(39) NUMERICAL INVESTIGATION ON SLIP CONTROLLED CYCLIC BEHAVIOR OF GROUP STUDS UNDER BIAXIAL LOAD ACTION

Chen XU[1], Kunitomo SUGIURA[2]

[1]JSCE member, Graduate School of Science and Technology, Kanazawa University (〒 920-1192 Kakuma-machi, Kanazawa)　E-mail: xuchen@se.kanazawa-u.ac.jp

[2]JSCE member, Dept. of Civil and Earth Resources Engineering, Kyoto University (〒 615-8540 Katsura, Kyoto) E-mail: sugiura.kunitomo.4n@kyoto-u.ac.jp

Nowadays, wide transverse cantilevers and web spacing have been introduced in many steel and concrete composite bridges with group studs. The passing-by moving load may result to biaxial load action effect. It consists of bridge longitudinal interlayer shear forces and transverse bending-induced action. So far, its cyclic effects on group studs have not been concerned enough. Thus we carried out a related study through cyclic push-out FEM analysis and fatigue strength evaluation. In the FEM analysis, we correspondingly established three cases to derive the related critical local cyclic strain and stress. The stud shank diameter and height were 13mm and 80mm. Based on the analysis results, we introduced the strain based multi-axial fatigue criterion to evaluate the stud fatigue performance. Generally, it showed that under the certain introduced slip controlled cyclic push load action, biaxial load action appeared little unfavorable cyclic effect to group studs fatigue behavior while its residual bending-induced concrete cracks seemed disadvantageous. Thus as to engineering practice, it is important to examine the fatigue performance of group studs in composite bridge with wide cantilevers and web spacing. Further systematic study will be carried out in future.

Key Words: *group studs, biaxial load action, cyclic FEM analysis, slip controlled, fatigue behavior.*

1. INTRODUCTION

The application of studs as shear connector in steel and concrete composite structures has an over 50years history. As to arranging studs in group, referred to as group studs, it is favorable in constructional perspective. For example precast concrete slab can be easily installed. But on the other hand, literature information[1-3] shows stud shear stiffness would be unfavorably affected by group arrangement. Nowadays, many composite bridges are characterized by wide transverse cantilevers and web spacing. The self-weights and relevant passing-by moving loads may lead to significant lateral bending moment, making shear stud subjected to combined longitudinal shear force and transverse bending-induced action. This can be referred to as biaxial load action. Xu C. et al. have discussed its effect on static behavior of group studs[1,4]. But the cyclic effect is still not clear. In this sense, a related study was carried out, which included slip controlled cyclic push-out FEM analysis and the following group studs cyclic evaluation through multi-axil fatigue damage criterion. Specifically, cyclic effects of uniaxial load action, biaxial load action and residual bending-induced concrete cracks on group studs fatigue performance were analyzed and evaluated.

And accordingly, engineering suggestions were proposed.

2. NUMERICAL ANALSIS SETUP

(1) General analysis procedure

Generally, the fatigue damage of shear studs usually appears at the positions around stud root, which are believed due to the local stress concentration. In terms of this, a local stress-strain fatigue analysis procedure was introduced in the study. It assumed that the fatigue life is determined by the local stress-strain response at the local critical position. The specific analysis procedure is composed by two parts, cyclic push-out FEM analysis and fatigue behavior evaluation. They are shown in **Fig.1**. The FEM analysis with inputted cyclic material constitutions and push load actions was executed to derive stable cyclic structural stress and strain response. In terms of the introduced multi-axial fatigue damage criterion, the critical local position and its cyclic strain and stress can be derived from FEM analysis results. Thus the fatigue performance of group studs can be evaluated.

