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DESIGN GUIDELINES FOR STRENGTHENING OF STEEL-CONCRETE COMPOSITE BEAMS WITH HIGH MODULUS CFRP MATERIALS

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Abstract

This paper proposes guidelines for the design and installation of high modulus carbon fiber reinforced polymer (CFRP) materials for strengthening typical steel-concrete composite bridge girders. A flexural model is proposed which can be used for the design including determination of the required geometric configuration and material properties of the composite materials. The design procedure is based on a specified increase of the elastic stiffness of the member and/or the live load carried by the bridge to satisfy specified serviceability requirements. The increase of the live load level for the strengthened beam is based on three design criteria to satisfy an allowable stress level, ultimate capacity of the strengthened member and also a function of the residual capacity of the unstrengthened beam. A bond model that can be used to calculate the maximum principal stress in the adhesive thickness is included in the proposed guidelines. To prevent a premature debonding failure of the CFRP materials, the characteristic strength of the adhesive used for the strengthening system should be greater than the maximum principal stress calculated using the bond model. The research findings conclude that high modulus CFRP materials provide a promising alternative for strengthening steel structures.

1. Introduction

Fiber reinforced polymer (FRP) composites have widely been studied for the repair and strengthening of concrete bridges and structures. A cost-effective means for strengthening steel structures is also desired, due to the frequent occurrence of these structures in conjunction with increasing traffic loads and deterioration of steel due to corrosion. High modulus CFRP laminates have shown promise for strengthening steel structures. The proper installation of these advanced materials is essential in ensuring both the long-term performance of the system and that their behavior matches the intentions of the designer. A certain level of care and expertise is required to ensure that these goals are met. The proposed design guidelines represent the current best practice available based on a thorough review of the literature as well as practical experience in bonding of composite materials during a comprehensive research program.

2. High Modulus CFRP Strengthening System

High modulus carbon fiber has a modulus of elasticity approximately three times higher than that of steel. The fiber is typically fabricated into pultruded laminates that may be bonded to steel structures as an external reinforcement using an epoxy, or other type of, adhesive. This system can be used to increase the strength and stiffness of steel bridges, and can therefore be used to upgrade existing steel bridges or rehabilitate bridges that have reduced capacity due to cross-section losses. Typical material properties for high modulus carbon fiber and high modulus CFRP laminates are provided in Table 1.

Table 1. Typical Material Properties for High Modulus Carbon Fiber

Material Property	Fiber	Laminate
Ultimate Strain	0.004	0.0033
Tensile Modulus of Elasticity	635 GPa	450 GPa
Ultimate Strength	2620 MPa	1540 MPa
Fiber Volume Fraction	-	70%

3. Design for Flexure

Installation of high modulus CFRP laminates can increase the elastic stiffness of a steel beam therefore reducing the elastic strain in the tension flange of the beam as compared to an unstrengthened beam at the same load level. Due to these two effects, the live load capacity of a steel beam can be increased using externally bonded CFRP materials. The following sections present a proposed design philosophy and procedure for the design of HM CFRP strengthening for steel flexural members to achieve a desired increase of the live load level.

3.1 Design Philosophy

The allowable increase of live load for a steel-concrete composite beam strengthened with high modulus CFRP laminates should be selected to satisfy three conditions. These three conditions are shown in Figure 1 with respect to the typical moment-curvature behavior of a strengthened beam. Due to the presence of the additional high modulus CFRP material, the yield moment of the strengthened beam is greater than that of the unstrengthened beam. The yield moment of the strengthened and unstrengthened beams, $M_{Y,S}$ and $M_{Y,US}$ respectively, are defined as the moments inducing initial yielding of the extreme fiber of the tension flange of the steel beam in both cases. The increase of the yield moment of the strengthened beam due to the presence of the HM CFRP materials is highly dependent on the level of the dead load acting on the member prior to installation of the strengthening system. To ensure that the member remains elastic under service loading conditions, the combined effect of the dead load, M_D, and the increased live load, M_L, should not exceed 60 percent of the increased yield moment of the strengthened beam. The total factored moment based on the appropriate dead load and live load factors, α_D and α_L respectively, should not exceed the ultimate capacity of the strengthened beam, $M_{U,S}$ after applying an appropriate strength reduction factor, ϕ. A reduction factor of 0.75 is proposed that is consistent with the American Institute of Steel Construction requirements for rupture type limit states[1]. To ensure that the structure remains safe in case of total loss of the strengthening system, the total load effect should not exceed the capacity of the unstrengthened beam, $M_{U,US}$. The fatigue life of the strengthened member under the effect of the increased live load should be verified according to the fatigue design provisions of the appropriate design codes.

