

# A COMPARATIVE INVESTIGATION ON SHEAR FATIGUE STRENGTH OF RC BRIDGE DECK SLABS

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## ABSTRACT

This comparative investigation aims at evaluating the applicability of the AASHTO shear design provision for shear fatigue strength prediction. Based on the existing equation developed through the past experimental dataset of RC slabs tested under moving wheel-type loading by Takeda, the shear fatigue strength was observed in this study. The results indicate that the AASHTO shear design provision could be used to predict the shear fatigue strength of RC slabs with modification to account for the influence of moisture and support conditions under fatigue loading.

**Keywords:** RC bridge deck slabs, fatigue damage, AASHTO shear design, shear fatigue strength

## 1. INTRODUCTION

Reinforced concrete (RC) bridge deck slabs could be deteriorated by several factors, which are able to induce damages, decreasing their performance during service life. As it is well known that bridge deck slabs are commonly subjected to the repeatedly concentrated vehicle wheel load, causing fatigue damage [1,2]. It finally causes the punching shear failure in RC bridge deck slabs. This phenomenon, fatigue failure taking place in the RC slabs, has interested a number of researchers in examining the fatigue life of RC slabs with various parameters throughout both experimental and numerical analysis [3-5]. Even though several investigations were ongoing, a shear fatigue life prediction approach that took the impact of moisture stage and boundary conditions into consideration was only proposed recently by Takeda [6,7]. These effects are also investigated in this study.

To ensure the shear fatigue strength, many well-known practical design codes (i.e., JSCE, fib model code 2010) provide the design approach for the predicting fatigue life of RC members; however, RC bridge deck slabs designed using AASHTO LRFD Bridge Design Specifications (AASHTO LRFD) [8] do not need to be investigated for the shear fatigue strength. Although many current design codes of practice provide the provision to evaluate the fatigue strength of RC members subjected to shear, fatigue damage is continuously investigated in RC bridge deck slabs such as RC deck slabs over prestressed concrete I-shape girders (PC I-girder) bridges [2].

As mentioned above, while no specific provision for shear fatigue strength prediction is established in AASHTO, it is widely adopted as a reference design specification in many countries. Therefore, this study

performs a comparative investigation to evaluate the applicability of the AASHTO shear design provision for shear fatigue strength prediction based on an existing equation developed through the past experiment of RC slabs under moving wheel-type loading by Takeda [7].

## 2. SHEAR STRENGTH FOR FATIGUE LIFE PREDICTION

### 2.1 Shear strength equations for one-way action

Matsui and Perdikis's studies [3,4] clarified that the typical cracking pattern of model RC slabs that failed under moving wheel-type loading in the experiment is a grid-like form. This cracking pattern generates the beam-formed element, which results in slab failure. To anticipate fatigue life as accurately as possible, it is necessary to investigate the shear strength equations in a one-way action, commonly known as beam shear. Regarding this study objective, the researchers would involve the investigation of the AASHTO shear design provision for fatigue life prediction of the bridge's RC deck slab, four models of the shear strength equation including the AASHTO equation as follows:

#### (1) AASHTO model

According to AASHTO LRFD [8], section 5.12.8.6, shear resistance,  $V_c$  (N), for a slab-type region without transverse reinforcement under the one-way action can be calculated by using Eq. 1. This equation is derived from the Modified Compression Field Theory (MCFT) of Vecchio and Collins [9], where the shear strength relies on the ability of diagonal cracked concrete to transmit tension and shear stresses taking place in the critical section. The expressions are as follows:

$$V_c = \beta \lambda \sqrt{f'_c} b_v d_v \quad (1)$$

where the shear resistance factor is denoted by  $\beta$ .

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$\lambda$  denotes concrete density modification in which 1 can be used for normal density concrete, and  $f'_c$ ,  $b_v$ , and  $d_v$  represent the compressive strength of concrete (N/mm<sup>2</sup>), effective width (mm), and effective shear depth (mm), respectively.

