Prediction of Extended Fatigue Life of RC Deck Slabs Strengthened with FRP Sheets

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Research on strengthening RC deck slabs of highway bridges by fiber reinforced polymer (FRP) sheets has been carried out. Up to date, a considerable amount of data has been acquired from the wheel-running fatigue tests for the FRP-strengthened deck slabs. In this paper, the relevant data are analyzed in order to quantify the overall strengthening performance. A method is proposed for predicting the fatigue life extension ratios of the strengthened deck slabs by evaluating the distinct effects due to the strengthening, which include the enhancements in shear resistance of concrete and anisotropic characteristic of deck slab as well as confinement of concrete cracks by the FRP sheets bonding.

Keywords: fatigue life prediction, FRP sheet, RC deck slabs, strengthening

1. INTRODUCTION

Strengthening of reinforced concrete (RC) structures with fiber reinforced polymer (FRP) sheets has become an increasingly popular method following extensive research and development to realize the potential of the strengthening method in various circumstances. Recently, research has been undertaken on strengthening of RC deck slabs of highway bridges to extend their fatigue life. Fatigue tests on full-scale RC deck slabs strengthened by bonding aramid fiber reinforced polymer (AFRP) or carbon fiber reinforced polymer (CFRP) sheets of different mechanical properties have been carried out by using the wheel running machine of Osaka University1)-5). Bottom surface of the deck slab specimens was strengthened by bonding the FRP sheets either in full or in part in a grid-like pattern. Repeated wheel load was applied at the mid-span of the slab and moved along the longitudinal direction. In this paper, the respective data compiled from the experiments are analyzed. The purpose is to propose a method of predicting the extended fatigue life of RC deck slabs as a result of the strengthening.

2. FATIGUE LIFE EXTENSION RATIO

Results of the tests conducted to date on the FRP-strengthened deck slab specimens are given in Table 1. The shear resistance of the deck slabs after losing continuity as a plate structure and when parallel 'transverse beams' are formed, P_{sx}, is calculated by adopting the following equation6):

$$P_{sx} = 2\tau_{s\max} X_m B + 2\sigma_{t\max} C_m B \qquad (1)$$

where $\tau_{s\max}$ and $\sigma_{t\max}$ are the maximum shear stress and maximum tensile splitting strength and of concrete, respectively; X_m is the effective concrete depth at the main bar cross section when tension side concrete is neglected; C_m is the concrete cover between the tension main bar to the slab bottom and B being the effective width for stress distribution on the neutral axis plane.

While the fatigue life of the strengthened specimens, in terms of total number of load passages, was obtained from the experimental results, fatigue life of the specimens under unstrengthened condition was predicted by employing the conventional *S-N* equation for RC deck slabs6):

Table 1 Results of wheel-running fatigue tests

Specimen	Design Thick-ness, t_c (mm)	FRP type	Bond pattern*	Tensile stiffness of FRP, S_f (kN/mm)	Shear resistance		Total loading passages		Refe-rences
					Unstreng-thened, P_{sxo} (kN)	Strengthened, P_{sxi} (kN)	Unstreng-thened, N_o (x10^3)	Strengthened, N_i (x10^3)	
t16-A24	160	AFRP	G1	24	260	266	257	1,476	(1)
t16-A36	160	AFRP	G1	36	257	265	213	1,594	
t16-C30	160	CFRP	G1	30	265	272	295	1,574	(2)
t16-C45	160	CFRP	G1	45	264	275	280	2,074	
t15-C68	150	CFRP	G1	68	208	226	14	187	(3)
t15-C80	150	CFRP	G1	80	211	231	16	115	
t18-C60a	180	CFRP	G2	60	276	296	491	13,634	
t18-C60b	180	CFRP	G2	60	275	292	487	4,350	
t18-C70	180	CFRP	G2	70	276	300	512	13,994	
L300*2	180	CFRP	F	82	274	295	595	14,455	(4)
L600	180	CFRP	F	84	274	296	595	17,319	
W600	180	CFRP	F	84	279	300	750	7,570	
W600D	180	CFRP	F	84	279	300	740	18,520	
W600D-H	180	CFRP	F	84	286	309	1,130	51,051	
S-GM	180	CFRP	F	38	291	302	1,013	8,092	(5)
S-HM1	180	CFRP	F	67	291	310	1,013	17,345	
S-HM2	180	CFRP	F	93	291	316	1,013	26,951	

