Simplified FE model predicting the bending behaviour of corroded tubular steel members rehabilitated using CFRP

Jerin Mathew GEORGE [1], Mehrdad KIMIAEI [1], Mohamed ELCHALAKANI [1]

[1] The University of Western Australia, Perth, Australia

Contact e-mail: jerin.george@research.uwa.edu.au

ABSTRACT: Offshore structural members will be forced to undergo repair and strengthening when either the structural components have degraded critically due to the corrosive marine environment or the structure needs to carry extra loads than they were designed for due to work over demands, heavier equipment or increased environmental loads. Using FRP composites is established as a cost-effective and efficient method for rehabilitation and non-structural repair of these type of structures. However, the use of FRP composite material in strengthening or structural repair of offshore facilities is still limited to a few basic applications due to the lack of a proper design framework. Tubular steel members are widely used in offshore platforms and in this paper, existing experimental test data for the ultimate strength of tubular sections retrofitted with CFRP under bending was used to develop an FE model. The accuracy of the model was examined against the experimental data and a reasonable match was found. The simplified FE modelling technique presented in the paper is expected to aid in the development of a design framework for CFRP retrofitted steel tubular members.

1 INTRODUCTION

Circular Hollow Sections (CHS) are widely used as structural members in the offshore industry. The highly corrosive marine environmental conditions in which these members are utilized makes it necessary to rehabilitate them. Due to the high specific strength, Carbon Fiber Reinforced Polymer (CFRP) composites are accepted as a suitable repair material for steel CHS (Saeed 2015). However, the rehabilitation of steel structural members with CFRP composites are practiced limitedly in the offshore industry due to the lack of a design framework for this kind of retrofitting (Alexander et al. 2008). The FE modelling technique presented in the paper will be a first step in addressing this issue for offshore structural systems.

Elchalakani (2016) & Elchalakani et al. (2017) presented experiments looking into the rehabilitation of corroded Circular Hollow Sections (CHS) using CFRP. The corrosion was artificially induced in the steel tubular members by machining them. The corrosion thickness was varied in order to understand the effect of the level of corrosion and the length of the corrosion was also parametrically investigated. The Structural Technology (ST) V-wrap, a unidirectional CFRP was utilized to retrofit the corroded specimens. The retrofitting showed a significant increase in the ultimate strength of the specimens under three-point bending. The experimental specimens which used only two layers of CFRP were selected from Elchalakani (2016) to develop the FE model in this paper.

The paper aims to present the development of a simplified Finite Element (FE) modelling technique to predict the three-point bending in steel CHS retrofitted with CFRP. The potential of the modelling technique in predicting the ultimate capacities FRP retrofitted steel tubular members is showcased in the paper.

2 METHODOLOGY

The modelling of bare steel specimens under three-point bending was the first step carried out in the FE modelling. The experimental set up as shown in Figure 1 was replicated in Abaqus software (Simulia 2019) by defining the saddle supports and loading rod as rigid bodies in contact with the steel CHS. The saddle supports were fixed and the loading rod had a degree of freedom in translation to facilitate the loading motion. The bare steel CHS was modelled as a deformable shell element in Abaqus. Elchalakani (2016) used mild steel CHS of grade B335JR confirming to ASTM A53 Schedule 30 in the experimental study. An elastic-plastic material model was employed to define the steel for the bare specimens in the FE model. The average yield stress (482.63 MPa) found out from the tensile coupon tests conducted by Elchalakani (2016) was used in the material definition.