The value  $\beta$  above has been developed to utilize a more convenient equation by Bentz et al. [10] in which a simplified expression (Eq. 2) for sections do not contain at least the minimum amount of shear reinforcement was given.

$$\beta = \frac{0.4}{1+750\varepsilon_s} \frac{1300}{1000+S_{xe}} \quad (2)$$

where  $\varepsilon_s$  is the net longitudinal tensile strain in the section at the centroid of the main reinforcement, which is calculated from  $(M_u/d_v+0.5N_u+|V_u|)/E_sA_s$ ;  $M_u$ ,  $N_u$  and  $V_u$  are the moment (N-mm), axial force (N), and shear force (N) at the section, respectively.  $E_s$  and  $A_s$  are the elastic modulus (N/mm<sup>2</sup>) and area of the main reinforcement (mm<sup>2</sup>), respectively.  $S_{xe}=S_x[35/(a_g+16)]$ , in which  $S_x$  denotes the crack spacing parameter taken as the greater of  $d_v$ ,  $0.9d$ , and  $0.72$  member height (mm), and  $a_g$  is the maximum aggregate size (mm).

#### (2) ACI318 model

The ACI 318 one-way shear provisions have been in place for a few decades; neither the effect of member depth (also known as the size effect) nor the effect of longitudinal reinforcement ratio on shear strength was calculated. To account for these effects when estimating shear stress capacity, in the 2019 edition [11], a new relationship for one-way shear strength of non-prestressed members without axial forces, including slabs,  $V_c$  (N) was established in Eq. 3.

$$V_c = 0.66\lambda_s\lambda(\rho_w)^{1/3}\sqrt{f'_c}b_wd \quad (3)$$

where  $\lambda_s$  represents the side effect modification factor, which can be calculated from  $\sqrt{2/(1+0.004d)}$  not greater than 1.  $\lambda$  and  $f'_c$  are defined as same as the AASHTO model.  $\rho_w$  denotes ratio of  $A_s$  to  $b_wd$  in which  $b_w$  and  $d$  are a web width (mm), and effective depth (mm) and area of the main reinforcement (mm<sup>2</sup>), respectively.

#### (3) JSCE model

The Standard Specification for Concrete Structures “Design” [12] published by the Japan Society of Civil Engineers (JSCE) suggested that to calculate the shear resistance of a one-way slab, which behaves like a beam, the equation for linear members,  $V_{cd}$  (N), can be

used as presented in Eq. 4

$$V_{cd} = \beta_d\beta_p f_{vcd}b_wd \quad (4)$$

where,  $f_{vcd} = 0.20\sqrt[3]{f'_c} \leq 0.72$ ,  $\beta_d = \sqrt[4]{1000/d} \leq 1.5$ ,  $\beta_p = \sqrt[3]{100p} \leq 1.5$ ,  $f'_c$  represents the compressive strength of concrete (N/mm<sup>2</sup>), and  $b_w$  and  $d$  are the width of a beam (mm) and the effective depth of the main reinforcement (mm) respectively, and  $p$  denotes the main reinforcement ratio.

#### (4) Takeda’s model

In 2018, Takeda and Sato [7] proposed the shear strength,  $V_{bc}$  (N), equation (Eq. 5) for the beam-formed member in order to predict the fatigue life of RC slabs. The width of a beam-formed member,  $b_{w,e}$  (mm), calculated by Eq. 6. Eq. 5 was developed based on the JSCE model by combining the influence of wetness conditions and support conditions with the modification factor  $\alpha_e$  and  $\alpha_B$ , respectively. Furthermore, the influence of main and distributing reinforcement was included in the shear strength calculation by multiplying with the coefficient of  $\beta_{p1}$  and  $\beta_{p2}$ , which can be obtained from Eqs. 7 and 8, respectively.

$$V_{bc} = \alpha_e\alpha_B\beta_{p1}\beta_{p2}\beta_d f_{vmcd}b_{w,e}d \quad (5)$$

where,  $\alpha_e = 1.0$  in the dry condition and 0.69 in the wet condition,  $\alpha_B = 0.64, 1.00,$  and  $1.50$  for the slab supported by 2-side simple and 2-side free, 2-side simple and 2-side elastic, and 4-side simple, respectively, and  $f_{vmcd} = 0.32\sqrt[3]{f'_c}$ .

$$b_{w,e} = b + 2d_d \quad (6)$$

$$\beta_{p1} = 100p_1^{[\frac{1}{3}+0.5(100p_2)]} \quad (7)$$

$$\beta_{p2} = 1 + 0.125\frac{p_2}{p_1} \quad (8)$$

where,  $d$  and  $d_d$  are the effective depth of main and distributing reinforcement (mm), respectively, and  $b$  denotes the loading plate length in the longitudinal direction (wheel-travel direction) (mm),  $p_1$  and  $p_2$  represents the main reinforcement ratio and the distributing reinforcement ratio, respectively.

