992). The applied primer was SWANCOR 984 purchased from Swancor Ind. Co., Australia. The liquid adhesive used to bond the CFRP to the steel surface after the primer was an epoxy based resin known as Hysol EA 9330 and sourced from Logistics Ltd, Australia.

Preparing and testing of Specimens

The jaws of the MTS testing machine (500 kN capacity) were converted to be suitable to catch the whole angle of dimensions (25 mm x 3 mm x 350 mm). The steel angle specimens were notched to simulate the corrosion effect. The reduction in the cross- sectional area for notched steel specimens was started from 3 mm rectangular shape edge notch in both angle legs at middle length of the specimen and then increased to 6 mm, 9 mm and 12mm long (in edge normal direction) notches for each leg of the angle. This caused reduction in cross-sectional area of the angle from 12.5% for 3 mm notch and up to 51% for 12 mm notch. These notches were made using a CNC Machine (at the mechanical workshop of the University of Southern Queensland). Each notched steel angle was reinforced by two CFRP laminates, each one attached to the outside edge of the angle legs. Figure 2 shows the method of reinforcement while Figure 3 shows a picture of notched steel angle. For each size of notch, three reinforced steel specimens and three unreinforced specimens were tested and the average for each three was compared with the intact sample.

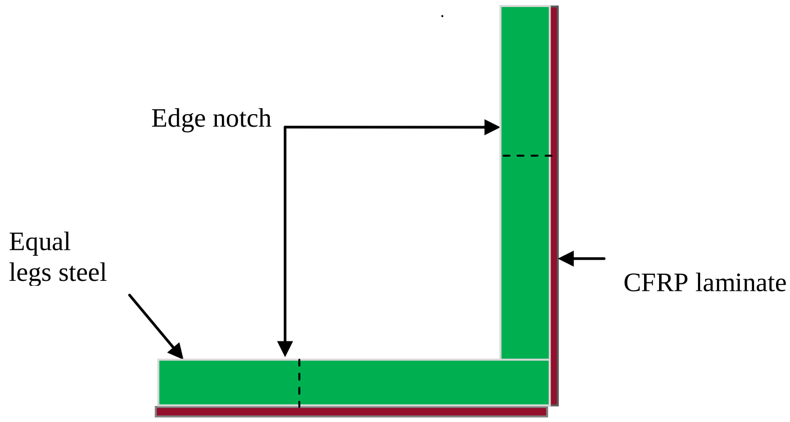

Figure 2. Method of reinforcing notched steel angles

Moisture Effect

The corroded steel specimens reinforced with CFRP laminates were immersed in water following a standard procedure previously reported to determine the effect of moisture in steel structures (Selzer and Friedrich, 1997 and Yang et al. 2005). In the current study we followed the effect of moisture on the 9 mm notched and rehabilitated steel samples up to 2000 hours of immersion in tap water. Samples were taken out of the water every 500 hours for testing.

Figure 3. Notched steel angle used in this research work.

Experimental results and discussion

Rehabilitation of corroded steel angles with CFRP laminates:

Reinforced steel angles of 9 mm notch with CFRP strips were subjected to tensile test with reference to AS 1391- 2007 standard, and for comparison a set of three unreinforced specimens were also tested. The average values of the tensile tests are presented in Table 1, which confirms the rehabilitation effect of the bonded CFRP on the damaged steel specimens. The tensile yield load increased by about 45.8%, while the ultimate load increased by 17.1%. The general trend of these results agreed well with the previous researches of Liu et al. (2001) and Tavakkolizadeh and Saadatmanesh (2001) on improving load carrying capacities of steel structures with CFRP reinforcement.

Table 1: Results of corroded steel angles

Sample: Steel angle truss	Tensile Yield load (N)			Ultimate Tensile Load (N)		
	without CFRP	With CFRP	Increasing ratio %	without CFRP	With CFRP	Increasing ratio %
Average	32310	47100	45.8	45320	53130	17.1

Figure 4 shows the stress-strain plots during the tensile test for 3 mm notch steel specimens with and without the CFRP reinforcement. As a comparison the tensile curve for the steel angle sample without notch is included. As shown, the tensile yield of the CFRP reinforced steel truss is higher than for the unreinforced sample but lower than the value for the undamaged steel plate.

