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INTERFACIAL STRESS OF STEEL BEAMS STRENGTHENED WITH PRESTRESSED CFRP LAMINATE AND MECHANICAL ANCHORAGE.

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ملخص

تزايد في السنوات الأخيرة استخدام ألواح المواد المركبة المقواة بالكربون في إصلاح وتقوية المنشآت الخرسانية المسلحة في حين ظل استخدامه لتقوية المنشآت المعدنية محدودا. يرجع هذا الى الانهيار الانفصالي عند نهاية طرف اللوح. لقد وجد في دراسات سابقة ان استخدام الواح كربونية سابقة الاجهاد يقلل من تأثير الاجهادات المتولدة في منطقة الاتصال بين الالواح وبين سطح العنصر الذي تتم تقويته. بعض الدراسات قامت بتقديم نموذج رياضي لحساب الاجهادات في منطقة الاتصال. هذه الدراسات اهملت تأثير التثبيت الميكانيكي للألواح والذي من شأنه تحسين قوة الالتصاق في منطقة التماس والمحافظة على القوى المسبقة الاجهاد في الالوا ح. تتناول هذه الدراسة برنامجا عمليا لاختبار وتقييم تسعة كمرات معدنية مقواه بألواح البوليمرات المسلحة بألياف الكربون ودراسة تأثير وفوائد استخدام التثبيت الميكانيكي على أدائها وعلى طريقة الانهيار الذي تتعرض له. كما تتضمن الدراسة تطوير نموذج رياضي لتحليل اجهادات القص والشد في منطقة الاتصال. وقد وجد ان النموذج الرياضي قد اعطى نتائج مرضية كما وجد من البرنامج العملي ان طريقة التثبيت الميكانيكي واجهاد الواح الكربون كان فعالاً وأعطى نتائج أفضل من التقوية بدونهم.

ABSTRACT

Strengthening substandard steel beams using Carbon Fiber Reinforced Polymer (CFRP) may be limited by the premature failure caused by debonding in the adhesive layer commonly used to attach the CFRP to the steel beam. Prestressing the (CFRP) lami-nates is a technique that can improve the effectiveness of such strengthening method and improve both the strength and serviceability behavior of steel beams by increasing the overall member stiffness. Previous studies introduced analytical models to predict the stresses distribution over the contact area between the (CFRP) laminate and the steel beam. However, such studies did not consider the importance of using mechanical an-chorage which was found essential to maintain the prestressing force in the (CFRP) la-minate. In this study, an analytical model is presented to predict the shear and normal stresses affecting the adhesive layer of steel I-beams subjected to flexural two point loads and strengthened with prestressed CFRP laminate when mechanical anchorage system is used. The equations were employed to calculate the stress on beams tested in an experimental program carried out to evaluate the performance of the proposed strengthening system.

KEYWORDS: CFRP Laminate, Adhesive, Mechanical Anchorage, Prestressing.

2 INTRODUCTION

Using CFRP strips in retrofitting and strengthening substandard steel structures is as commonly as its usage for concrete structure [1]. This strengthening method usually consists of CFRP layer which typically is attached to the substandard steel beam lower flange using a layer of adhesive [2 & 3]. The drawback of using such a procedure is the premature failure of the steel - CFRP hybrid section due to the debonding failure of the adhesive layer. Some studies have introduced prestressing to the CFRP laminates as a solution to debonding issue and to fully utilize the strengthened section. It is found that prestressing has a positive effect on delaying the debonding premature failure [2]. Previous studies highlighted the importance of applying pretension force to the CFRP laminates [4]. Several techniques can be used to apply the pretension force to the CFRP but none of these techniques can be effective without using mechanical anchorage because of the debonding. Adding mechanical anchorage at both ends of the laminate can ensure more ductile behavior also increasing the allowable level of prestressing that can be applied. Researchers found that the use of a mechanical anchorage can result in a great improvement in serviceability and strength [2 & 6]. Some studies proposed an analytical model to calculate the shear and normal stress developed in the contact zone between the steel surface and the CFRP layer attached to it [7, 8, 9 &10]. However, the presence and the effect of using mechanical anchorage was not considered. In this study, an analytical model to predict the shear and normal stress affecting the adhesive layer in a prestressed CFRP system with mechanical anchorage for strengthening steel beams under flexural loading is introduced. The results obtained from the analysis is compared to the results obtained from the experimental program which was carried out in King Abdulaziz University (2014) to investigate the effectiveness and the feasibility of that system.