Table 1 presents the comparison between the shear strength equations mentioned above. They are compared from the viewpoint of material properties and geometrical properties as the main influencing parameters in the shear strength of the members under one-way action. The former properties consist of the

Table 1 Comparison between shear strength equations for one-way action

Parameter	AASHTO [8]	ACI318 [11]	JSCE [12]	Takeda [7]
Material properties				
- Compressive strength of concrete	●	●	●	●
- Ratio of flexure reinforcement	● <sup>a</sup>	●	●	● <sup>b</sup>
- Moistures effect	x	x	x	●
Geometrical properties				
- Size effect (member depth)	●	●	●	●
- Support condition	x	x	x	●

Remarks: ● = Considered; x = Not considered

<sup>a</sup> considered as reinforcement amount.

<sup>b</sup> considered both main and distributing reinforcement.

compressive strength of concrete, the ratio of flexure reinforcement, and the moisture effect. The latter properties comprise size effect and support conditions. With these parameters, the AASHTO model clearly shows that the MCFT-based shear strength equation completely covers the major parameters similar to other design codes of practices, i.e., ACI318 and JSCE; however, this model does not take into account the moisture effect and the influence of support conditions as involved in Takeda's model. In addition, only Takeda's equation considers the influence of distributing reinforcement. Since various forms of the equation are used to consider those parameters in estimating shear strength, the following section will compare predicted shear strengths using different models.

## 2.2 Comparison of shear strength prediction

The RC deck slabs over the typical prestressed concrete I-shape girder (PC I-girder) in-service bridge were investigated in this study as illustrated in Fig. 1. This RC slab was used as a studied slab, with a thickness of 0.2 m erected over five different length PC I-girders placed 1.66 m. apart, resulting in the transversely clear span of the RC deck slab into 1.26 m long. The slabs were steel-reinforced by deformed bars with 16-mm diameter (D16) placed at 200 mm spaces in the transverse direction of both top and bottom layers. Meanwhile, a 12-mm diameter (D12) placed at 150 mm spaces was used as the distributing reinforcement in both layers. In addition, the material properties of this investigated RC deck slab comprising of concrete cylinder compressive strength and yield strength of reinforcing steel are 25.5 MPa and 295 MPa, respectively. It should be noted that all properties are based on the structural bridge drawing.

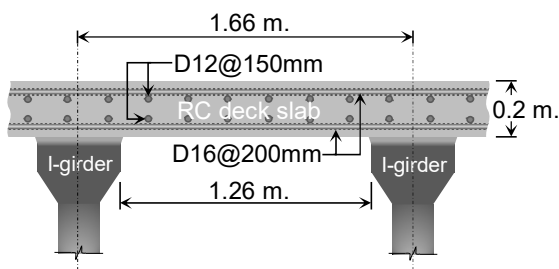
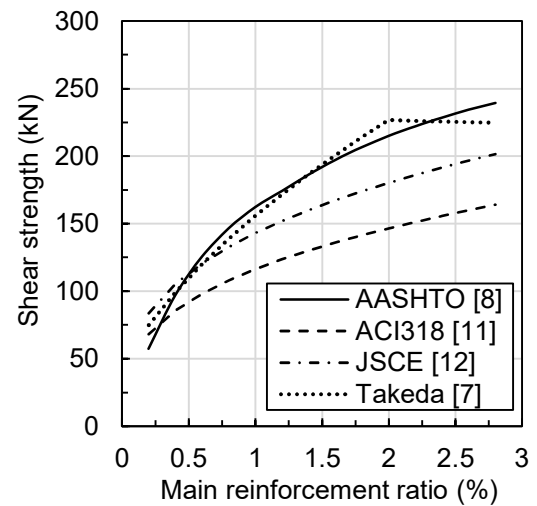


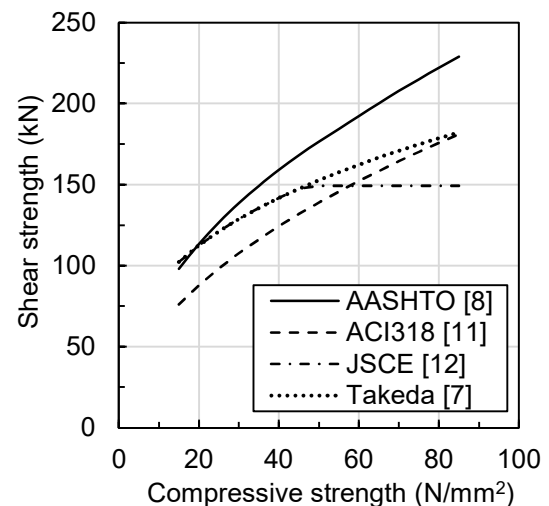
Fig.1 Typical cross-section of studied RC slabs

