Numerical simulation of debonding of CFRP strengthened steel beam

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Abstract— *Carbon Fiber Reinforced Polymer (CFRP) is an advanced engineering material introduced to aerospace industry, recently. Later, the applications of CFRP extended to other field as well. In Civil Engineering, CFRP is popular in retrofitting of damaged and deteriorated structures. Although the material has been successfully applied to concrete structures, applications in steel structures have been limited due to some drawbacks. One of such drawbacks is debonding of CFRP. In an effort to identify the factors affecting debonding, this study explored how the properties of adhesive could affect debonding.*

Non-linear finite element analysis was carried out for a 3D model of steel I girder subjected to four point bending. The model was validated using the experimental results available in the literature. CFRP laminate was attached to the bottom of the flange using three different types of adhesives having different material properties.

The results of the numerical simulation showed that both the increment in load carrying capacity and the failure mode is affected by the properties of the adhesive significantly. As the shear strength and the elastic modulus of the adhesive increases, a considerable increase in the load carrying capacity is observed. However, the increment in load carrying capacity with respect to the increment in elastic modulus seems to become less significant as the elastic modulus increases. For example the increment in load carrying capacity per unit increment of elastic modulus between the first two adhesives is 3.7 kN while the same between the second and third adhesives is 0.21 kN. Also, the failure mode is found to be switched from below load point debonding (failure of the bond between the CFRP and adhesive) to below load point splitting (failure of CFRP plate in transverse direction)

Therefore, it can be concluded that when designing a CFRP strengthening system for structural steel, considerable attention must be given to the adhesive properties as well

Keywords— **CFRP, Steel, Finite Element Analysis**

I. INTRODUCTION

In most of the cases, retrofitting of old structures is considered as the most feasible solution comparing to replacement of those old structures with new structures. Therefore, retrofitting of structures have gained sufficient attention since long in the construction industry. Among the retrofitting techniques in practice such as addition of steel plates or supports or post tensioning of parts, CFRP can be introduced as a relatively new technique. CFRP has found successful application as a retrofitting technique due to its light weight, corrosion resistance and improved fatigue properties.

CFRP, initially introduced to the aerospace industry and later extended its application in the construction industry, is a composite material consists of carbon fibers embedded in a polymer resin. As a result, CFRP behaves as an orthotropic material having different properties in longitudinal and transverse directions. Currently, CFRP can be found in a wide range of elastic moduli values of which the highest value can be above 400 GPa. Due to these remarkable properties, CFRP has been widely employed in retrofitting of concrete structures in most of the countries in the world as well as in Sri Lanka (Fernando, 2011). However, usage of CFRP in retrofitting of steel structures has been limited due to some drawbacks out of which debonding has become a major concern. However, considerable use of steel can be found in the construction industry of Sri Lanka (Chandrasiri & Jayasingha, 2005). Therefore, it is important to check for the provisions of using this advanced technique of retrofitting for the steel structures in Sri Lanka.

Debonding between steel and adhesive and also between CFRP and adhesive has been identified as a major drawback of CFRP (Narmashiri et al, 2010). Environmental temperature, humidity level and surface preparation have been identified as the factors affecting bonding of CFRP to steel (Abeygunasekara et al, 2014). Even though several studies have focused on the improvement of load carrying capacity due to CFRP, only a limited number of studies have been dedicated to study the causes for debonding (Kamruzzaman et al, 2014). Therefore, this study focuses on the effect of adhesive properties on debonding of CFRP and steel.

II.METHODOLOGY

In order to study the effect of adhesive properties on the performance of CFRP strengthened steel I girder, non-linear finite element analysis was carried out in ANSYS 14.5. A 3D model of a steel I girder subjected to four point bending was considered in the analysis. The dimensions and the material properties of the steel I girder subjected to the analysis were given in Table 1. Pure penalty method was used as the contact algorithm.