3 THE EXPERIMENTAL PROGRAM

A total of nine steel beams strengthened with different configurations of prestressed CFRP laminate were tested in flexure under static loading up to failure.
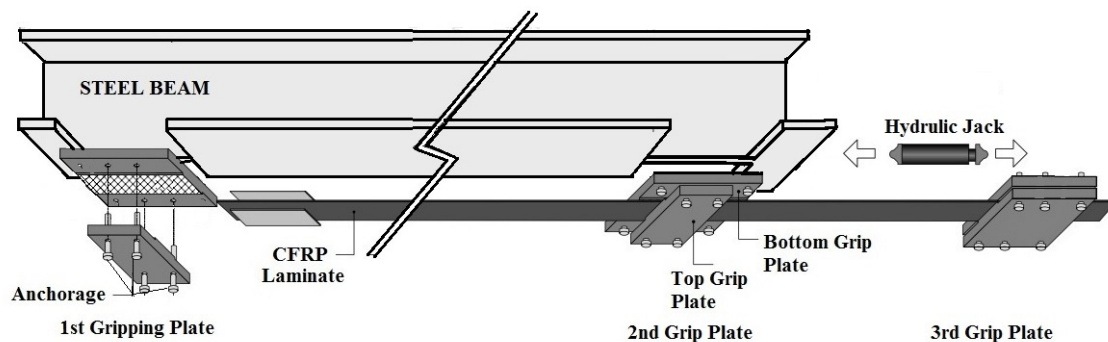

Fig. 1. Pretension system adopted for all beams strengthened with CFRP prestressed laminate.

The main parameters considered in the experimental program are the prestressing levels, the yield strength of the steel beam and the presence or absence of the mechanical anchorage at both ends of the CFRP laminate. A simple jacking system configuration as shown in Figures (1) to (3) is used.
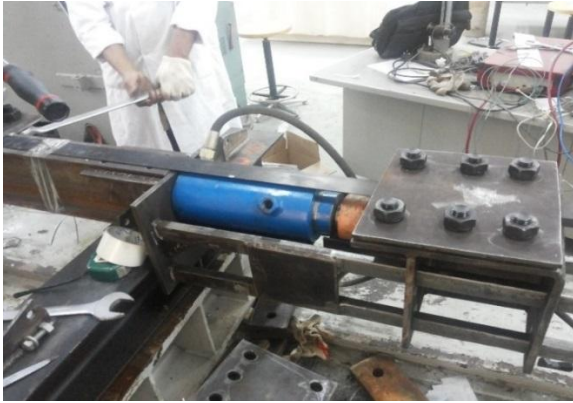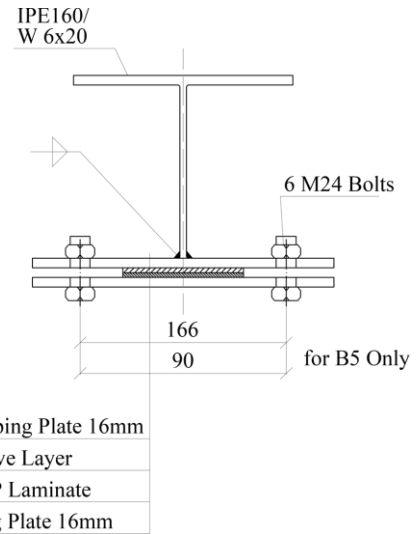
Figure 2. Applying pre-tension force.

IPE160/
W 6x20

6 M24 Bolts

166

90   for B5 Only

Bottom Gripping Plate 16mm
1mm Adhesive Layer
1.2mm CFRP Laminate
Top Gripping Plate 16mm

**Figure 3. Strengthened steel beam's cross-section
at the location of the gripping plates.**

3.1 Description of the Beams

The details of the experimental program are given in Table (1). The section of the 1st beam tested is IPE160. The other eight beams have a cross-section of W6x20. The total length of each of the nine steel beams is 2,900 mm. The yield strength of the steel beams is shown in Table (2). Specimen CB1 and CB1A are the control specimens which with no CFRP strips. Specimen CB2 is strengthened with bonded CFRP which is not prestressed.

Table 1. Test Specimen Details.