Three push-out FEM models were included in the cyclic analysis, labeled with FA, FAB and FAC with different load actions. The dimensions shown in **Fig.2** were mainly based on Ref.[5]. The vertical and lateral spacing of studs are respectively 65mm and 50mm. The stud shank diameter is 13mm and the stud height is 80mm. In terms of biaxial symmetric attributes, only three-dimensional quarter FEM models were established in ABAQUS. As shown in **Fig.3**, the model includes solid elements of concrete slab, shear studs and steel plates and truss elements of reinforcements. It was analyzed by explicit module. Concerning boundary condition, it was configured in terms of the symmetrical mechanical feature. And the nodes of reinforcement element are tied to related nodes of concrete elements. The interlayer surfaces between steel flanges and concrete slabs and between stud shafts and surrounding concrete were simulated by contact pair algorithm. The interlayer friction coefficient was assumed 0.3.

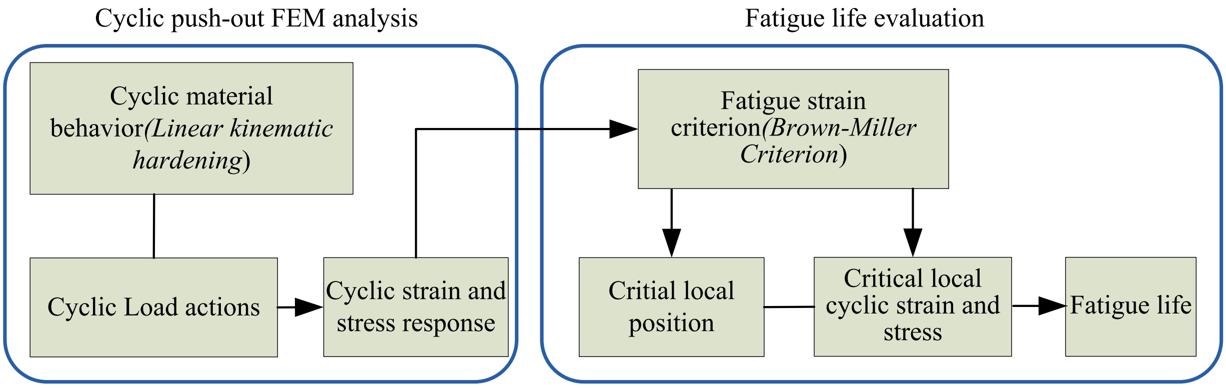


Fig.1 General cyclic analysis procedure

Table 1 Cyclic push-out FEM models

Models	Load actions & effect	Lateral loads (kN)	Maximum crack width(mm)	Cyclic disp. Pattern	
				△D/2 (mm)	R
FA	Uniaxial	0	0	0.2	-1
FAB	Biaxial	36	-0.15	0.17	-1
FAC	with concrete cracks	36*	-0.15	0.21	-1

*This load will be removed before applying cyclic load.