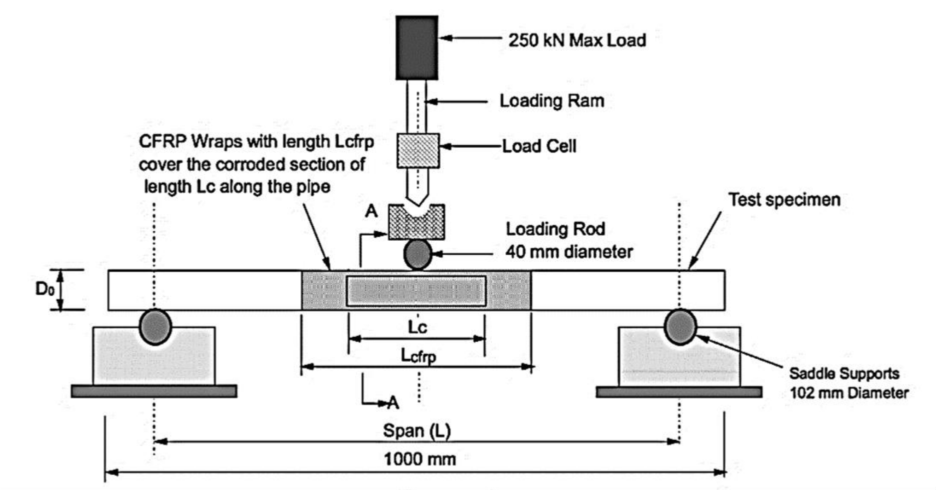

Figure 1. Experimental set up for three-point bending, Elchalakani (2016).

The experimental specimens were cut from CHS of outside diameter, D_o = 101.6 mm and thickness, t_o = 5 mm. The clear span of specimens between the saddle supports was 900 mm. The corrosion was artificially induced by machining 360° around the pipe for various depth. T5 is the control specimen representing a 0% corrosion in the wall (i.e., 5 mm thickness). The same logic was applied to T4, T3, T2 and T1 representing a 20%, 40%, 60% and 80% corrosion in the wall respectively (i.e. 4 mm, 3 mm, 2 mm and 1mm thickness). L1 and L2 represented the length of corrosion (L_c) equal to 100 mm and 200 mm respectively. C0 or C2 was indicative of 0 and 2 CFRP layers respectively used to retrofit the specimen. 1T1L was conveying the orientation of the CFRP layers, one layer in the transverse (T) direction and one layer in the longitudinal (L) direction (Elchalakani 2016).

The second step in FE modelling was the development of the retrofitted model. The same setup utilized earlier was used for this as well. The corroded region was filled with an elastic filler material of negligible structural stiffness and the retrofitted zone was wrapped with CFRP layers similar to the experimental specimens. In the experimental study by Elchalakani (2016), parameters like length of corrosion (L_c), length of CFRP wrapping (L_{CFRP}) and corrosion percentage were investigated. The effects of these parameters were studied using the FE model too.

The CFRP properties were defined using an elastic-plastic orthotropic lamina with a stronger elastic modulus in the predominant direction. The elastic moduli in a lamina were defined by strong and weak directions which simulated the properties along and across (longitudinal and transverse for the pipe) the fiber orientation. The elastic properties along the thickness were considered negligible by default in a lamina definition. The Poisson's ratio and the shear moduli in all 3 planes were required to complete the elastic lamina definition. The Hashin damage model was included to define the failure of the composite layer (Hashin 1980). A Hashin coefficient (α) equal to 1 was employed. The damage initiation was modelled by defining tensile, compressive and shear strengths in the longitudinal and transverse directions. Damage evolution was defined with tensile and compressive fracture energies in both directions. Damage stabilization was defined with the corresponding viscose regularization for each fracture energy. The material data provided by the CFRP manufacturer was not sufficient to define all the above properties. Hence, the microscopic material definition for CFRP developed by Rentsch et al. (2011) was utilized as the basis for the CFRP material definition in Abaqus for fiber strengths in the transverse directions, fracture energies and viscose regularization. The CFRP layers were defined with the properties as presented in Table 1 to have the best representation of the fibers used in the experiments by Elchalakani (2016).

Table 1. CFRP material definition in the FE model.