Specimen	CFRP laminate	Anchorage	Pretension Force
TB	50 x 1.2mm	Yes	Yes
CB1	No	No	No
CB1A	No	No	No
CB2	100 x 1.2mm	No	No
B1-25-NA	100 x 1.2mm	No	25 kN
B2-45-NA	100 x 1.2mm	No	45 kN
B3-25-AN	100 x 1.2mm	Yes	25 kN
B4-45-AN	100 x 1.2mm	Yes	45 kN
B5-25-AN	50 x 1.2mm	Yes	25 kN

All other specimens (Table 1) are strengthened with CFRP strips which are prestressed to different levels with/without end mechanical anchorage. The pretension levels in the CFRP strips are either 25 kN or 45 kN. The width of the CFRP laminate is 100 mm except for Specimens TB and B5-25-AN where the width is 50 mm. Figure (3) shows the beam cross section and the CFRP reinforcement. To prevent the local buckling of the beams web, vertical stiffeners are added to all beams above the supports and below the load application points. The beams are also laterally restrained to prevent lateral torsional flexure buckling except for specimen (TB).

3.2 Material Properties

The mechanical properties of the steel beam and CFRP are obtained from both material testing and manufacture data sheet. The measured material properties of the steel beam are shown in Table (2). The mechanical properties of the CFRP laminate are obtained from the manufacturer data sheet and presented in Table (3). Epoxy adhesive is used to bond the CFRP laminate to the surface of the steel beam. The average mechanical properties of the adhesive are shown in Table (4).

Table 2. Mechanical properties of the analyzed beams.

Specimen	Yield Stress (MPa)	Tensile Strength (MPa)
TB	380	450
CB1	390	560
CB1A	350	520
CB2	390	560
B1-25-NA	390	560
B2-45-NA	390	560
B3-25-AN	390	560
B4-45-AN	350	520
B5-25-AN	390	560

Table 3. Properties of the CFRP laminate.

Mechanical properties	Value (MPa)
Tensile modulus	165,000
Tensile strength	3,100

Table 4. Properties of the epoxy adhesive

Mechanical properties	Value (MPa)
Tensile strength	24.8
Compressive strength	61
Shear strength	24.8
Bond strength	18
Tensile modulus	4,400

3.3 Test Set-up

The beams are simply supported and subjected to two points loading as shown in Figure (4). The load was applied incrementally to the beam using a universal testing machine.
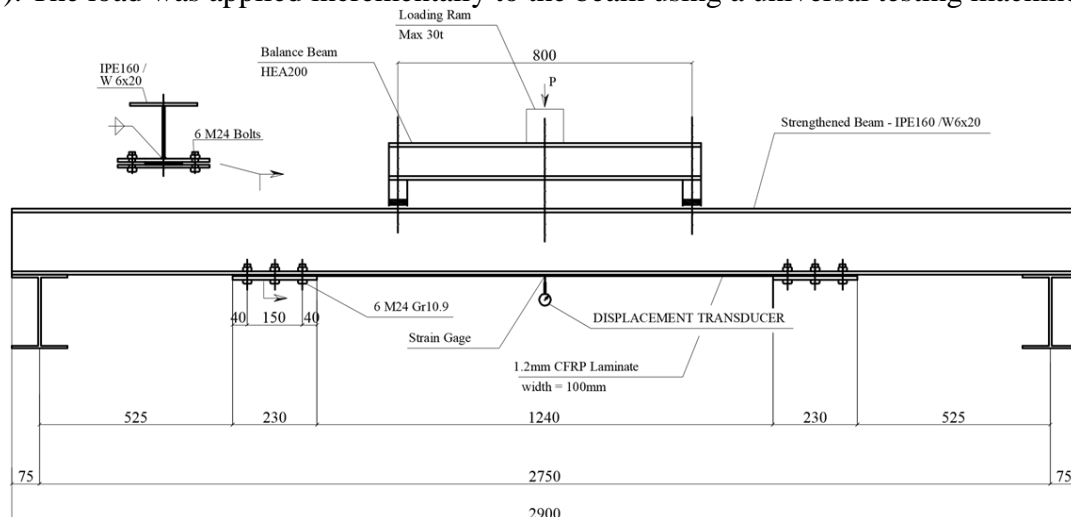