(2) FEM model setup

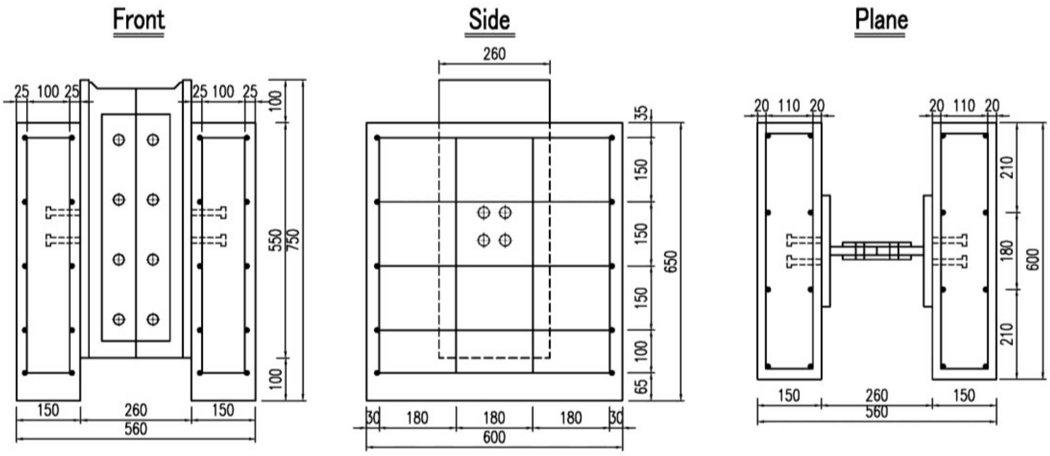


Fig.2 Dimension of push-out model

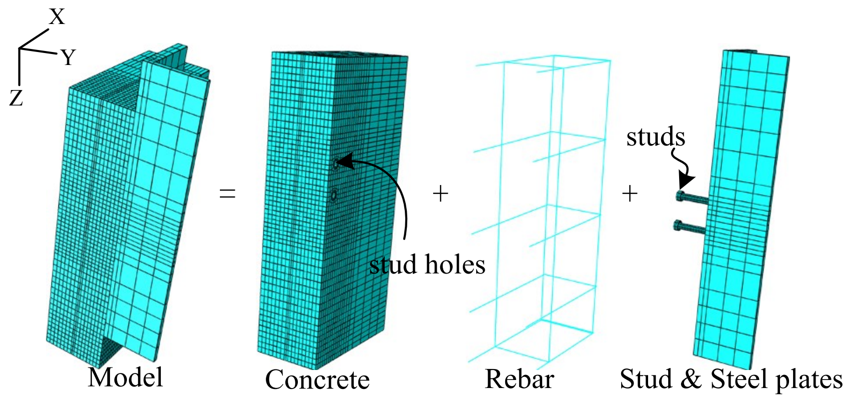


Fig.3 Parametric FEM push-out model

(3) Load action

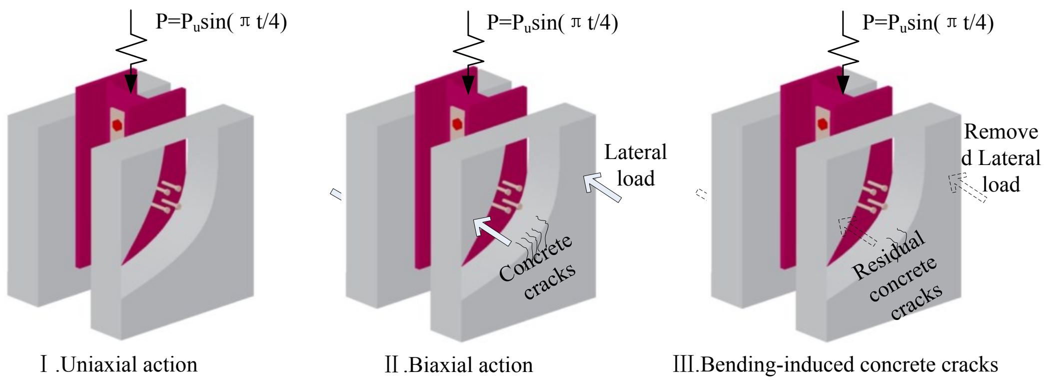


Fig.4 Loading actions applied on cyclic push-out FEM models

Table 1 lists the models and related load actions. Meanwhile the load actions are depicted in **Fig.4** as well. The load steps are specified in **Table 2**. It is worth mentioning here the cyclic push-load was actually controlled by steel concrete interlayer cyclic slip history. This is for that some presented experimental results of composite girder under cyclic wheel load action showed a nearly constant interlayer cyclic slip history[6]. In fact, the displacement controlled cyclic push analysis has experienced an iteration process to achieve the cyclic slip pattern listed in **Table 1**. **Fig.5** shows the typical cyclic interlayer slip history. The specific slip amplitudes were from static stud stiffness proportion among the models FA, FAB and FAC. It is 1:1.15:0.95[1]. Thus, compared with a 0.2mm cyclic slip amplitude in FA, a 0.17 mm cyclic slip amplitude and a 0.21mm cyclic slip amplitude were applied on FAB and FAC. Concerning the lateral load depicted in **Fig.4** for biaxial load action(FAB) and residual bending-induced concrete cracks(FAC), its value was set 36kN. This equivalents to the bending moment that can induce tensile cracks with 0.15mm maximum crack width based on Ref.[7] As to the cyclic analysis results, it was considered stable when variation differences of stress strain amplitudes in cycles become less than 10%. In this sense, 4 cycles was found to be enough.