CFRP Material Properties		
Elastic Lamina Properties	E Modulus, L (GPa)	270
	E Modulus, T (GPa)	8.5
	Poisson's Ratio	0.32
	Shear Modulus (MPa)	3260
Hashin Damage Parameters	Hashin coefficient	1
	Tensile Strength, L (MPa)	4820
	Compressive Strength, L (MPa)	3000
	Tensile Strength, T (MPa)	48
	Compressive Strength, T (MPa)	200
	Shear Strength, L (MPa)	79
	Shear Strength, T (MPa)	79
	Tensile Fracture energy, L (N/mm)	0.01
	Compressive Fracture energy, L (N/mm)	0.005
	Tensile Fracture energy, T (N/mm)	0.0009
	Compressive Fracture energy, T (N/mm)	0.006
	Viscose Regularization (all)	1.0E-07

The FE model of the CFRP retrofitting was developed using the composite layup technique in Abaqus. The composite layup is an inbuilt feature in Abaqus where multiple layers of different materials can be modelled with ease (Simulia 2019). Instead of taking the thickness of the entire composite which is the sum of resin and fiber thickness, the thickness of the fiber (0.23 mm) was only used in the model. This was done as only the fiber will be actively participating in the load sharing with steel. In the layup shell element, the transverse (T) and the longitudinal (L) layers of the CFRP are distinguished based on their orientation angles. The disadvantage of the model is that debonding and delamination of the fibers due to adhesive failures will not be simulated. In an ideal case scenario, debonding and delamination failures should be avoided until the retrofitted fitted specimen reaches the ultimate strength. If this condition is achieved in the experimental specimens, the FE models would be capable of capturing the bending behaviour of the CFRP retrofitted steel specimens. This capability was demonstrated through the visual comparison between the experiment and the FE model of a CFRP retrofitted steel CHS under bending presented in Figure 2.

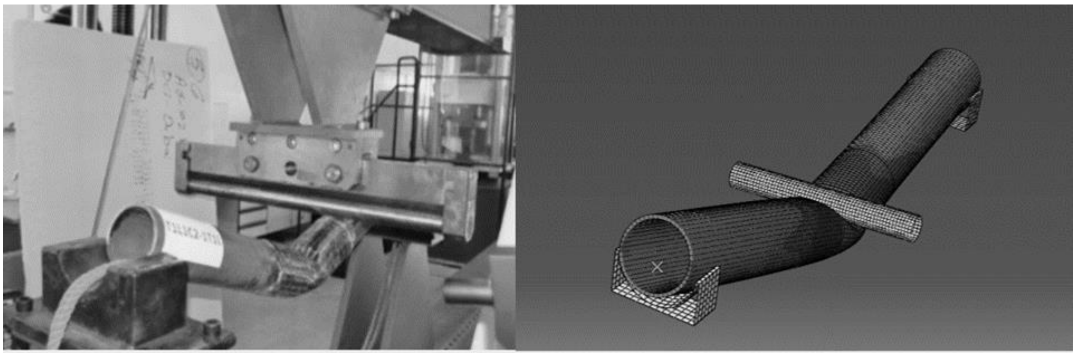

Figure 2. Comparison of the experimental specimen [left] with the FE model [right].

3 RESULTS AND DISCUSSION

The comparison between the FE models with the experimental results for typical bare steel specimens is presented in Figure 3. It is seen that the bare steel models are showing a very good agreement with the experimental results. A high level of agreement in the ultimate strength, as well as the load-displacement behaviour of bare steel specimens, was observed. However, the agreement decreased as the level of corrosion increased. The reason behind this was the fact that the stress concentration at the sudden drop in thickness cannot be properly simulated in the FE model. Due to this, the FE model was predicting a slightly lower capacity than what was observed in the experimental study.