Based on the sectional properties of the investigated bridge's deck slab described above, the shear strength calculated using mentioned equations referred to the slab supported by 2-side simple and 2-side free supports. Fig. 2., thus, it compares the investigated shear strengths, using a unit width (1 meter) as an effective width of the typically comparative slabs, gained from Eqs. 1 to 8. To examine the influence of flexure reinforcement, the shear strengths with varying amounts of main flexure reinforcement, while other parameters do not, are plotted in Fig. 2a. All models demonstrate that the shear strength would gradually increase when the main reinforcement increase. The ACI318 shear strength displayed in the dashed line

shows the most conservative prediction. In contrast, shear resistances obtained by the AASHTO and Takeda models exhibit the same trend with the highest value among others. Regarding those models, it could be obviously seen that the shear stress carried by concrete directly increases proportionally to the square root of compressive strength for AASHTO and ACI318 and the cube root for the JSCE and Takeda models. These different power functions cause a differently increasing rate between the American and Japanese models, as shown in Fig. 2b; however, those results are on the same trend. For the size effect, the calculated shear strength decreases inversely proportional to the member depth, especially for the members with large effective depth [13]. Consequently, this effect is negligible because the present study focuses on the slab members, which usually have a small thickness and a narrow range of thickness resulting in a small effective depth.



a) varied main flexure reinforcement



b) varied compressive strength of concrete

Fig.2 Comparison of calculated shear strength

Based on the investigated bridge, the moist stain with efflorescent was found. This gathered evidence indicates that the water on the road surface penetrates through the wearing surface (asphaltic concrete) layer to

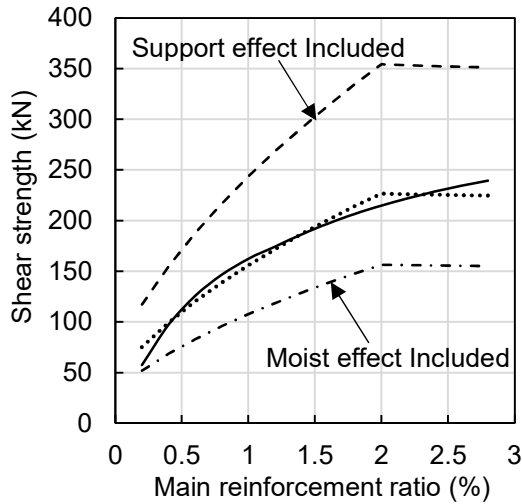


Fig.3 Influence of moisture and support conditions

the concrete slabs beneath. Consequently, the RC deck slab has been fully saturated along the entire depth of the slab section. Here, this wet condition could significantly reduce the fatigue life of the concrete [14]. Since Takeda's model consider both the influence of support condition and the moisture effect, it was suitably chosen to evaluate those effects on shear strength predicted by the AASHTO model. Besides this unique point, the well-agreed result between Takeda's model and the AASHTO model was observed when the amount of main reinforcement varied (Fig. 2a). To focus on the effect of support and moisture conditions, the comparison is conducted using calculations with varying main reinforcement. The results in Fig. 3, plotted with broken lines for Takeda's model and a solid line for the AASHTO model, demonstrate that the support and moisture conditions significantly impact the shear strength of slab members. These results suggest that the AASHTO model could be used with no significant change for slabs supported by 2-side simple and 2-side free under normal (dry) conditions; however, it might need some modification for other conditions, i.e., wet condition and restrained support slabs.

### 3. SHEAR FATIGUE STRENGTH PREDICTION

#### 3.1 Experimental database

The experimental data used in a previous study [7] was also adopted in this study to investigate shear fatigue strength prediction using the AASHTO shear strength equation. The experimental dataset, including 81 RC slabs that failed under a moving wheel loading tested with a constant load, was collected and summarized in Table 2. The data are categorized by support condition into three main groups: 1) 2-side simple and 2-side free supports; 2) 2-side simple and 2-side elastic supports; and 3) 4-side simple supports. Additionally, Group 2 includes the slabs were tested under the wet condition.