(4) Material constitutions

Nonlinear material constitutions and damage plasticity models were introduced in the analysis. The material stress-strain relationships are shown in **Fig.6**. The concrete material constitutions, as plotted in **Fig.6(a) and (b)**, were based on Eq. 2 and Eq. 3[8], where ε_c and ε_t are the strains related to compressive and tensile peak stresses; α_a , α_d and α_t are regression parameters. It can be seen the concrete compressive and tensile strength are respectively 50MPa and 3.0MPa. **Fig.6(c)** shows the uniaxial stress plastic strain relationships of studs, steel plates and reinforcement, all of which include linear hardening stages. In addition, descending stages have been taken into account in the materials of stud and reinforcement. This may due to that stud and nearby reinforcement may happen to experience the material softening stages in the push-out process. The tensile strength of stud is around 480MPa.

Table 2 Load procedure for cyclic push-out FEM analysis

Load step	FA	FAB		FAC	
	push load	push load	Lateral loads	push load	Lateral loads
1	started	None	started	None	started
2	continued	started	continued	None	stopped
3	continued	continued	continued	started	None

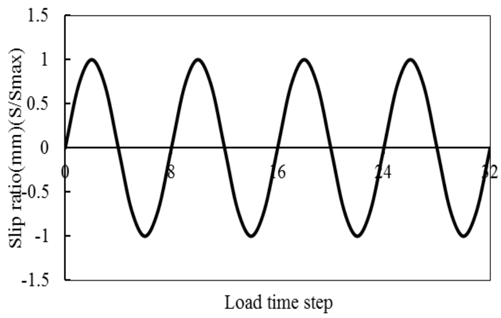
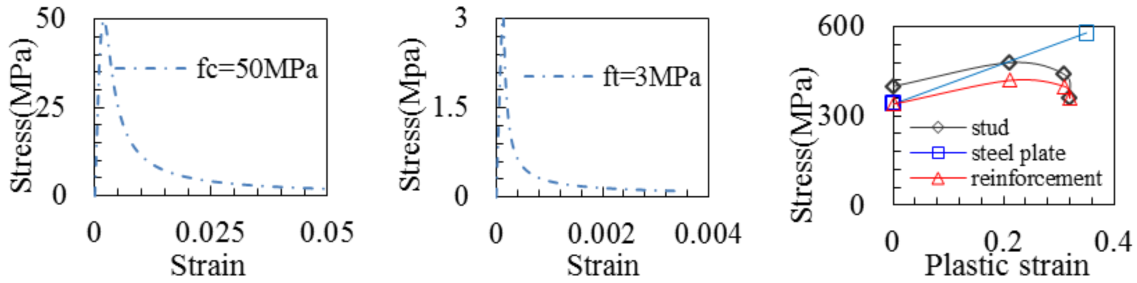
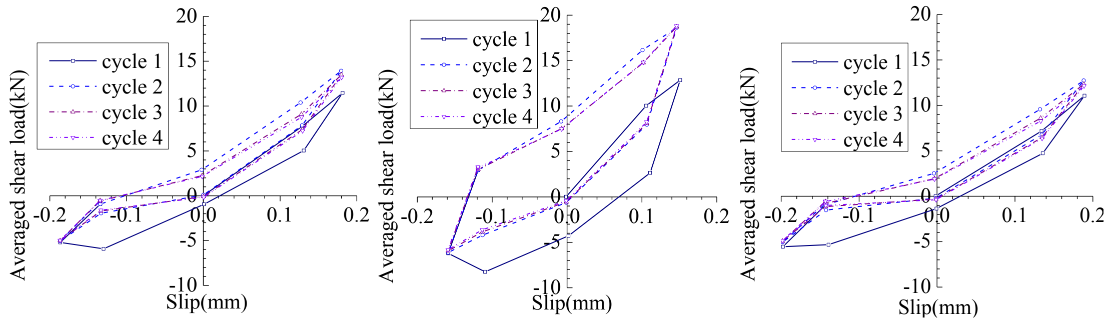