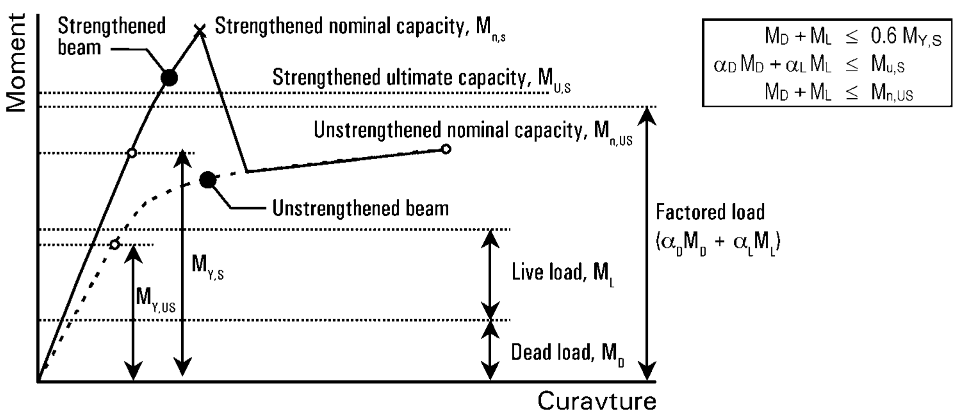

Figure 1. Conditions for calculation of the allowable live load for a steel-concrete composite beam strengthened with high modulus CFRP laminates

3.2 Design Procedure

The design of the high modulus CFRP strengthening for a steel-concrete composite beam is conducted using a moment-curvature analysis. This analysis is based on the cross-sectional geometry as well as the stress-strain behavior of the constituent materials using the principal of strain compatibility. The moment curvature analysis should be conducted using a non-linear constitutive model for the concrete since it will likely not remain elastic. A detailed description of the procedure is available in other sources[2,3].

The moment-curvature behavior of a given cross-section is determined based on the strain at the top level of the compression flange together with an assumed neutral axis depth. The cross-section is broken down into levels corresponding to the concrete deck, the longitudinal steel reinforcement of the concrete deck, the flanges and web of the steel beam, and the CFRP laminate. For each level the strain can be determined based on compatibility of strains and horizontal force equilibrium.

From the strain profile and the constitutive relationships of the materials, the stress profile for the beam can be established. Integration of the stress profile provides the resultant forces of the different components of the cross-section. Horizontal equilibrium can be achieved by several iterations of the neutral axis location. Once horizontal force equilibrium is satisfied, the nominal moment and corresponding curvature of the section can be calculated. The top surface strain can then be increased to determine the next increment of curvature and the procedure repeated. Using this technique, the full moment-curvature diagram can be obtained. The ultimate capacity of the section will be governed by rupture of the CFRP laminate when the strain at the level of the CFRP reaches its limiting value. The mean rupture strain of the FRP materials should be reduced by three times the standard deviation to account for the statistical uncertainty of the material properties. This value should further be reduced by a factor of 0.85 for CFRP materials to account for possible environmental degradation of the composite[4].

4. Design and Detailing for Bonded Joints

The flexural design of a steel girder strengthened with FRP materials is based on the assumption that perfect bond exists between the girder and the strengthening material. Proper design of the adhesive joint is essential to ensure that this assumption is satisfied. For a beam strengthened with a bonded laminate plate, load is transferred by the adhesive through a combination of shear and normal, or peeling, stresses. Due to the presence of discontinuities in the beam, the adhesive or the strengthening plate, localized stress concentrations can develop in the adhesive joint. These stress concentrations can form near cracks in the strengthened beam, near defects in the adhesive or near the plate ends[5]. If the magnitude of these stress concentrations exceeds the capacity of the adhesive system, a premature debonding failure may occur. This section focuses on the design of a bonded joint to account for the effect of the peak bond stresses that form near the end of the strengthening plate. Stress concentrations that form near defects in the adhesive joint can be easily avoided by following proper installation procedures. A detailed discussion of the effects of bond defects is presented elsewhere[6].