#### 3.2 Fatigue life prediction of RC slabs

Since Takeda and Sato [7] revealed that the boundary and wet condition considerably affect the shear

Table 2 Summarized experimental database

Group	1	2	3
$t$ (mm)	167-205	70-220	150
$f'_c$ (N/mm <sup>2</sup> )	26.2-52.5	13.6-54.0	24.8-35.2
$p_1$ (%)	0.84-1.74	0.74-1.59	0.85
$p_2$ (%)	0.29-1.36	0.28-1.19	0.94
$P$ (kN)	157	24-323	100
$N$ ( $10^3$ cycles)	0.29-3250	0.30-1449	63.1-379

strength, Eq. 9 that describes the relationship between the experimentally obtained fatigue life  $N$  and the normalized amplitude  $S$  developed by the same authors was adopted in this section in order to conduct the investigation of fatigue life prediction of RC slabs using the AASHTO shear design equation. The shear strength  $V_{bc}$  in Eq. 9 is multiplied by a constant of 2 to account for the fact that the constant load  $P$  was applied at the mid-span of the RC slabs in the tests.

$$S = P/2V_{bc} = 1 - K \log N \quad (9)$$

where,  $K = 0.057$  and  $0.061$  for the dry condition and the wet condition, respectively, and  $N$  denotes the number of cyclic moving loads at failure.

The S-N diagrams of empirical fatigue life prediction equations (Eq. 9) and experimental fatigue life is plotted in Fig. 4., where the vertical and horizontal axes represent the applied load normalized with double shear strength capacity determined by AASHTO model and Takeda's model and number of loading cycles, respectively. The  $S$  values for Group 1 computed using the AASHTO model are generally lower than those obtained using Takeda's model. However, the result in Fig. 1a. shows a good agreement between both models. This is due to the influence of compressive strength of concrete  $f'_c$  on the calculated shear strength, which the AASHTO shear strength is higher than Takeda's shear strength when  $f'_c$  increase as shown in Fig. 1b. This effect is also observed in the result in Group 2 in which some  $S$  values calculated by AASHTO model show a very similar result comparing to that of Takeda's result. These results suggest that shear strength equation should be modified when using AASHTO model to predict fatigue life of RC deck slabs. Moreover, it can be clearly seen from result in Groups 2 and 3 that fatigue life was incredibly dominant by support conditions. This is because the shear strength of the laterally restrained slabs is increased by the compressive membrane forces, so-called arching action [15]. Therefore, it is important to consider this action while predicting the fatigue life using AASHTO shear strength equation of the RC deck slab like investigated bridge, which is laterally restrained by adjacent spans.

Although, most results in Group 2 estimated by the AASHTO model are affected by support condition resulting in higher  $S$  value than that of predicted S-N curve, few results plotted with diamond shape can be observed under the S-N curve. This deviation is found in the slabs experimented under wet condition. As a results, it may be concluded that the moisture impacts the fatigue life of RC slabs as well.