Fig.5 Cyclic push load applied on FEM models



(a) Concrete compression (b) Concrete tension (c) non-concrete materials

Fig.6 Uniaxial material constitutions



(a) FA model (b) FAB model (c) FAC model

Fig.7 Cyclic load-slip curves

(5) Multi-axial fatigue criterion[9)]

The Brown-Miller criterion proposes that the maximum fatigue damage occurs on the material plane which experiences the maximum shear strain amplitude. It fits well with the fatigue damage happening to shear stud, shear fracture with slight bending[10)]. The damage is a function of both such shear strain and the strain normal to this plane, as given in Eq. 1.

$$\frac{\Delta\gamma_{\max}}{2}+\frac{\Delta\varepsilon_{n}}{2}=C1\frac{(\sigma'_{f}-\sigma_{nm})}{E}(2N_{f})^{b}+C2\varepsilon'_{f}(2N_{f})^{c} \quad (1)$$

$$b\approx-\frac{1}{6}\lg\left(\frac{2\sigma_{f}}{\sigma_{b}}\right) \quad (2)$$

$$\varepsilon'_{f}\approx\ln\left(\frac{1}{1-\psi}\right) \quad (3)$$

In this equation, $\gamma_{\max}$ is the maximum shear strain and the strain normal to the maximum shear strain is ε_{n}, which can be respectively expressed as $\gamma_{\max}/2=(\varepsilon_1-\varepsilon_3)/2$ and $\varepsilon_n=(\varepsilon_1+\varepsilon_3)/2$ in terms of material Mohr's circle. For elastic stresses, the constants C1 equals 1.65 and C2 equals 1.75. σ_{nm} is the mean normal stress on the shear plane. Concerning the coefficients, fatigue strength exponent b can be deduced approximately by Eq. 2 where σ_{f} is the true tensile strength and σ_b is the ultimate tensile strength. Regarding fatigue ductility coefficient ε'_{f}, it is close to the value derived from the Eq. 3 where ψ is the percentage reduction of area. Moreover the value of c is suggested -0.6 for ductile material[11)]. Concerning fatigue strength coefficient σ'_{f}, its value seems quite close to σ_{f} for most of metals. Based on the tensile test on stud material[12)], ψ =70.9%. The σ_b and fracture tensile strength have been assumed 480MPa and 320MPa. Thus σ_{f} was 1103MPa. Accordingly, b, c, σ'_{f}, ε'_{f} can be derived, which are -0.11, -0.6, 1103MPa and 1.235.

3. RESULTS AND DISCUSSION

(1) Cyclic structure performance

Fig.7 provides the cyclic analyzed load-slip curves. The positive averaged shear load direction is the push load direction. The related slip ranges of FA, FAB and FAC are [-0.187mm, 0.180mm], [-0.159, 0.146] and [-0.198, 0.189]. As to the cyclic stud shear loads in these models, they tends to become stable after the initial cycles.

(2) Critical fatigue position and fatigue strength

Generally, stud fatigue damage appears at the positions of stud root(A), stud welding collar(B) or sometimes stud shank(C). In case of weld collar height is large the fatigue failure position may happen at the interface between weld collar and steel flange. Since the cyclic push-out FEM models did not take welding effect into account, local positions of A and B coincides with one another. Accordingly, the fatigue local positions will be decided in the area of stud roots colored by red in **Fig.8**. Fatigue damage at position C is not considered in this analysis.

Fig.9 shows the maximum and minimum principal strains distributed along upside stud root outline as depicted in **Fig.8** at the 26th and 30th load steps. Accordingly, the maximum amplitude of shear strain on upside stud root can be detected in the positions of 0 degree and 180 degree. This is in terms of $\Delta\gamma_{\max}/2 = \Delta(\varepsilon_1 - \varepsilon_3)/2$. The situation appeared on down side stud root was similar. Since these positions have the same fatigue features, fatigue evaluation on one of them can be representative to reflect the effect of the loading actions. Thus position at 180 degree on upside stud root was selected as the critical local position.