4.1 Design Procedure

An analytical procedure was developed to calculate the shear and normal bond stress distribution for a beam strengthened with externally bonded FRP materials[2]. The analysis includes the effect of the applied loading, the thermal effects resulting from differing coefficients of thermal expansion, as well as any prestressing applied to the FRP laminate before bonding. For a steel-concrete composite beam strengthened with a

FRP laminate with square ends and loaded in four-point bending as shown in Figure 2, the shear stress distribution is given by,

$$\tau(x) = \begin{cases} B_1 \cosh(\lambda x) + B_2 \sinh(\lambda x) + m_1 P & 0 \le x \le (b-a) \\ B_3 \cosh(\lambda x) + B_4 \sinh(\lambda x) & (b-a) \le x \le L_{frp}/2 \end{cases} \qquad \text{Equation 1}$$

where,

$$\lambda^2 = \frac{G_a b_{frp}}{t_a}\left[\frac{(y_s + y_{frp})(y_s + y_{frp} + t_a)}{E_s I_s + E_{frp} I_{frp}} + \frac{1}{E_s A_s} + \frac{1}{E_{frp} A_{frp}}\right]$$

$$m_1 = \frac{G_a}{t_a \lambda^2}\left(\frac{y_s + y_{frp}}{E_s I_s + E_{frp} I_{frp}}\right)$$

$$B_1 = \frac{-G_a}{t_a \lambda}\left[(\alpha_{frp} - \alpha_s)\Delta T - \frac{y_s}{E_s I_s} Pa\right] - m_1 P e^{-k}$$

$$B_2 = \frac{G_a}{t_a \lambda}\left[(\alpha_{frp} - \alpha_s)\Delta T - \frac{y_s}{E_s I_s} Pa\right]$$

$$B_3 = \frac{-G_a}{t_a \lambda}\left[(\alpha_{frp} - \alpha_s)\Delta T - \frac{y_s}{E_s I_s} Pa\right] + m_1 P \sinh(k)$$

$$B_4 = \frac{G_a}{t_a \lambda}\left[(\alpha_{frp} - \alpha_s)\Delta T - \frac{y_s}{E_s I_s} Pa\right] - m_1 P \sinh(k)$$

$A_{s,frp}$ = cross – sectional area
$E_{s,frp}$ = tensile modulus of elasticity
$I_{s,frp}$ = moment of inertia
$y_{s,frp}$ = distance to the centroid from the adhesive
$\alpha_{s,frp}$ = coefficient of thermal expansion
b_{frp} = width of FRP laminate
G_a = shear modulus of adhesive
t_a = thickness of adhesive
ΔT = temperature change
k = $\lambda(b-a)$

where the subscripts *s* and *frp* represent the transformed properties of the steel-concrete composite beam and the FRP laminate, respectively. The remaining constants are defined in Figure 2. The calculated shear and normal stress distributions near the end of the high modulus CFRP laminate for a typical strengthened steel-concrete composite beam, loaded in four-point bending, are shown in Figure 3. It can be seen that the peak stresses quickly diminish approximately 100 mm from the end of the CFRP laminate.