Fig. 4. Test Setup for a typical strengthened beam

4 EXPERIMENTAL RESULTS
4.1 Failure Modes

Generally, prestressing the CFRP laminate reduced the deflection and delayed the premature debonding failure. Both the reduction of the deflection and the delay in debonding were proportion to the level of the laminate prestress. The control beams CB-1 and CB-1A failed in a typical flexural manner. Failure of the beam strengthened with nonprestressed CFRP laminate CB-2 started by the debonding of the laminate with a 1.2% slight increase in the failure load. The CFRP- prestressed beams without end anchorage B1-25-NA and B2-45-NA failed by debonding of the CFRP laminate from the steel bottom flange which took place immediately after releasing the grip anchor at both ends of the beam. The debonding started at the ends of the CFRP laminate which remained attached along the middle part of the beam. Final failure took place with total debonding of the laminate with a slight increase in the failure load.

Table 5. Results of the experimental investigation .

Beam No.	CFRP Jacking Strain (με)	Yield Load P_y (kN)	CFRP debonding load		CFRP rupture load		CFRP Failure
			P_{de} (kN)	Associated Strain (με)	P_{fru} (kN)	Associated Strain (με)	
TB	3050	108.1	No debonding	No debonding	No Rupture	No Rupture	No Failure
CB	–	172.7	N/A	N/A	N/A	N/A	N/A
CB1A	–	161.0	N/A	N/A	N/A	N/A	N/A
CB2	–	174.8	193.2	5290	No Rupture	No Rupture	Debonding
B1-25-NA	3092	N/A	64.8	15.16	No Rupture	No Rupture	Debonding
B2-45-NA	4021	N/A	76.33	16.48	No Rupture	No Rupture	Debonding
B3-25-AN	3140	193.0	204.5	3953	199.7	4435	Rupture
B4-45-AN	3984	166.3	178.9	5725	190.5	9601	Rupture
B5-25-AN	3103	195.2	No debonding	No debonding	202.3	12101	Rupture

The CFRP-prestressed beams B3-25-AN and B5-25-AN with end anchorage and Fy =390 MPa failed in a typical flexural manner. The CFRP laminate experienced a sudden rupture failure with a considerable increase in the failure load of 12% to 13% respectively compared to the non-strengthened control beam CB-1. Both these beams developed a full plastic hinge at failure after CFRP rupture without encountering any premature debonding failure. The same failure mode was also recorded for beam CFRP-prestressed beams B4-45-AN (Fy =350 MPa) with end anchorage, but the achieved strength enhancement was 3.3% in yield load which is lower than the previous beams. The results of the experimental investigation are summarized in Table (5).

5 PROPOSED ANALYTICAL MODEL AND THEORETICAL APPROACH

The debonding failure mode is caused by interfacial stress concentration in the contact surface in the end zone. Closed-form solutions of such stresses are thus essential in developing any design guidelines for strengthening beams with bonded prestressing CFRP laminates. Consider a steel beam with a typical I − section strengthened with a prestressed laminate bonded to the tension face as shown in Figure (5). in this analysis the following assumptions are made:

- All materials are assumed to follow linear elastic behaviour.
- Stiffness of the steel beam is much greater than the stiffness of the CFRP laminate.
- Plane section remains plane After deformation
- Bending deformations of the adhesive can be neglected
- No slip will occur at the interface area before failure take place.
- Constant stresses through the thin adhesive layer thickness.

Figure (5) shows a schematic sketch of a beam strengthened with a bonded prestressed laminate where P_l is the residual prestressing force in the laminate. The loss of prestressing force in the laminates is

$$\Delta P_l = P_0 - P_l \tag{1}$$

However, in case of using a well fastened mechanical anchorage and applying proper adhesive layer, the loss of the prestressing P_l force can be neglected and it can be assumed that $P_l = P_0$, hence the prestressing force in the steel beam P_s can be expressed as below:
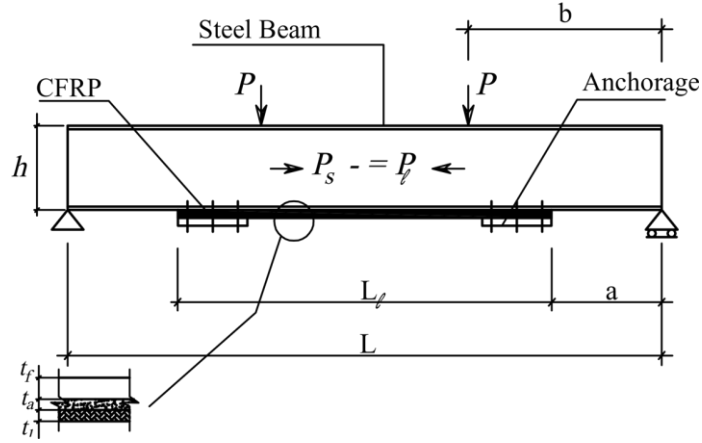
$$P_s = -P_l \tag{2}$$

Fig. 5. Schematic sketch of analyzed Beam.