The mechanical tests of the rehabilitated steel samples showed the presence of a strong adhesion bond between the FRP laminate and the surface of the steel plates. The tensile tests also demonstrated that the reinforcement of the damaged steel plates with CFRP laminates significantly increased the load capacity of the damaged plate in comparison with the steel specimens without CFRP. This confirms that CFRP laminates are able to rehabilitate and fix a steel structure damaged by corrosion or by a physical or mechanical induced deterioration.

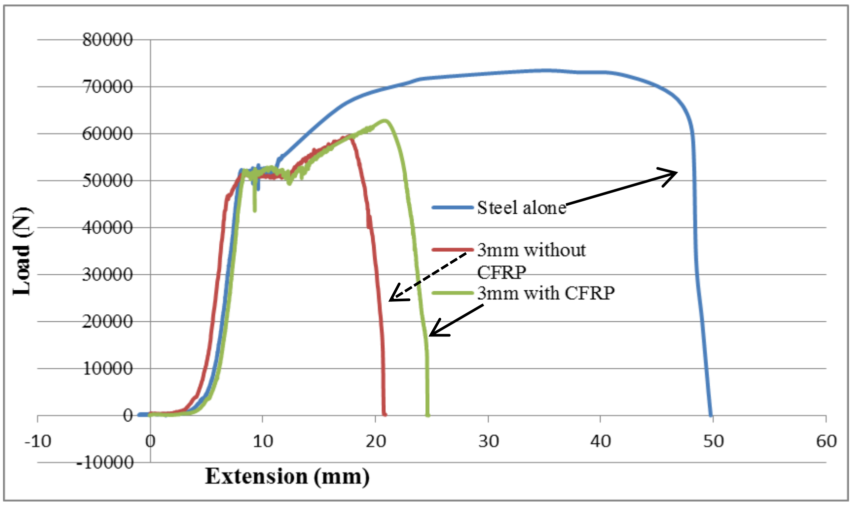

Figure 4. Effect of CFRP on load-extension diagram for 3mm notch specimen and for the original steel material.

It can be seen from Figure 4 that the CFRP strengthening increased the average ultimate load by about 4.6% and the average yield load by about 14% in comparison with specimen without CFRP. In addition to that, there was increase in ductility. Similar observations and results were previously reported (Zhao et al., 2006), which confirmed the increases in strength and ductile behaviour of the steel beams with CFRP reinforcement. In the present work for all three tested specimens of 3 mm notch with CFRP, the delamination of the CFRP layers occurred after the yielding point of the specimen which increased the max tensile strength and the ductility during the test of the reinforced steel angles in comparison with the equivalent steel angles without CFRP reinforcement. This effect is due to the increases in strength of the steel specimens provided by the bonded CFRP laminates.

Table 1 show the yield and ultimate loads for rehabilitated notched specimens compared with those without CFRP for different notch sizes. Figures 5 and 6 give a graphical representation of the effect of CFRP rehabilitation on the ultimate and yield loads, respectively, of steel angles with different percentages of corrosion. It was observed that the delamination of the CFRP strips happened after the yielding phase, confirming the strong bond of the carbon strips to the steel plates and the rehabilitating effect of the CFRP on the damaged steel structures.

Table 1. Yield and ultimate loads of rehabilitated notched steel specimens.