*F- full surface bonding of FRP sheet
G1- grid pattern with width of FRP sheet = 250 mm and gap between FRP sheets = 100 mm
G2- grid pattern with width of FRP sheet = 250 mm and gap between FRP sheets = 150 mm

$$\log P/P_{sx} = -0.07835\log N + \log 1.520 \qquad (2)$$

where P is the reference load and N is the total number of load passages. The fatigue life extension ratio, α, can thus be evaluated by dividing the total number of passages of the strengthened specimens, N_i by that of specimens without the FRP-strengthening.

By bonding FRP sheets to the bottom surface of deck slabs, effects that contribute to the extension of the slab fatigue life include the followings:

(a) Improvement of shear resistance, P_{sx},
(b) Enhancement of the anisotropic characteristic of deck slab,
(c) Confinement of cracks and resistance towards crack propagation, etc.

By considering the above mentioned effects, the total extension of fatigue life can be attributed to a number of discrete extension ratios as given below:

$$\alpha = \alpha_p \alpha_{an} \alpha_{cr} \qquad (3)$$

where α_p and α_{an} are fatigue life extension ratios due to improvement of P_{sx} and anisotropic characteristic of slab, respectively, and α_{cr} takes into account the crack confinement effects and other potential effects of the FRP-strengthening. The respective fatigue life extension ratios are discussed and evaluated. The evaluation methods are very similar to that undertaken by Kobayashi[7)], except for the incorporation of some newly acquired data and certain modifications in order to verify and to refine the proposed prediction for fatigue life of the FRP-strengthened deck slabs.

2.1 Improvement of P_{sx}

The depth of neutral axis of a deck slab increases by strengthening with the FRP sheets. This is followed by the increase of the slab stiffness and P_{sx}. As indicated by Eqs. (1) and (2), the increase of P_{sx} is always associated with the increase of the slab fatigue durability. Incorporating the Miner's rule for fatigue damage accumulation, the fatigue life extension ratio due to the improvement of P_{sx} is given by

$$\alpha_p = (P_{sxi}/P_{sxo})^n \qquad (4)$$

where P_{sxi} and P_{sxo} are the shear resistance of slab with and without FRP-strengthening, respectively. Parameter n is taken as 12.76, which is the inverted value for the gradient of the S-N equation as shown by Eq. (2). The relations between α_p and tensile stiffness of

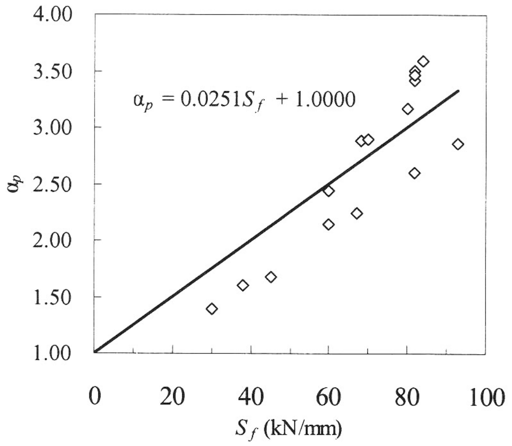


Fig. 1 α_p vs. S_f

FRP sheet, S_f, are depicted in Fig. 1. Boundary condition is set in such a way that when $S_f = 0$ (no FRP sheet), $\alpha_p = 1$, which signifies that there is no extension of fatigue life when the slab is not strengthened. A moderate relation between α_p and S_f with a linear equation as given below is yielded to facilitate simple estimation of α_p from the value of S_f:

$$\alpha_p = 0.0251S_f + 1.0000 \tag{5}$$

2.2 Enhancement of anisotropic characteristic

In the existing RC deck slabs designed in accordance with previous versions of specifications, the amount of distributing bar (in longitudinal direction) has been less than that of main bar (in transverse direction) because of one-way slab design philosophy. Therefore, a highway bridge slab is often considered as an anisotropic plate structure. Under repeated wheel loading, cracks in an anisotropic plate structure propagate in a grid-like pattern. The cracking results in a more significant anisotropic characteristic of slab. Due to the anisotropy, the effective width of deck slab for sustaining the fatigue load in the longitudinal direction decreases accordingly. This causes the shear stress acting on the cross section to increase, which shortens the fatigue life of deck slab. By strengthening with the FRP sheets, the effective area for stress distribution can be increased and this will improve the anisotropy characteristic of these deck slabs. Thus, higher fatigue durability can be expected.

To investigate the behavior of an anisotropic slab in sustaining fatigue load, a numerical analysis was performed by using ABAQUS Ver. 6.5.1 commercial finite element package. A simply supported 3000 mm x 2000 mm x 160 mm deck slab with an effective span length of 1800 mm was chosen as the analytical model.

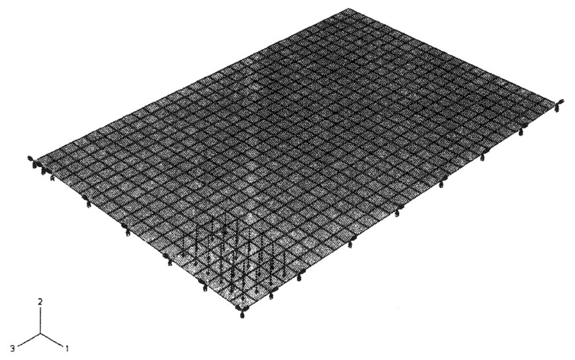


Fig. 2 FEM model

Considering the geometric symmetry and the load condition, only 1/4 of the deck slab width was considered the model with proper boundary conditions. In the model, 4-node plane stress elements were used to model the deck slab, as shown in Fig. 2. Loading was at the center of the slab. In the actual fatigue tests, the wheel load had a contact area of 300 mm x 120 mm. By considering that shear stress is acting on a plane with inclination of 45°[7)], the loading area becomes larger as the distance from the top surface increases. In the analysis, loading was assumed to be employed at the centroid of the slab model with an effective area of 460 mm x 280 mm.

Orthotropic material properties are adopted to simulate the anisotropic characteristics of the model. The elastic modulus in the main bar direction, E_x is 30000 N/mm^2. For the elastic modulus in the distributing bar direction, E_y, the following relation is employed:

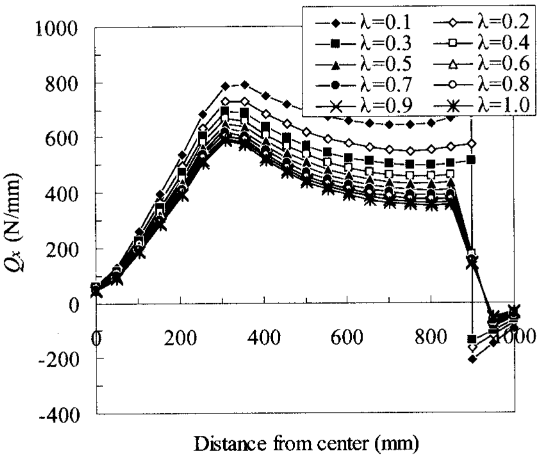
$$E_y = \lambda E_x \tag{6}$$

where λ is the stiffness ratio. λ can be expressed as follow:

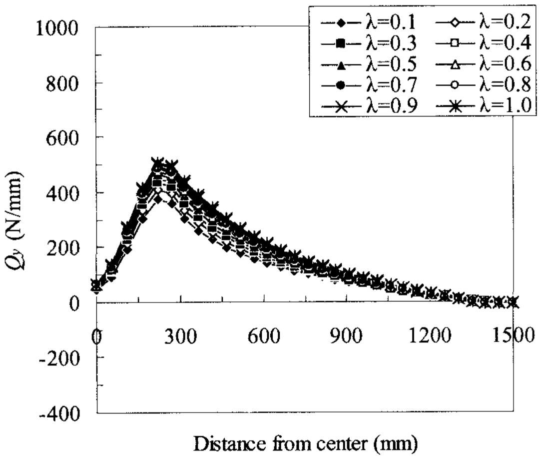
$$\lambda = {(E_c I_d)}\Big/{(E_c I_m)} = {I_d}\Big/{I_m} \tag{7}$$