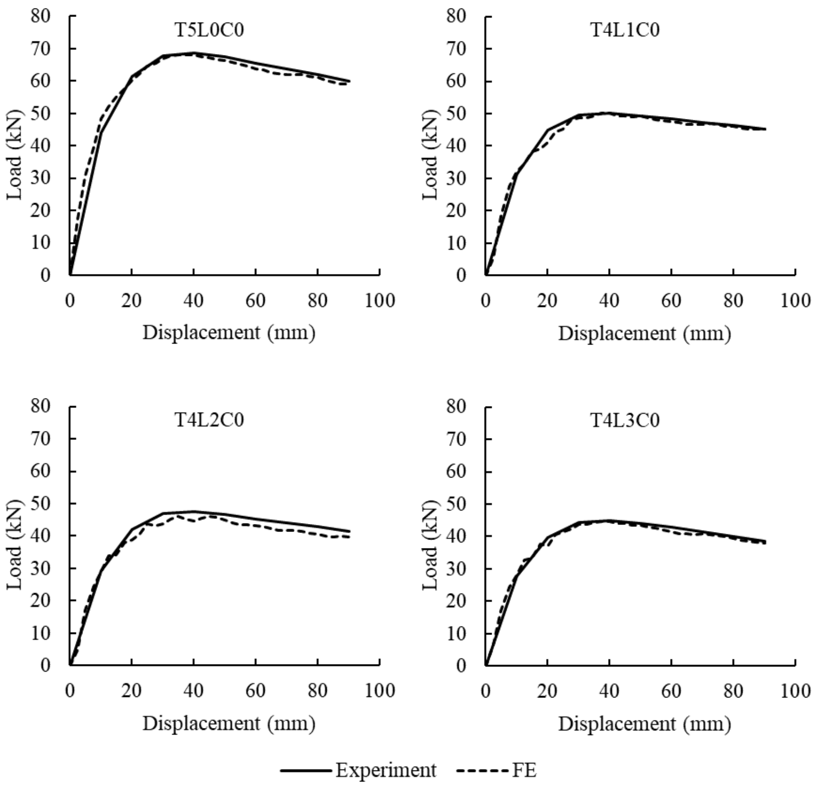

Figure 3. Comparison of the FE model with the experimental results for typical bare steel specimens.