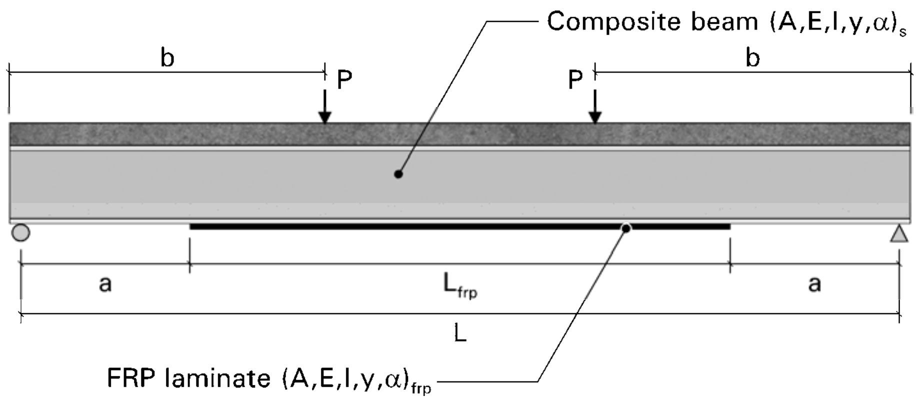

Figure 2. Beam configuration for bond stress equations

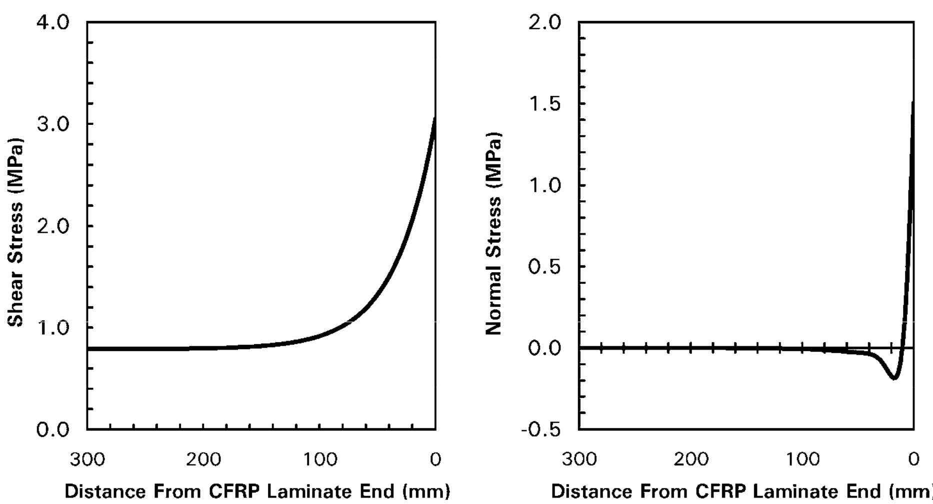

Figure 3. Bond stress distributions near the CFRP laminate end

From the calculated bond stresses, the maximum principal stress, σ_p, in the adhesive can be calculated using Equation 2.

$$\sigma_p = \frac{\sigma}{2} + \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \qquad \text{Equation 2}$$

The calculated maximum principal stress in the adhesive joint should not exceed the characteristic strength of the adhesive system, σ_c. This characteristic strength can be established using appropriate lap shear coupon tests prepared using the same materials and installation techniques that will be implemented for the in-situ strengthening application[5]. This strength should then be reduced using appropriate material partial factors to account for the effect of fatigue, possible environmental degradation, and to the high level of uncertainty regarding the use of adhesive joints in civil infrastructure applications. Safety factors as high as 17 have been proposed for some cases[7].

4.2 Detailing to minimize adhesive bond stresses

Careful detailing of the CFRP laminate end can reduce the peak stresses near the end of the strengthening plate. Since these stresses are typically critical, the overall capacity of the bonded joint can be increased. By locating the end of the strengthening plate in a region of low moment, the force transferred to the strengthening at the end of the laminate can be minimized. This can reduce the maximum bond stresses and minimize the possibility of a premature debonding failure. The peak stresses can further be minimized by installing a reverse taper near the end of the strengthening plate as shown in Figure 4. Preliminary tests of CFRP to CFRP double-lap shear coupons demonstrate that the installation of a reverse taper with an angle of 20 degrees can double the ultimate capacity of a bonded joint. This technique is particularly promising for use with splice-plated joints that, due to geometric constraints, may be required to be installed at locations of relatively high moment. Research in this area is ongoing and additional results will presented at the conference.

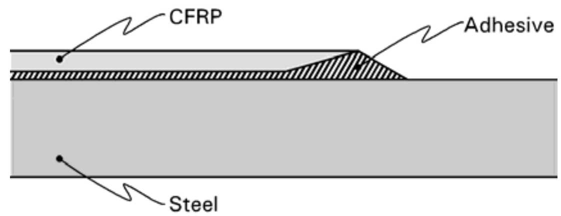

Figure 4. Schematic representation of reverse-tapered plate end

5. Installation

5.1 Surface Preparation of the CFRP Laminate

For the CFRP surface, it is usually desirable that the high modulus CFRP laminate be fabricated with a peel-ply on one or both sides of the laminate. This peel-ply is an easily removable layer that is weakly attached to the surface of the laminate during its manufacture, and protects the surface from contamination. The peel-ply should be left on the CFRP laminate until just before bonding, to prevent contamination of the surface. If a peel-ply is not available for the CFRP laminate, it is recommended to lightly abrade the CFRP surface with sandpaper and cleaned with a solvent, such as methanol[8].