Table 1 Dimensions and material properties of steel I section

Steel I-section dimension (mm)				E-modulus (N/mm2) Mean value	Stress (N/mm2)		Strain	
Width	Height	Flange tk.	Web tk.		Yielding (Fy)	Ultimate (Fu)	Yielding (εy)%	Ultimate (εu)%
100	150	10	6.6	200,000	250	370	0.12	13.5

Table 2 Properties of adhesives

Adhesive type	E-modulus N/mm2	Tensile strength N/mm2	Shear strength N/mm2	Strain at break %
Sikadur	4500	32	20	0.9
TyfoMB	1230	45.8	19	1.88
Carbon epoxy	142,000	100	55	1.77

Behaviour of steel was modelled using Bi-linear stress-strain relationship. In the plastic region, tangent modulus was taken as 90 GPa. 20 node brick element and 10 node tetrahedral elements were employed for steel I-section. CFRP plate of thickness 1.2 mm and width 50 mm was attached to the bottom of the steel flange. Length of CFRP plate was 1500mm. the orthotropic nature of CFRP laminates was taken in to account by using an elastic modulus of 160,000 MPa in longitudinal direction and 10,000 MPa in transverse direction Namashri et al. (2010). CFRP laminate was assumed to possess linear stress strain relationship and was modelled using 8 node shell element.

Three different adhesives with the properties given in Table 2 were considered in the analysis. Adhesive thickness was taken as 1 mm.

Further, the adhesive was assumed to possess non-linear material behaviour. Interface elements following bi-linear slip model was used in the contact region. Failure was identified at the point where the internal stresses exceeds the respective strength values.

III.RESULTS & DISCUSSION

In order to verify the numerical model created, the results obtained from the model were checked against the experimental results presented by Narmashiri et al (2010). To be compatible with the experimental conditions, a steel I girder of depth 150 mm and width 100 mm is considered with 1500 mm long CFRP plate attached to the bottom flange at the center of the beam. An adhesive with an elastic modulus of 9600 MPa (Narmashiri et al, 2010) was used to attach the CFRP plate to steel.

Comparison between the load vs deflection curves obtained from the numerical analysis in this study and from the experimental analysis in the study done by Narmashiri et al (2010) is given in Figure 2.

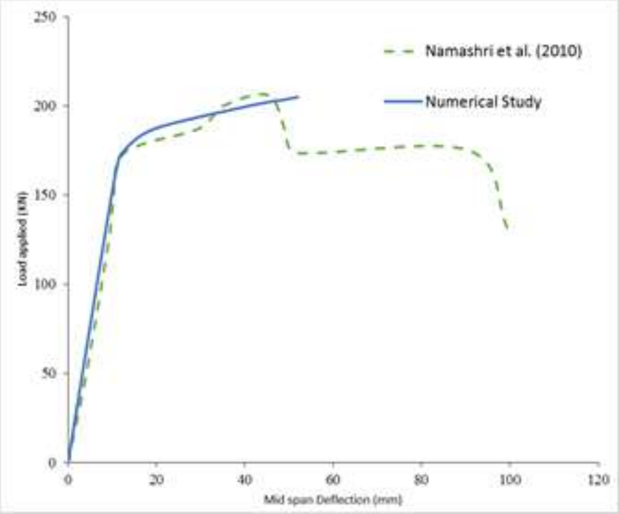

Figure 1: Verification of the numerical model

It can be seen from the figure that both the curves are in good agreement with each other especially in the elastic region. In their study, Narmashiri et al reported the load bearing capacity as 206.24 kN at which the splitting of CFRP started below the load point. In our study, this value is found to be 201 kN which deviates only by 2.6% from the value obtained by Narmashiri et al (2010). This difference could be attributed to the experimental errors such as energy losses in strain gauges. Therefore, the numerical model developed in this study can be considered as an accurate model.