A differential segment of a plated beam is shown in Figure (6), where the interfacial shear and normal stresses are denoted by $\tau(x)$ and $\sigma(x)$, respectively. Figure (6) also shows the positive sign convention for the bending moment, shear force, axial force and applied loading.
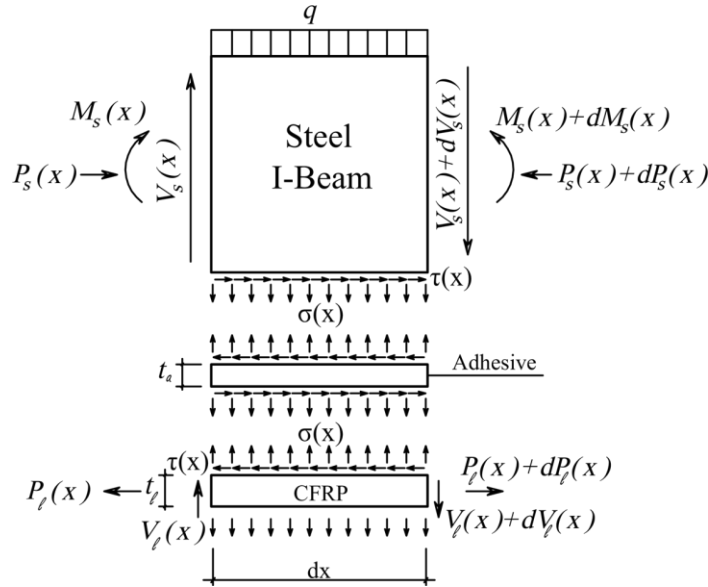

Fig. 6. Finite element of a strengthened beam with acting forces.

5.1 Adhesive Shear Stress

Shear stress in the adhesive layer is directly related to the difference in deformation between the laminate and lower flange of the steel beam:

$$\tau(x) = \frac{G_a}{t_a}[u_l(x) - u_s(x)] \tag{3}$$

where G_a is the adhesive shear modulus, t_a is the thickness of the adhesive layer, u_l and u_s denote the displacement of the steel beam at the bottom of lower flange, and the displacement of the externally bonded prestressed laminate at the boundary of the bond, respectively. Equation (3) can be expressed in terms of the mechanical strain of the steel beam, $\varepsilon_s(x)$, and the prestressed laminate $\varepsilon_l(x)$ after differentiating the equation with respect to x, since tensile strain at the bottom of the beam is induced by two basic stress components: (1) the tensile stress induced by the bending moment $M_s(x)$ in the beam and (2) the axial stress induced by the adhesive shear stress at the bond interface.

$$\frac{d\tau(x)}{dx} = \frac{G_a}{t_a}[\varepsilon_l(x) - (\frac{M_s(x)h}{2E_sI_s} - \frac{P_s(x)}{E_sA_s})]$$ (4)

Where A_s is the steel beam cross-sectional area, I_s is the second moment of area of the steel beam, E_s is the modulus of elasticity of the steel beam, t_l is the thickness of the CFRP laminate, b_l is the width of the CFRP laminate and E_l is the tensile modulus of the CFRP laminate. Strain in the laminate can be expressed as:

$$\varepsilon_l(x) = A_{11}^x \frac{N_x}{b_l}$$ (5)

Where $A_{11}^x = \frac{b_l}{A_lE_l}$ which is the extensional matrix component in the laminate overall

stiffness matrix and $N_x = P_l$ since the axial load in the beam's longitudinal axis is the only load considered. Substitute in Equation (4) and obtain second derivative:

$$\frac{d^2\tau(x)}{dx^2} = \frac{G_a}{t_a}[\frac{A_{11}^x dP_l(x)}{b_l dx} - \frac{dP_s(x)}{E_sA_sdx} - \frac{h}{2E_sI_s}\frac{dM_s(x)}{dx}]$$ (6)