Steel Sample	Yield load (N)			Ultimate load (N)		
	without CFRP	With CFRP	Percentage increase (%)	without CFRP	With CFRP	Percentage increase (%)
Steel alone	52125	-	-	73521	-	
3 mm notch	45803	52268	14.11	60608	63377	4.56
6 mm notch	39133	51856	32.51	51222	53646	4.73

9 mm notch	32311	47133	45.86	45321	53077	17.11
12 mm notch	25836	35456	37.23	39128	42898	9.63

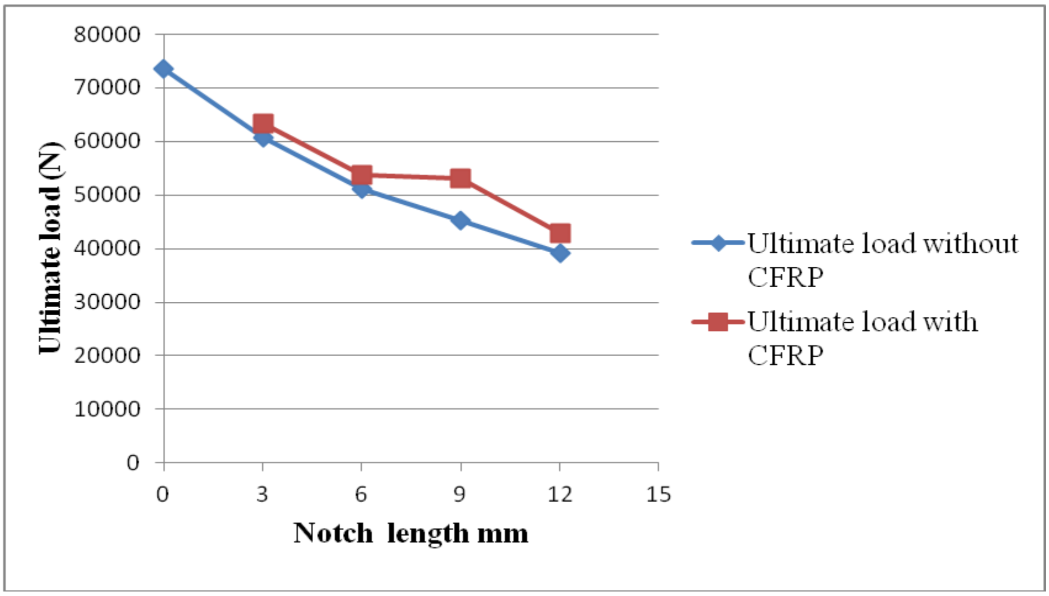

Figure 5. Improvement in ultimate loads of rehabilitated notched specimens.

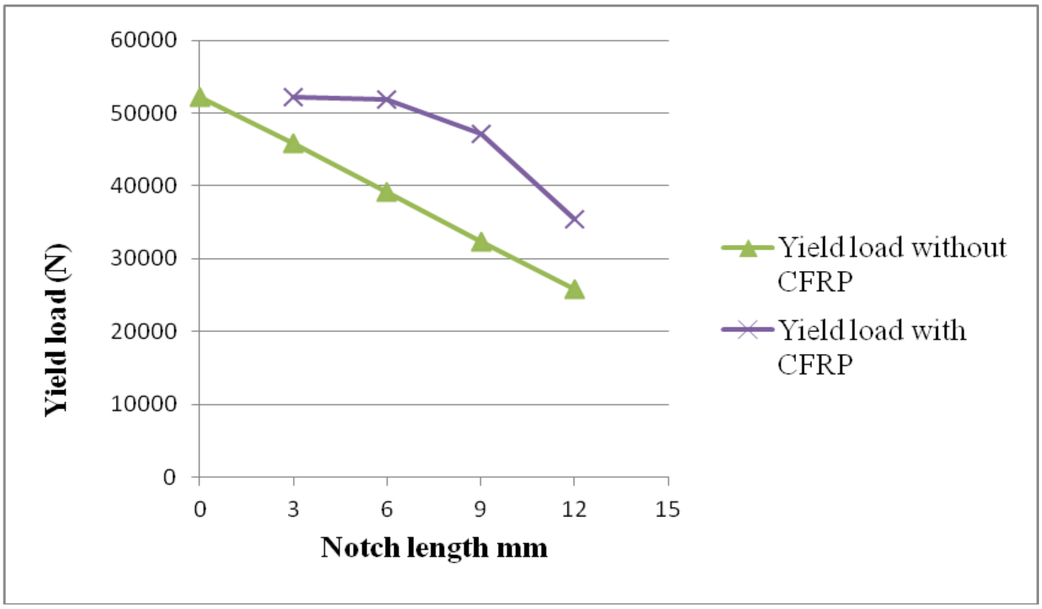

Figure 6. Improvement in yield loads of rehabilitated notched specimens.