After verifying the model, analysis was carried out to see the effect of adhesive properties on the retrofitting performance of CFRP. Three different adhesives with the properties given in Table 2 were used for the analysis. All the other parameters except the material properties of adhesive were kept the same in all the cases of analysis.

Different types of failure modes were observed during the analysis. In CFRP laminates, fibers are oriented in one direction (longitudinal direction). Therefore, the laminate is stronger in one direction and weaker in the transverse direction. As a result, CFRP laminates tend to split and this failure is called "below load splitting" and has been denoted as BL-S in this paper. Another mode of failure observed is due to the debonding of epoxy. When the shear stress of epoxy exceeds the shear capacity, this mode of failure can be observed. This is called below the load debonding and denoted by BL-D in this paper. In addition, end debonding which is a result of higher interfacial stresses at the tip of the CFRP and side debonding which is a result of poor bonding has been identified as other modes of failure.

The load carrying capacities obtained for different type of adhesives along with the failure modes observed are reported in Table 3. It can be seen from the results in Table 3 that as the Elastic modulus of adhesive increases, the load carrying capacity of the beam has also been increased. However, the increment in load carrying capacity with respect to the increment in elastic modulus seems to become less significant as the elastic modulus increases. For example, the increment in load carrying capacity per unit increment of elastic modulus between the first two adhesives is 3.7 kN while the same between the second and third adhesives is 0.21 kN.

It was also observed from the results that the failure pattern of the beam is also affected by the properties of adhesive. For the first two adhesives in which the elastic modulus and the shear strength is considerably lower than the third adhesive, the failure pattern observed is the debonding of CFRP below the load points (BL-D). This is a result of higher shear stress in the adhesive which exceeds the shear capacity of the adhesive. A snapshot showing the stress levels at this failure is shown in Figure 2. For the third adhesive having a high elastic modulus, the failure occurs due to splitting of CFRP below the load point (BL-S). This is attributed to the fact that the elastic modulus in the transverse direction of CFRP is lower than the elastic modulus of the adhesive. A snapshot showing the stress levels at this failure is shown in Figure 3.

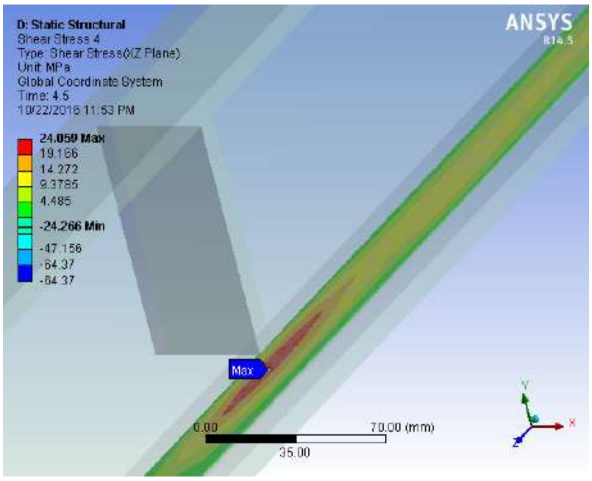
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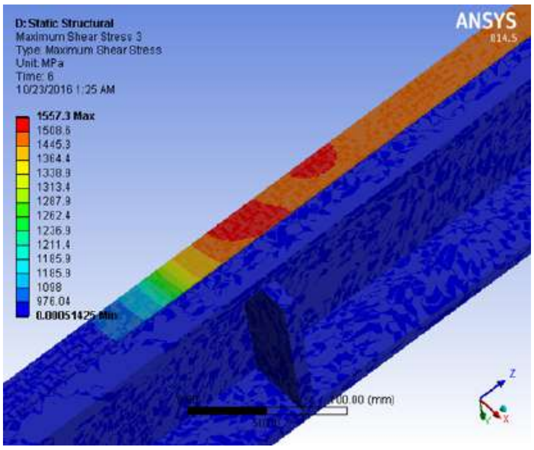
Figure 2: Stress levels at the failure for "BL-D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Maximum Shear Stress 3
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Figure 3: Stress levels at the failure for "BL-S

The load deflection curves of beam obtained for the three cases are given in Figure 4. It can be seen from the figure that in the elastic region, all three adhesives show the same behaviour. However, in the plastic region, clear difference can be observed in the load-displacement behaviour.