From equilibrium of segment shown in Figure (7) the following relations can be obtained:

$$\frac{dP_s(x)}{dx} = b_l\tau(x), \frac{dP_l(x)}{dx} = -b_l\tau(x) \,\&\, \frac{dM_s(x)}{dx} = V_s(x) - b_l\frac{h}{2}\tau(x)$$ (7)

Substituting in Equation (6), the general solution of the resulted deferential equation is

$$\tau(x) = B_1\cosh(\lambda x) + B_2\sinh(\lambda x) + \frac{G_ah}{2E_sI_st_a\lambda^2}V_s(x)$$ (8)

Where

$$\lambda^2 = \frac{G_a}{t_a}[A_{11}^x + \frac{b_l}{E_sA_s} + \frac{h^2b_l}{4E_sI_s}]$$ (9)

And B_1 and B_2 are the deferential equation constants. For the case of two point loads where the distance from end of laminate to the end of the beam (a) is smaller than the distance from the point load to the end of the beam (b), the adhesive shear stress can be calculated on two intervals:

1st Interval: for $0 \leq x \leq (b-a)$, at this interval based on Equation (8), the general solution for the interfacial shear stress considering value of $V_s = P$ is

$$\tau_1(x) = B_1\cosh(\lambda x) + B_2\sinh(\lambda x) + m_1P$$ (10)

Where

$$m_1 = \frac{G_ah}{2E_sI_st_a\lambda^2}$$

2nd Interval: for $(b-a) \leq x \leq L_l$, at this interval, the general solution for the interfacial shear stress

$$\tau_2(x) = B_3\cosh(\lambda x) + B_4\sinh(\lambda x)$$ (11)

To solve Equations (10) & (11), the boundary conditions are:

1st boundary condition: based on the symmetry of the structure, the displacement at middle of the structure is zero. Therefore, at $x = L_l/2$,

$$\tau(\frac{L_l}{2}) = u_l(\frac{L_l}{2}) = u_s(\frac{L_l}{2}) = 0$$ (12)

Substitute in Equation (11), this will result that

$$B_3 = -B_4 \tag{13}$$

2nd boundary condition: at $x = (b - a)$, $\tau(x)$ is continuous, this means that $\tau_1(b - a) = \tau_2(b - a)$

3rd boundary condition: at $x = (b - a)$, $\dfrac{d\tau(x)}{dx}$ is continues so $\dfrac{d\tau_1(b-a)}{dx} = \dfrac{d\tau_2(b-a)}{dx}$

This two boundary condition require continuity of the interfacial shear stress and its first derivative under the point load. Substitute in Equations (10) & (11) gives the interfacial shear stress equations:

$$\tau_1(x) = -B_2 e^{-\lambda x} + m_1 Px \tag{14}$$

and

$$\tau_2(x) = -B_3 e^{-\lambda x} \tag{15}$$

4th boundary condition: at the end of the laminate due to the presence of the mechanical anchorage

At $x = 0$, $P_l(0) = -P_s(0) = P_0$ and $M_s(0) = P\,a$, by substituting in Equation (4) and equating the result to the 1st derivative of Equations (14) & (15) the value of B_2 and B_3 can be detrained

$$B_2 = \frac{G_a}{\lambda t_a}\left[\left(\frac{A_{11}^x}{b_l} + \frac{1}{E_s A_s}\right)P_0 - \frac{Pah}{2E_s I_s}\right] + \frac{m_1}{\lambda}P \tag{16}$$

and

$$B_3 = \frac{G_a}{\lambda t_a}\left[\left(\frac{A_{11}^x}{b_l} + \frac{1}{E_s A_s}\right)P_0 - \frac{Pah}{2E_s I_s}\right] + \frac{m_1}{\sinh\lambda(b-a)}P \tag{17}$$

5.2 Adhesive Normal Stress

Analyzing the adhesive segment after loading the beam, vertical separation occurs between the steel beam and CFRP lamina. This delamination creates an interfacial normal stress acting on the adhesive layer. The normal stress, $\sigma(x)$, can be calculated as:

$$\sigma(x) = \frac{E_a}{t_a}[v_l(x) - v_s(x)] \tag{18}$$

Where $v_l(x)$ and $v_s(x)$ are the vertical displacements of laminate and steel beam, respectively. E_a is the Young's modulus of adhesive material. From equilibrium in Figure (6) of steel beam and laminate, and after neglecting second-order terms, following relationships can be obtained for the Steel beam:

$$\frac{dV_s(x)}{dx} = -q - b_l\sigma(x), \quad \frac{d^2 v_s(x)}{dx^2} = \frac{-M_s(x)}{E_s I_s} \quad \text{and} \quad \frac{dM_s(x)}{dx} = V_s(x) - \tau(x)b_l\frac{h}{2} \tag{19}$$