Fig.10 respectively shows the cyclic principal strain and stress vs. load time step at selected critical local position of FA. In **Fig.10(a)**, it shows cyclic maximum principal strain ε_1, minimum principal strain ε_3, maximum shear strain $\gamma_{\max}$ and related normal strain ε_n to the plane with maximum shear strain. The cyclic principal stress vs. load time step of FA is displayed in **Fig.10(b)**, which consists of maximum principal stress σ_1, minimum principal stress σ_2 and stress σ_n normal to the plane with maximum shear stress. Based on these tow figures, it confirmed that the cycles becomes stable after the initial one or two cycles. In terms of **Fig.10**, the related cyclic strain and stress characteristics are listed in **Table 3** which include cyclic peaks, valleys, ranges and mean values.

The symbol of "Δ" denotes the cyclic ranges. According the Eq. 1, the fatigue lives of FA, FAB and FAC under such cyclic load actions are calculated and compared with each other. The comparison ratio is listed in **Table 3**. Since some parameters of Eq. 1 is based on assumed values, the evaluated fatigue strength of these models are not listed here. The listed comparison ratios shows biaxial load action appears little unfavorable effect on cyclic behavior of group studs. However, its residual bending-induced concrete cracks tend to be unfavorable. This summarization is in condition of the certain introduced cyclic load patterns which corresponds to the live loads passing through composite girders with wide transverse cantilevers and web spacing. Since residual bending-induced cracks will keep existing on the girder, fatigue performance of group studs in this situation should be concerned carefully in real engineering practices.