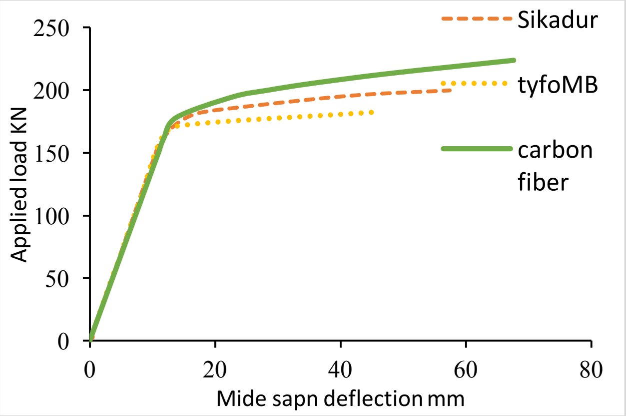

Figure 4: Load-displacement curves

Table 3: Load carrying capacities and failure modes for different adhesives

Epoxy	Failure mode	Max. Shear stress (MPa)	Load carrying capacity (kN)	Mid – span deflection (mm)
TyfoMB	BL-D	20.2	182.35	45.3
Sikadura	BL-D	32.12	194.4	57.34
Carbon epoxy	BL-S	55.58	223.96	67.6

IV. CONCLUSION

The results obtained in this study, through a non-linear finite element analysis of a steel I beam strengthened with CFRP plate attached to the bottom flange, reveal that the material properties of adhesive not only affect the load carrying capacity of the beam, but also affect the failure mode. As the elastic modulus of the adhesive increases, the failure mode was found to switch from debonding to splitting of CFRP below the loading point. Also, it can be seen from the results that increment in load carrying capacity due to a unit increment in elastic modulus or shear strength of adhesive decreases as the elastic modulus or shear strength increases.

This paper focused only on the effect of material properties on debonding failure of CFRP strengthened steel beam. In addition, factors such as humidity and environmental temperature could also play a vital role in debonding. Therefore, it is worth studying the effect of those factors as well to identify the suitability of applying CFRP as a retrofitting technique to Sri Lankan conditions. This will be helpful in understanding why CFRP has not become a popular retrofitting technique in Sri Lanka although it has been widely used in other countries.

V.REFERENCES

Abeygunasekera S, Gamage JCPH and Fawzia S (2014). Effect of environmental conditions during installation process on bond strength between CFRP and steel, Proceedings of SAITM Research Symposium on Engineering Advancement

Chandrasiri, .B.Y.D.N. and Jayasinghe M.T.R. (2005). REIIABILITATION OF STEEL BRIDGES IN SRI LANKA. Deputy Director, Maintenance Management & Construction Division. Road Development Authority.

Fernando, S and Hettiarachchi, D. (2011).FRP STRENGTHENING OF CONCRETE STRUCTURES – DESIGN AND PRACTICAL EMPHASIS IN SRI LANKA

Kamruzzaman M, Jumaat M. Z, Sulong N. H. R and Islam A. B. M. S (2014), A REVIEW ON STRENGTHENING STEEL BEAMS USING FRP UNDER FATIGUE, The Scientific World Journal, Volume NO.

Narmashiri, K., Sulong N.H. and Jumaat, M.Z. (2012), FAILURE ANALYSIS AND STRUCTURAL BEHAVIOR OF CFRP STRENGTHENED STEEL I BEAMS Construction and Building Materials, 30 [Accessed on 16.10.2015].