In the FEM analysis, λ varies from 0.1 to 1.0. Fig. 3 presents the distribution of shear forces in the longitudinal and transverse directions, Q_x and Q_y, respectively. It is found that as the stiffness in the longitudinal direction decreases by lowering the value of λ, Q_y and M_y decrease. On the contrary, Q_x and M_x increase with the deck slab thickness and the stiffness in the longitudinal direction.

Fig. 4 gives the relation between the maximum shear force and λ. It can be noticed that $Q_{x,max}$ increases with λ, whereas $Q_{y,max}$ decreases with λ. This indicates the importance of improving the anisotropic characteristic of deteriorated deck slab in order to achieve a better distribution of stresses in both the longitudinal and the



(a) Shear force along longitudinal direction



(b) Shear force along transverse direction

Fig. 3 Distributions of shear force

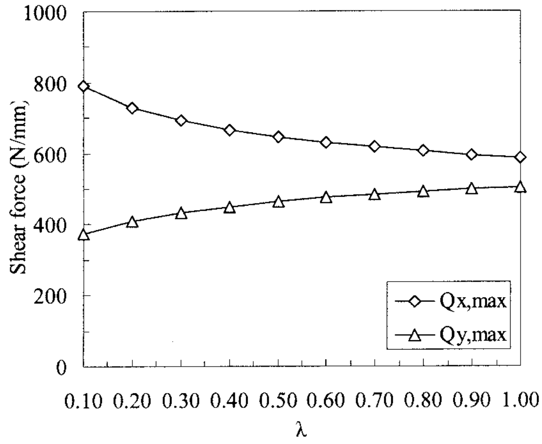


Fig. 4 Maximum shear force vs. λ

transverse directions can be achieved to optimize the deck slab fatigue durability.

By dividing $Q_{x,max}$ for respective λ with $Q_{x,max}$ when $\lambda = 1$, normalized values Q_x^* are obtained. The relation between Q_x^* and λ is presented in Fig. 5. A good polynomial relation can be formed. The normalized

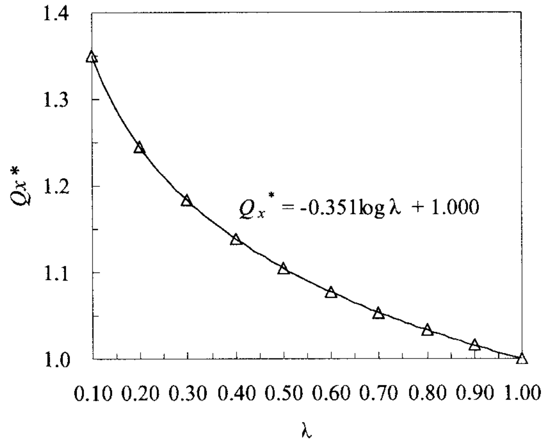


Fig. 5 Q_x^* vs. λ

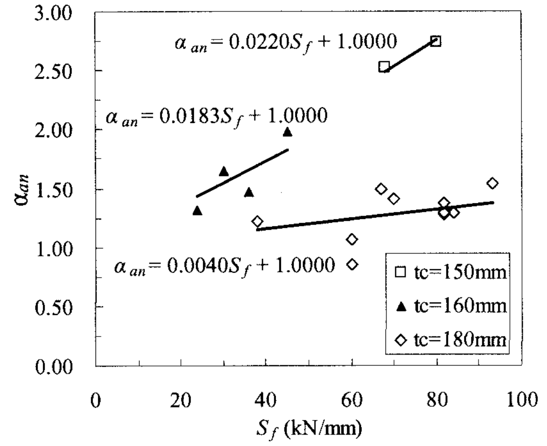


Fig. 6 α_{an} vs. S_f

relation is represented by the following equation:

$$Q^* = Q_x^* = -0.351\log\lambda + 1.000 \qquad (8)$$

Incorporating the concept of Miner's rule for fatigue and also the *S-N* relations for normal RC deck slabs without the FRP strengthening, the following empirical equation is proposed to estimate the length of extension in fatigue life due to enhancement of the anisotropic characterstic by the FRP strengthening, α_{an}:

$$\alpha_{an} = (Q_o/Q_i)^n = (Q_o^*/Q_i^*)^n \qquad (9)$$

Q^*_o and Q^*_i can be acquired by using Eq. 9, in which λ is subsituted with λ_o and λ_i, which are the stiffness ratios obtained under unstrengthened and FRP-strengthened conditions, respectively. The relation between α_{an} and S_f is depicted in Fig. 6. Because it is considered that the trend for enhancement of the slab stiffness is case-sensitive towards the slab thickness, t_c, as well as reinforcement designs, separate linear relations should be proposed. By implementing boundary condition that $\alpha_{an} = 1$ when $S_f = 0$, the following equations are obtained:

For $t_c = 150$mm,

$$\alpha_{an} = 0.0220S_f + 1.0000 \tag{10}$$

For $t_c = 160$mm,

$$\alpha_{an} = 0.0183S_f + 1.0000 \tag{11}$$

For $t_c = 180$mm,

$$\alpha_{an} = 0.0040S_f + 1.0000 \tag{12}$$

By multiplying α_P with α_{an} and relating the multiplied products with $\alpha = N_{eqo}/N_{eqi}$, plots as shown in Fig. 7 are obtained. It is apparent that the plots are not suggesting a firm relation between α and $\alpha_P\alpha_{an}$. The reason could be that there are one or more other factors that influence the extension of the fatigue life. One of other factors, i.e. effect of crack confinement by the bonded FRP sheets, is suggested and will be evaluated in the following section.

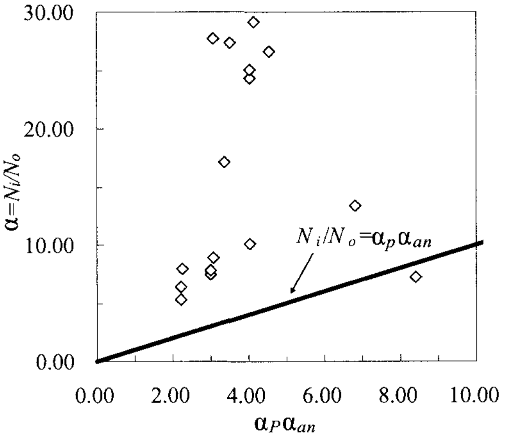


Fig. 7 N_i/N_o vs. $\alpha_P\alpha_{an}$.

2.3 Effect of crack confinement

When a slab is subjected to repeated wheel loading, normally cracks propagate. Subsequent loading causes the cracks to progress and this results in the loss of stiffness of the slab. The following movements take place at concrete crack tips$^{8)}$:

(i) opening of crack faces due to tensile stress at a plane perpendicular to the direction of crack;

(ii) relative movement between crack faces in cracking direction due to shear stress; and

(iii) relative movement between two crack faces along the plane perpendicular to cracking direction due to shear and torsion, in which the plane sections can no longer be considered plane when the relative movement of the crack faces becomes extensive.

By bonding FRP sheets to the surface of cracked concrete, confinement of concrete can be achieved. As a result the crack movemet as mentioned in (i) is restricted because of high tensile stiffness given by the FRP sheets. It is considered that as the tensile stiffness of the FRP sheets, S_f increases, the effect of the crack confinement also increases, therefore results in higher fatigue durability of the strengthened deck slab.

Another noteworthy phenomenon about the strengthening by FRP sheets is that no significant debonding of the sheets can be found at the vicinity of concrete cracks before extensive shearing and punching occur at late stage of fatigue loading of RC deck slab. This is considered because the FRP sheets usually 'follow' the movement of the cracks. Therefore, crack confinement by FRP sheet bonding can be attained with high efficiency. With this characteristic, it is reckoned that movements of the cracks as mentioned in (ii) and (iii) can also be restricted up to a certain extend.