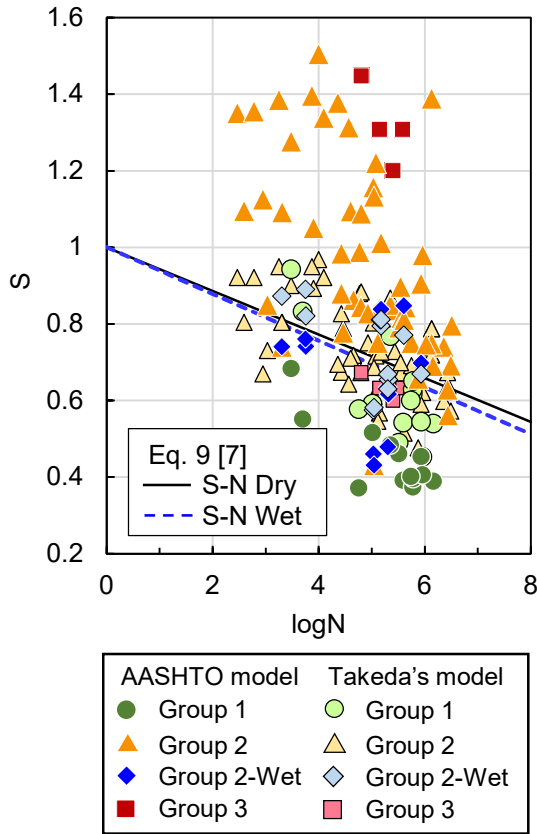


Fig.4 Calculated S-N diagrams of RC slabs

### 3.3 Modified AASHTO shear strength equation

As discussed earlier, the fatigue life predicted by using the shear strength equation provided in the AASHTO LRFD mostly exhibits different trend comparing to the existing S-N curve proposed by Takeda [7]. Also, Table 3 demonstrates that the average ratio between calculated and experimental normalized shear forces ( $S_{cal}/S_{exp}$ ) by using the AASHTO model in all group significantly deviates from value 1.0 as well as resulting in the highest standard deviation value (SD). It mainly influences by the support and wet conditions. The present study, hence, proposes the shear strength equation,  $V_{mc}$ , (Eq. 10) to consider those effects based on AASHTO model. The proposed equation is developed by modifying the AASHTO model with coefficients of wet condition effect,  $\alpha_{wc}$ , and support condition effect,  $\alpha_{sc}$ . Both coefficients were obtained from the inversion of the average ratio of  $S_{cal}/S_{exp}$  in the case of AASHTO, as listed in Table 3. The expression are as follows.

$$V_{mc} = \alpha_{wc} \alpha_{sc} \beta \lambda \sqrt{f'_c} b_v d_v \quad (10)$$

where,  $\alpha_{wc} = 1.0$  in the dry condition and 0.72 in the wet condition,  $\alpha_{sc} = 0.64, 1.37,$  and  $1.87$  for the slab supported by 2-side simple and 2-side free, 2-side simple and 2-side elastic, and 4-side simple, respectively.

In Fig. 5, the S-N diagram in which the S values are calculated by using proposed shear strength equation comparing to Takeda's model. It is found that the results agree well with the existing S-N relation derived from

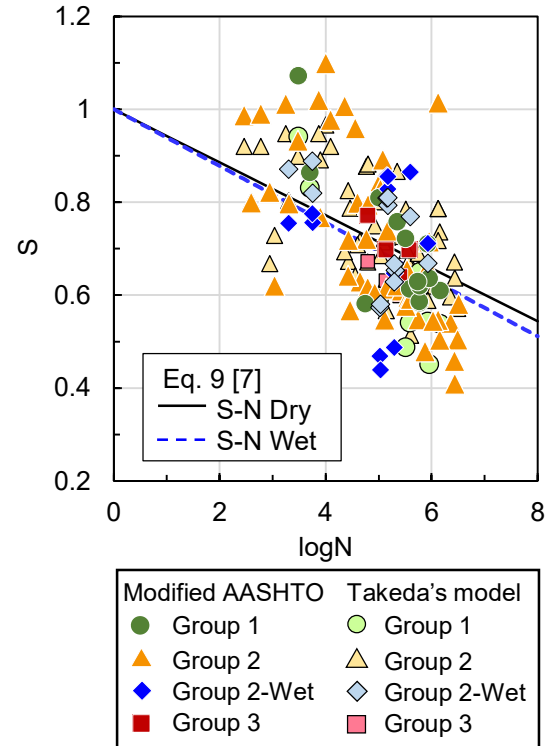


Fig.5 Calculated S-N diagrams of RC slabs with modified AASHTO shear strength equation

the tested RC slabs. These robust agreement points to the proposed equation's reliability. In addition, the average ratio between normalized shear force from Eq. 9  $S_{cal}$  and obtained from P divided by double of different shear strength  $S_{exp}$  is tabulated in Table 3. The  $S_{cal}/S_{exp}$  ratio computed by using proposed shear strength equation in all groups shows a good improvement throughout the values very close to 1.0. On top of that, the standard deviation value (SD) of the proposed result is improved.

Table 3 Average  $S_{cal}/S_{exp}$  from different shear strength equations

Average $S_{cal}/S_{exp}$	Takeda [7]	AASHTO [8]	Proposed Equation
Group 1	1.145	1.597	1.017
Group 2	0.987	0.828	1.046
Group 3	1.108	0.535	1.003
Overall	1.020	0.946	1.039
SD	0.143	0.373	0.202

## 4. CONCLUSIONS

- (1) Since the AASHTO shear design provision obviously indicates that the MCFT-based shear strength equation takes into account the major parameters similar to other practical design codes, it could be potentially applied for shear fatigue strength prediction with additional modification.
- (2) The RC slabs' fatigue life is incredibly impacted by support conditions. Therefore, it is important to consider this effect when predicting fatigue life using the beam shear strength equations.

- (3) The proposed shear strength equation developed by modifying the AASHTO shear strength equation could be used to predict shear fatigue strength of RC slabs failed under moving wheel loading with various support conditions as well as under wet condition.

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