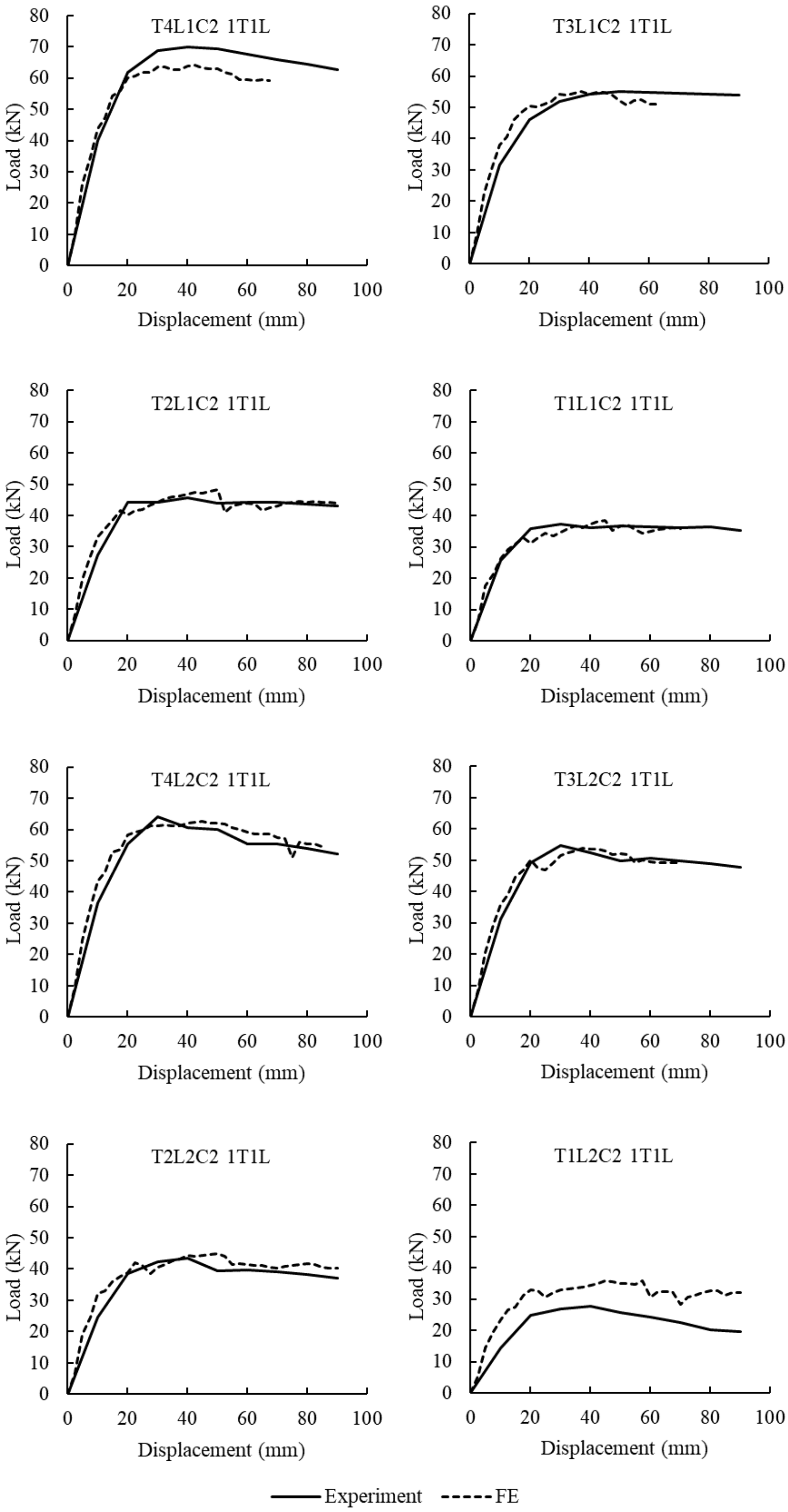

Figure 4. Comparison of the FE model with the experimental results of 1T1L series.

The FE models of CFRP retrofitted specimens showed a good agreement with the experimental results as presented in Figure 4. In the elastic region, the FE model was slightly higher than the experimental load-displacement behaviour. The ultimate load and post-failure behaviour were matching very well for most of the cases. The ratio of the ultimate load from the FE model to the experimental value was calculated and presented in Table 2. The ratio from all the specimens in the 1T1L series showed an average of 1.04 and a standard deviation of 0.11 indicating the good reliability of the FE model in predicting the bending behaviour of CFRP retrofitted CHS.

Table 2. Validation of the FE model for 1T1L series.

Specimen	Length of Corrosion (mm)	Corrosion (%)	Ultimate load - Experiment (kN)	Ultimate load - FE (kN)	Ratio
T4L1C2 1T1L	100	20	70.0	64.0	0.91
T3L1C2 1T1L		40	55.0	55.0	1.00
T2L1C2 1T1L		60	45.7	48.2	1.05
T1L1C2 1T1L		80	37.3	38.6	1.03
T4L2C2 1T1L	200	20	64.1	62.6	0.98
T3L2C2 1T1L		40	54.7	53.8	0.98
T2L2C2 1T1L		60	43.5	45.0	1.03
T1L2C2 1T1L		80	27.8	35.8	1.29
Average					1.04
Standard Deviation					0.11

The FE model for T4L1C2 1T1L was under predicting the experimental results by 9% which was the worst case scenario of the FE model failing to reach the ultimate capacity as in the experiment. Even in this case, the load-displacement behaviour was reasonably matching well until the yielding started.

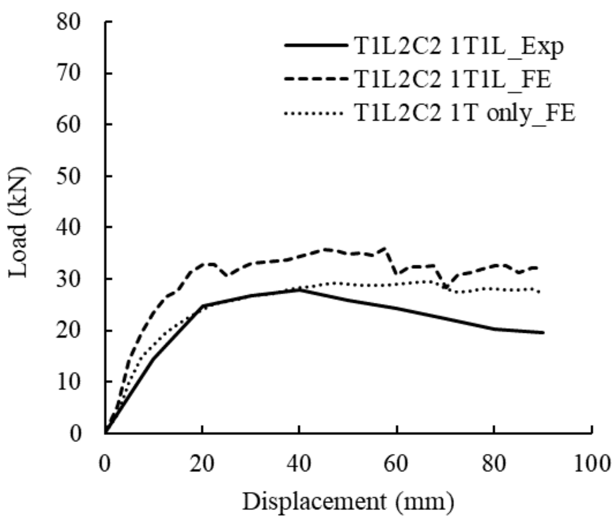

Figure 5. Investigation of the over prediction in the FE model of T1L2C2 1T1L.