Effect of moisture

It is important to identify the effect of moisture on this rehabilitation technique because it is a significant parameter which can influence the ultimate mechanical performance of the steel structure rehabilitated with the CFRP laminates. Table 2 present the results of the recorded ultimate tensile stress of the 9 mm notch rehabilitated steel specimens at different times (hours) of immersion in water in comparison with the control sample, which is the rehabilitated steel specimen measured at the beginning of the test (0 hours).

Table 2: Effect of moisture on ultimate tensile stress of the rehabilitated steel truss samples.

Time under water (hrs.)	Ultimate tensile stress (MPa)	Reduction in ultimate tensile stress %
0	497.7	0.0
500	489.1	1.76
1000	484.5	2.73
1500	478.8	3.95
2000	465.5	6.92

As the moisture time in hours increased, there was a continue reduction in the ultimate tensile stress of the tested specimens (see Figure 7). The reduction rate significantly increased after 1000 hours of immersion time with an ultimate decrease in the tensile stress yield of 6.92% at 2000 hours of testing in comparison with the value of the initial steel sample. Smith et al.(2005) found a similar general effect of moisture exposure leading to a decrease of the strength and Karbhari et al. (2003) reported that the effect of long-term moisture exposure will induce degradation and decrease in the load carrying capacity of the steel structure.

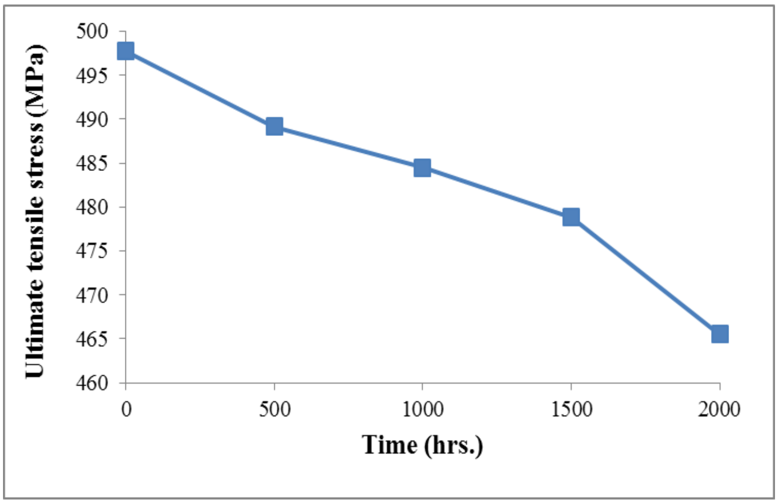

Figure 7. Moisture effect on the ultimate tensile stress of rehabilitated steel truss with CFRP.

Conclusions

This study confirmed the possibility of strengthening corroded steel angles in axial force applications using Carbon Fibre Reinforced Polymer (CFRP) laminates. The focus of this study was on tension angle members in truss type of steel structures. The analysis of the obtained testing results can be summarised in the following conclusions:

- The artificial notch on the steel specimens even of small size, sharply affect the strength and ductility of the steel truss in comparison with the original one.
- For the corroded steel truss the load –extension behaviour and stress distribution are largely affected by the size of the notch.
- Strong bonding of the CFRP laminates to the surface of the steel samples is fundamental for the effective rehabilitation of the damaged steel and can be achieved with the primer and adhesive used in this study.
- The CFRP strips used in this study for the rehabilitations of the artificially corroded steel angle samples improved the ductile behaviour of the steel samples, especially for the 3 mm notch samples.
- The CFRP strips used in this study increased the load carrying capacity of 9 mm notch deteriorated steel samples up to 46% in yield load and 17% in ultimate load in comparison with the samples without CFRP reinforcement.

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