5.2 Surface Preparation of the Steel

Surface preparation of the steel is fundamental in ensuring adequate bond and involves cleaning, followed by the removal of weak layers and then re-cleaning[9]. Surface preparation of the steel must be undertaken to enhance the formation of chemical bonds between the steel and the adhesive that resist moisture ingress. This requires a chemically active surface, free from contaminants and laitance. The most effective way of achieving a chemically active surface is by grit blasting[4,10,11]. Grit blasting procedures, using angular grit, remove the inactive oxide and hydroxide layers on the surface of the steel by cutting and deformation of the base material. Before grit blasting, the steel surface should be completely free from oils or other contaminants by cleaning using acetone, or a solvent suitable to remove the particular contaminant. Grit blasting should be completed until a "white metal" surface, with a rough texture is achieved. After grit blasting, any surface dust should be removed by brushing, vacuuming or blowing with a clean uncontaminated air supply. A final solvent cleaning after grit blasting may be completed, making sure that liberal amounts are used, such that contaminants are removed from the surface and not merely redistributed.

5.3 Use of Adhesion Promoters

For application in a moist environment, the use of silane adhesion promoters on the steel surface is recommended. These adhesion promoters have been shown to increase the durability of metal to epoxy bonds without affecting the bond strength[11,12]. Adhesion promoters work by favoring the development of covalent bonds. These bonds reduce the primary mechanism for strength reduction in moist environments: interfacial attack by the moisture, which is energetically attracted to the steel surface. This moisture can adsorb onto the surface of the steel, displacing the secondary bonds between the adhesive and the substrate[13]. Compounding this effect is that moisture ingress occurs at the edges of a joint, where the bond stresses are the highest. Due to the excellent lab performance of adhesion promoters, they have been used in a recent field application[14].

5.4 Application of the Adhesive and Installation

A trowel with a v-notch should be used to spread the adhesive to ensure a uniform coating is achieved. Guidelines have indicated that metal and FRP joints in general should have a target thickness of 0.5-2.0 mm[7]. Thin bond lines result in result in the efficient transfer of longitudinal stresses into the bonded material, however thin bond lines also result in higher shear and normal stresses in the adhesive at the ends of the laminate. For the specific case of steel-concrete composite beams strengthened with high modulus CFRP laminates, adhesive thicknesses of 0.1-1.0 mm have been successfully used for beams that were tested in fatigue[3]. Furthermore, considering the potential for galvanic corrosion, thicker bond lines may be desirable to ensure proper insulation between the steel and CFRP laminate to minimize the potential of galvanic corrosion.

5.5 Installation, Clamping and Coating

The CFRP laminate, with adhesive on one side, should be pressed into the steel from one end, and gradually worked towards the other edge to allow air to escape. Care must be taken to ensure that too much adhesive is not squeezed out of the ends of the laminate. In this region, it is particularly critical to maintain a bond line that is consistent with the rest of the laminate. Glass beads can be used to ensure the design adhesive thickness is achieved. Once the CFRP laminate, the adhesive and the steel surface are completely in contact, clamping of the laminate to the steel should be completed within the pot-life of the adhesive. Extremes in temperature should be avoided when installing the CFRP material due to the stresses that temperature changes can induce in the adhesive. For the same reason, heat cured adhesives must be carefully considered to account for the stresses induced during the heated cure and the subsequent cooling.

Prevention of galvanic corrosion is a particular requirement for design. Three conditions are necessary for galvanic corrosion to occur. An electrolyte must bridge the two materials, there must be direct electrical connection between the materials and there must be a sustained cathodic reaction on the carbon fiber. Controlling any one of these conditions is sufficient to ensure that no galvanic current is generated. Providing a consistent thickness of adhesive between the steel and the CFRP material is the first defense against galvanic corrosion. A second, necessary, step is a top coating of epoxy or other sealant to ensure moisture is excluded from the bond line. In the presence of repeated wetting, the bond line can absorb moisture together with any electrolytic ions present in the environment. These can allow electrical currents to be established, leading to the formation of galvanic corrosion. By excluding moisture from the bond line, no electrolytic solutions can bridge between the steel and the CFRP material, and the electrical resistance of the adhesive layer is ensured.

Glass fiber layers within the bond line have been proposed to eliminate the potential for galvanic corrosion. However, epoxy is inherently hydrophilic[15] and electrolytic ions may be leached out of the glass fiber in the presence of moisture[16]. The ion concentration gradient generated by this process has been found to lead to blistering of CFRP materials that included glass fiber due to concentration gradients that favor the movement of moisture into the joint.

7. Conclusion

Design and installation guidelines that can be used by practitioners for the proper installation, analysis and design of strengthening systems using high modulus CFRP materials are essential to its successful implementation. Simplified analytical tools can be used to determine the geometric configuration and required material properties of the CFRP material, and to accurately predict their performance.

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