For the CFRP laminate:

$$\frac{dM_l(x)}{dx} = V_l(x) - \tau(x)b_l\frac{t_l}{2}, \quad \frac{dV_l(x)}{dx} = b_l\sigma(x) \tag{20}$$

$$\frac{d^2 v_l(x)}{dx^2} = \frac{-D_{11}^x}{b_l}M_l(x) \tag{21}$$

Where D_{11}^x is the laminate flexural stiffness matrix and for simplification it can be considered $D_{11}^x = \dfrac{12}{t_l^3 E_l}$ for symmetric unidirectional laminate

The governing differential equations for the deflections of steel beam and laminate based on the equilibrium, can be expressed in terms of the interfacial shear and normal stresses for the Steel beam and the CFRP laminate respectively as follows:

$$\frac{d^4 v_s(x)}{dx^4} = \frac{1}{E_s I_s} b_l \sigma(x) + \frac{h}{2 E_s I_s} b_l \frac{d\tau(x)}{dx} + \frac{1}{E_s I_s} q \text{ and } \frac{d^4 v_l(x)}{dx^4} = -D_{11}^x \sigma(x) + D_{11}^x \frac{t_l}{2} \frac{d\tau(x)}{dx} \quad (22)$$

The governing differential equations of the interfacial normal stress can be expressed by substitution of Equation (22) into the fourth derivation of Equation (18) gives the governing differential equation for the interfacial normal stress. The general solution for the resulted expression (based on the assumption that all normal stress on the adhesive layer tends to zero) is

$$\sigma(x) = e^{-\beta x}[C_1 \cos(\beta x) + C_2 \sin(\beta x)] - n_1 \frac{d\tau(x)}{dx} - n_2 P \quad (23)$$

Where:

$$\beta = \sqrt[4]{\frac{E_a}{4 t_a}\left(D_{11}^x + \frac{b_l}{E_s I_s}\right)} \quad (24)$$

$$n_1 = \frac{(\frac{h}{2})b_l - D_{11}^x E_s I_s (\frac{t_l}{2})}{D_{11}^x E_s I_s + b_l} \quad (25)$$

$$n_2 = \frac{1}{D_{11}^x E_s I_s + b_l} \quad (26)$$

Adhesive normal stress general expression can be found by determining the constants C_1 and C_2 in Equation (23) with the following boundary conditions.

1st boundary condition: Bending moment at both ends of the laminate equal to zero. Differentiating Equation (18) to the second order and substituting Equations (19, 20 & 21) into the result expression gives the following relationship at laminate end knowing that $M_l(0) = 0$ gives

$$\frac{d^2 \sigma(0)}{dx^2} = \frac{E_a}{t_a E_s I_s} M_s(0) \quad (27)$$

2nd boundary condition: Shear force at both ends of the laminate equal to zero. Differentiating Equation (18) to the third order and substituting Equations (19) & (20) into the resulting expression lead to the following relationship at the laminate end knowing that $V_l(0) = 0$ gives

$$\frac{d^3 \sigma(0)}{dx^3} = \frac{E_a}{t_a}\left(\frac{1}{E_s I_s} V_s(0)\right) - n_3 \tau(0) \quad (28)$$

Where:

$$n_3 = \frac{E_a}{t_a}\left(\frac{h b_l}{2 E_s I_s} - \frac{t_l}{2} D_{11}^x\right) \quad (29)$$