Taking into account the complex combinations of crack movements, it is extremely difficult to clarify the mechanism of crack confinement by FRP sheet bonding and to evaluate the effect on extension of fatigue life by theorectical approach. Therefore, regression of the experimental results is carried out. In this contex, fatigue life extension ratio due to the confinement of cracks, α_{cr} is calculated by dividing the overall fatigue life extension ratio, α with the product of $\alpha_P\alpha_{an}$. The relation between $\alpha/(\alpha_P\alpha_{an})$ and S_f is given in Fig. 8. By neglecting the extreme values obtained from specimens W600D, t18-C60b, t16-A48 and t15-C80, a moderate linear relation is obtained, as given by the following:

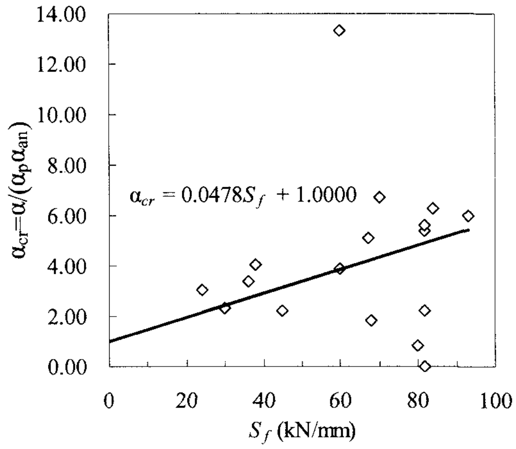


Fig. 8 α_{cr} vs. S_f

$$\alpha_{cr} = 0.0478S_f + 1.0000 \qquad (13)$$

2.4 Prediction of fatigue life extension

By multiplying α_P, α_{cr} and α_{an}, predicted lifespan extension ratio is calculated and compared with that obtained experimentally. The plots are shown in Fig. 9. The relations are not essentially in good fit. The values obtained theorectically tend to be higher than that otainened by calculations of experimental results, especially in the case for 150-mm thick slabs. Nevertheless, it is to be noted that uncertainties could have occurred in the experiements, which might have affected the overall accuracy of the evaluation. More input of experimetal data is thus imperative to further verify the consistancy and to increase the accuracy of the regression equations. The current proposed method can be considered useful as a reference and as a guideline in the process of predicting the fatigue life extension of FRP-strengthened slabs.

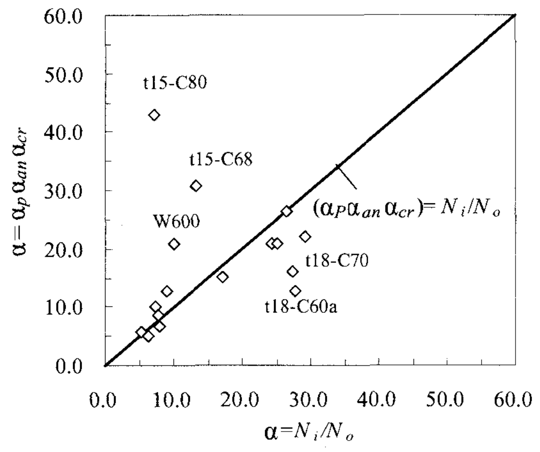


Fig. 9 $\alpha_p\alpha_{an}\alpha_{cr}$ vs. N_i/N_o

3. CONCLUSIONS

FRP sheets-strengthening method has been verified as a highly effective method in extending the fatigue life of RC deck slabs. Based on evaluatio of the data acquired in the experiments, a fatigue life prediction method for RC deck slabs strengthened with the FRP sheets is presented. Several distinct effects of the strengthening were analyzed to account for the overall fatigue life extension ratio. The proposed method can be considered useful as a reference and as a guideline in the process of predicting the fatigue life extension of FRP-strengthened deck slabs. However, due to the existance of extreme values, which were probably caused by experimental defects, more data are thus required to refine the the regressions equations obtained through the analysis and to improve the accuracy of the prediction method proposed in this paper.

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