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# Theoretical assessment of the limit strengthening criterion of strengthened bridge decks based on failure characteristics

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**Abstract**

The dominant failure modes of bridge deck are either flexure-shear or punching shear. Bridge decks strengthened with fiber reinforced polymers (FRPs) have an increased punching shear strength as well as improved flexural strength. This transforms the failure mode from biaxial bending to punching shear. Therefore, it is desirable to design the strengthened bridge deck so that it fails due to similar ductile behavior and with similar failure patterns as unstrengthened bridge decks, even though the ultimate strength of a strengthened deck with external reinforcements is much greater than its punching shear strength. For this reason, the concept of a strengthening limit criterion is introduced in this paper to ensure that strengthened decks have ductile dominant failure modes. The concept of failure mode transition, which is dependent on the amount of strengthening, is introduced in the practical design procedure, and a criterion for selecting the strengthening ratio is developed.


*Keywords:* Fiber reinforced polymers; Bridge deck; Strengthening limit criterion; Structural strengthening

## 1. Introduction

Permanent deformations of decks caused by excessive repeated heavy traffic loads are one of the main deterioration phenomena leaded to failure of decks. The deteriorated bridge decks then fail either due to spalling of the concrete or a punching shear failure [1–6]. During the last decade, many studies have focused on repair and rehabilitation techniques for concrete structures, and more efficient strengthening techniques and design methods have been reported [2,6]. The authors have verified the failure mechanisms of bridge decks strengthened with fiber reinforced polymers (FRPs) based on static and fatigue test results, and proposed an efficient strengthening method and simplified flexural design procedure [7–9]. In previous studies, the authors have also reported that two-directional strengthening with FRP strips is the most effective strengthening technique; it increases the ultimate strength of the deck and the fatigue resistance. A simplified strengthening design procedure to control brittle failures and extend the life cycle of deteriorated decks has also been developed.

The typical failure patterns of strengthened decks have been classified as bending failures due to the flexural stress and punching shear failures due to the shear stress. However, it is difficult to estimate the optimal amount of strengthening for a deteriorated bridge deck, because practical analysis methods for strengthened decks have not yet been developed. Oh and Sim [9] used static tests with various FRPs to experimentally assess the enhanced punching shear strength of strengthened decks. They proposed a modified yield line analysis for strengthened decks, which considered the failure characteristics of the FRPs. To prevent compressive failures, Bae [10] derived a maximum strengthening ratio, which corresponded to the existing reinforcement ratio, based on test results of strengthened beams.

In this study, we contemplate why the failure patterns of bridge decks strengthened with various materials change