Further differentiation of Equation (23) leads to the second and third derivatives of the interfacial normal stress at the anchorage end. The second and higher order derivatives of q tends to zero. Substituting the boundary conditions into leads to determining C_1 and C_2 in terms of the bending moment $M_s(0)$ and shear force $V_s(0)$ at the end of the CFRP laminate. By substituting the value

of $M_s(0) = Pa$, $V_s(0) = P$, $\tau(0) = -B_2$, $\dfrac{d^3\tau(0)}{dx^3} = \lambda^3 B_2$ and $\dfrac{d^4\tau(0)}{dx^4} = -\lambda^4 B_2$ C_1 and C_2 can be obtained as:

$$C_1 = \frac{PE_a}{2t_a\beta^3 E_s I_s}[1-\beta a] + \frac{n_3}{2\beta^3}B_2 + \frac{n_1 B_2}{2\beta^3}\left(-\lambda^4 + \beta\lambda^3\right) \tag{30}$$

$$C_2 = \frac{(Pa)E_a}{2t_a\beta^2 E_s I_s} - \frac{n_1}{2\beta^2}\lambda^3 B_2 \tag{31}$$

With the constants C_1 and C_2 determined, the adhesive normal stress can be found using Equation (23).

5.3 Analysis results

The results of the peak value of both shear and normal stress for the specimens TB, B3, B4 & B5 are shown in Table (6). A comparison of the interfacial shear stress for the 3 specimens with similar steel beam cross section B3, B4 & B5 at $x = 0$ and concentrated load of 100 kN is shown in Figure (7). Changing the width of the CFRP plate b_l from 100mm to 50mm increased the stress at the peak point by 75% at the same prestressing load of P0=25 kN.

Table 6. Peak interfacial shear and normal stress for specimen tested.

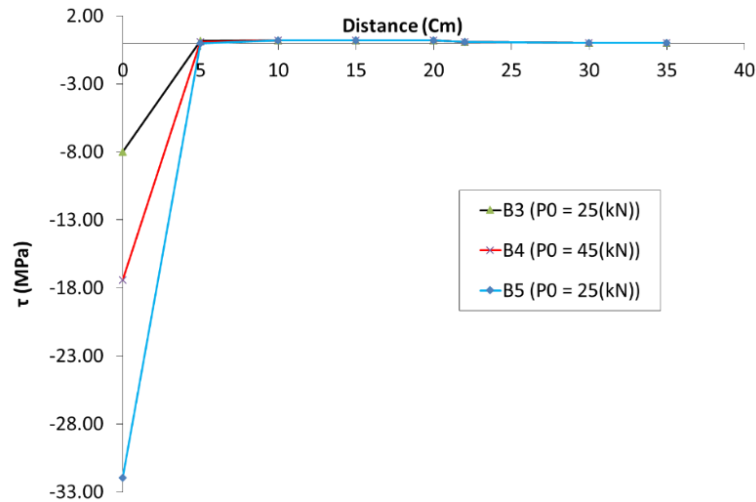| Sample	Prestressing Force P_0 (kN)	Premature Failure Load (kN)	Failure Mode	Calculated Peak Shear Stress (MPa)	Calculated Peak Normal Stress (MPa)
TB	25	108	Torsional Buckling	13.83	7.09
B3-25-AN	25	199.7	CFRP Rupture	7.44	3.5
B4-45-AN	45	178.9	CFRP Rupture	5.17	2.7
B5-25-AN	25	202.3	CFRP Rupture	15.868	8.12

Fig. 7. Adhesive Shear Stress at P=100 kN and variable distance from laminate end.

6 CONCLUSIONS

This study presented the results of an experimental program carried out through nine tests to evaluate the performance of steel beams strengthened by bonded and prestressed CFRP laminate with mechanical end anchorage technique under flexural four point loads an analytical model to predict the shear and normal stress on the adhesive layer. It

is found that the CFRP prestressing increased the ultimate load of the strengthened beam and moderately delayed the premature debonding failure of the CFRP laminate. It is also concluded that using mechanical end anchorage is essential to maintain the CFRP laminate prestress after releasing the jacking force. It is also concluded that epoxy mortar is not sufficient to maintain the laminate prestressed by itself even at a very low level of prestressing. Although the CFRP prestressing levels of (7% to 12% of the ultimate CFRP strength) were moderately low, significant enhancement in the ultimate load of the strengthened beam was recorded. The premature debonding failure was avoided and CFRP laminate were utilized up to their rupture strength. The analytical model results agreed well with the experimental results. Increasing the pretension force from 7% to 12% reduced the normal stress affecting the Adhesive layer. The Peak stress point found at the end of the CFRP laminates however the premature failure was observed near the mid span of the beams which implies that the mechanical anchorage prevented the typical debonding failure mode usually occurs for such strengthening technique.

7 ACKNOWLEDGMENTS

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