The comparison of the FE model and the experimental results for the specimen T1L2C2 1T1L showed considerable disagreement. This was the only case where the FE model significantly over predicted the experimental results. The FE model predicted the ultimate load to be 29% higher than the observed experimental ultimate load. The occurrence of premature debonding in the CFRP layers could be a probable explanation for the low ultimate load in experiments. In order to investigate this issue, the exterior layer of the CFRP retrofitting system was removed and analysis was carried out to examine its effect. The comparison of the FE models with that of the experimental results is presented in Figure 5. The FE model with only the transverse (T) layer of CFRP showed a closer match with the experimental results confirming the probable cause of the low values from this experiment. The difference in the ultimate load had dropped from 29% to 6% due to this assumption made in the FE model. Hence it would be reasonable to presume that the exterior longitudinal (L) layer of CFRP in the experiment debonded prematurely and did not contribute to the load carrying abilities of the T1L2C2 1T1L. Elchalakani (2016) had reported debonding for this specimen, but whether this debonding was initiated prematurely as inferred from the FE model is unclear.

Moreover, when the ultimate strength was studied with the corrosion percentage, an overall linear decreasing trend was observed as shown in Figure 6. The data points were grouped based on the two different lengths of corrosion, L1 = 100 mm and L2 = 200 mm. All the FE results have agreed to the general trend line presented and a good fit was found for most of the experimental results. The two experimental results showing an out of trend results suggest the possibility of non-standardized CFRP retrofitting process for them. Even though the exact reason for such discrepancy cannot be explained, the mismatch between the FE results and the experiments for these cases can be attributed to the application procedure of the CFRP repair system.

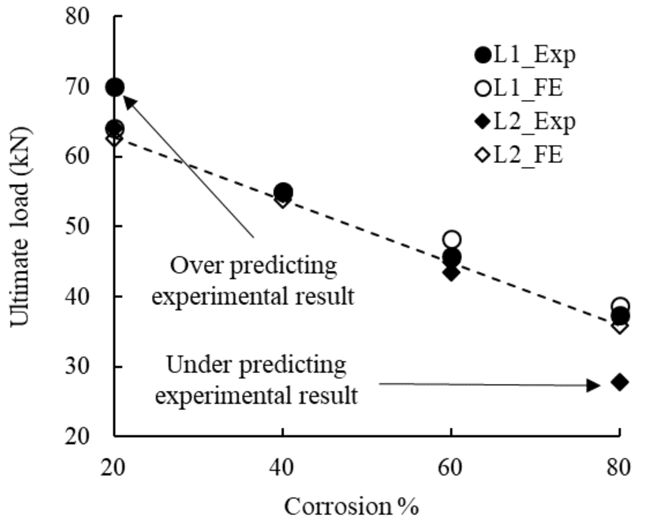

Figure 6. The trend for the ultimate load with the change in the percentage of corrosion.

The simplified FE model presented appears promising to predict the bending behaviour of CFRP retrofitted steel tubular members. The work presented in this paper was limited to only retrofitting of 2 layers of CFRP. The model needs to be checked for its accuracy in predicting the behaviour of more than 2 layers of CFRP. Fawzia et al. (2006) had experimentally found the decreasing strain distribution towards the exterior layers of CFRP. This consideration will have to be accommodated into the FE model to get the accurate behaviour of the CFRP retrofitting as the number of layers increases. This could be a potential avenue for further development in this FE model.

4 CONCLUSION

The paper presented a simplified FE modelling technique for CFRP retrofitted steel tubular members under bending loads. The accuracy of the model in predicting the load-displacement behaviour of the CFRP retrofitted CHS under three-point bending was demonstrated successfully. On average, there was only a variation of 4% in the ultimate load simulated by the FE model to that of the experimental results. The paper also attempted to address certain unexpected behaviour in an experimental program. The accuracy of the model could be further improved by the inclusion of cohesive elements between the CFRP layers and the steel surface. Overall, an FE model which can be easily developed for typical offshore tubular sections was demonstrated and the effectiveness of the model was discussed in detail.

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