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**Nomenclature**

| | |
|---|---|
| $a$ | the loading width in the transverse direction |
| $a_b$ | the depth of equivalent stress block |
| $A_p$ | the area of strengthening material in unit width |
| $A_s$ | the area of reinforcing steel bars in unit width |
| $b$ | the loading width in the longitudinal direction |
| $b_1$ | the width of beam section |
| $b_p$ | the width of strengthening material |
| $c_b$ | the depth of neutral axis |
| $C_p$ | the compressive force of concrete corresponding to the strengthening materials |
| $C_s$ | the compressive force of concrete corresponding to the steel bars |
| $d$ | the effective depth of beam section |
| $D$ | the diameter of the anchor bolt |
| $d'$ | the effective depth of compression reinforcement |
| $d_a$ | the maximum aggregate size |
| $E_p$ | the elastic modulus of the strengthening material |
| $E_s$ | the elastic modulus of reinforcing steel bar |
| $f_c'$ | the compressive strength of the concrete |
| $f_p$ | the ultimate strength of the strengthening material |
| $f_p^*$ | the maximum strength of the strengthening material |
| $f_{psy}$ | the stress of the strengthening material when the reinforcements yield |
| $f_s$ | the stress of steel bar |
| $f_{sp}$ | the spalling strength of concrete |
| $f_t$ | the tensile strength of the concrete |
| $f_y$ | the yield strength of steel bar |
| $h_p$ | the height of beam section |
| $l$ | the clear span of deck panel |
| $l_a$ | the length of anchor bolt |
| $m_n$ | the positive yield moment per unit width |
| $m_n'$ | the negative yield moment per unit width |
| $n_p$ | the ratio of $E_p$ to $E_s$ |
| $P_{anchor}$ | the resistance of the anchor bolts |
| $P_{bond}$ | the pull-out strength by bonding effect |
| $P_{cone}$ | the pull-out strength by concrete cone |
| $P_{c1}$ | the vertical component of the tensile force from the compression side to $0.1d$ |
| $P_{c2}$ | the vertical component of the tensile force from $0.1d$ to $d$ |
| $P_{c3}$ | the vertical component of the tensile force from $d$ to $h_p$ |
| $P_{dow}$ | the dowel action of the flexural reinforcement |
| $P_{pun,s}$ | the punching shear strength of deck panel |
| $P_{y,s}$ | the flexural strength of deck panel |
| $r_s$ | the radius of an equivalent column circle in a slab-column system |
| $t_p$ | The thickness of strengthening material |
| $T_p$ | the tensile force of strengthening materials |
| $T_s$ | the tensile force of steeel reinforcing bars |
| $u$ | the length of the unbonded part of anchor bolt |
| $u_s$ | the bond strength |
| $x_c$ | the critical depth of the first cone failure of anchor bolt |
| $\sum^{bars} A_s$ | the sum of the cross sectional areas of the reinforcing steel bars embedded in the punching cone |
| $\beta$ | the tan $\phi$ in failure surface of anchor bolt |
| $\beta_1$ | 0.85 |
| $\varepsilon_p$ | the ultimate strain of the strengthening material |
| $\varepsilon_p^*$ | the maximum strain of the strengthening material |
| $\zeta$ | the ratio of $f_s$ to $f_y$ |
| $\eta$ | the coefficient of loading area effect |
| $\theta_1$ | the first inclination angle of the failure surface from the top of the compression side to $d'$ |
| $\theta_2$ | the second inclination angle from $d'$ to $d$ |
| $\theta_3$ | the third inclination angle from $d$ to $h_p$ |
| $\lambda$ | the experimental coefficient for strength reduction factor of strengthening material (0.72) |
| $\mu$ | The efficient of orthotropy |
| $\mu_a$ | the coefficient of aggregate size effect |
| $\xi$ | the coefficient of reinforcement effect |
| $\rho_s$ | the reinforcement ratio |
| $\rho_{s,b}$ | the balanced reinforcement ratio |
| $\rho_{s,max}$ | the maximum reinforcement ratio |
| $\rho_{equi}$ | the equivalent reinforcement ratio of FRP |
| $\rho_p$ | the strengthening ratio |
| $\rho_{p,b}$ | the balanced strengthening ratio |
| $\rho_{p,max}$ | the maximum strengthening ratio |
| $\phi$ | the apex angle of the cone |
| $\phi_s$ | the diameter of steel bar |
| $\cot \psi/2\sqrt{\frac{m_n}{m_n'}}$ | |

from flexure to shear. We also use yield line and punching strength analyses to analyze the theoretical flexural and shear strength of strengthened prototype decks according to the amount of strengthening. From this analytical approach, a strengthening limit criterion is proposed for the design of strengthening in bridge decks. A design criterion that can be used to select an appropriate strengthening ratio that ensures the ductile failure of a strengthened deck is also suggested from the results of a parametric study of the relationship between the reinforcement ratio and the strengthening limit criterion.

## 2. Failure criteria of strengthened decks

### 2.1. Maximum strengthening ratio

Without strain hardening, most strengthening materials, such as FRP plastics, have a perfect elastic behavior up to their ultimate strain. Therefore, the balanced steel reinforcement ratio and balanced strengthening ratio of a strengthened beam indicate when the tensile failure of the FRP reinforcements and compressive failure of the concrete occur at the same time, as shown in Fig. 1. The relationship between the reinforcement ratio $\left(\rho_s = \frac{A_s}{b_1 d}\right)$, strengthening ratio $\left(\rho_p = \frac{A_p}{b_1 h_p}\right)$, and failure pattern of a strengthened concrete member is depicted in Fig. 2.