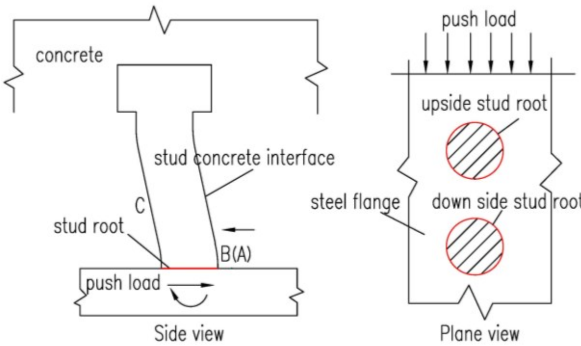


Fig.8 Typical fatigue damage positions on stud

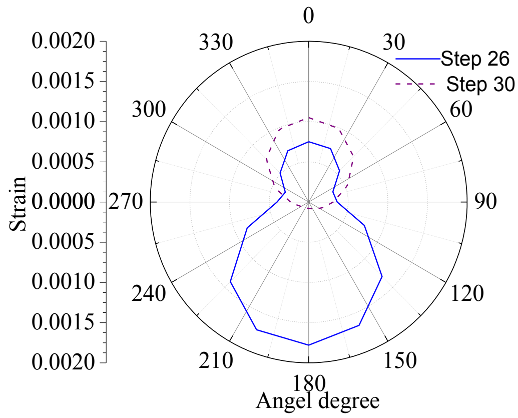


Fig.9(a) Max. Principal strain

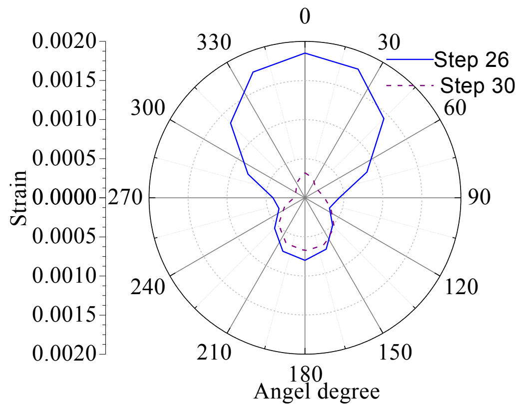
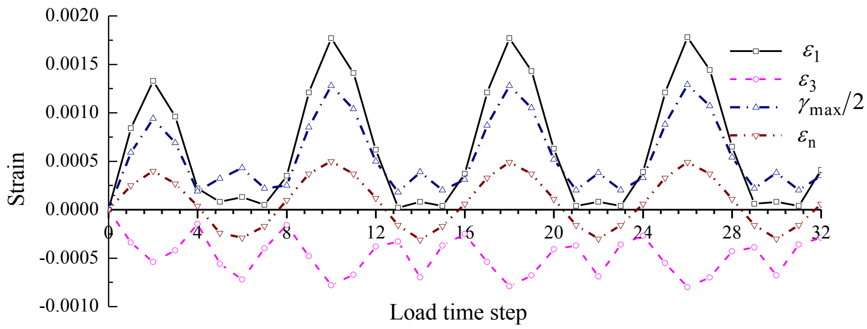
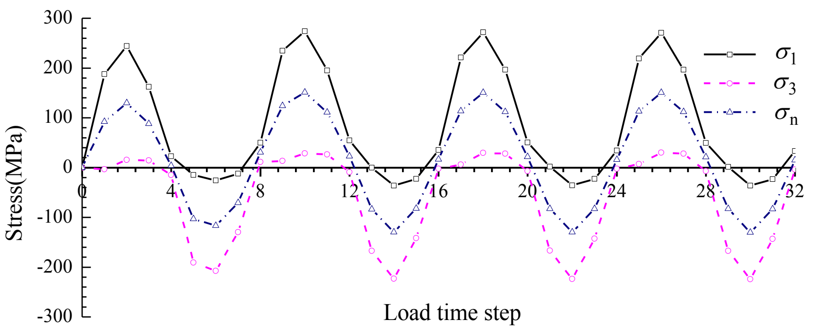


Fig.9(b) Min. Principal strain



(a) Cyclic principal strains of FA



(b) Cyclic principal stresses of FA

Fig.10 Cyclic principal strains and stresses of FA

Table 3 Fatigue evaluations

Model	$\Delta\gamma_{max}/2$	$\Delta\varepsilon_n/2$	$\sigma_{n,mean}$	N_f(unit ratio)
FA	0.00109	0.0004	10.065	1
FAB	0.00098	0.000315	18.75	2.0
FAC	0.00118	0.00041	11.58	0.45

4. CONCLUSIONS

Influences of biaxial load action and its residual bending-induced concrete cracks on fatigue performance of group studs were analyzed. Based on the cyclic FEM analysis and cyclic behavior evaluations, the following summarizations can be derived.

Generally, it can be found that biaxial load action appears little unfavorable effect on cyclic behavior of group studs. However, its residual bending-induced concrete cracks tend to be unfavorable. This summarization is in condition of the certain introduced cyclic load patterns which corresponds to the live loads passing through composite girders with wide transverse cantilevers and web spacing. As to the engineering practices, fatigue performance of group studs in this situation should be concerned carefully.

REFERENCES

1) Xu C., Sugiura K., Wu C., Su Q. T. Parametrical static analysis on group studs with typical push-out tests. Journal of constructional steel research, Vol.72, pp 84-96, May, 2012.

2) Okada J., Yoda T., Lebet J.P. A study of the grouped arrangements of stud connectors on shear strength behavior. Structural engineering/Earthquake engineering, JSCE, April; Vol.23, No.1: 75-89, 2006.

3) Shim C. S., Lee P. G., Chang S. P. Design of shear connection in composite steel and concrete bridges with precast decks. Journal of constructional steel research. 57(2001)203-219, 2001.

4) Xu C., Sugiura K. Parametric push-out analysis on group studs shear connector under effect of bending-induced concrete cracks. Journal of constructional steel research, Vol.89, pp 86-97, October, 2013.

5) EUROCODE 4. EN 1994. Design of composite steel and concrete structures. Part 1 General rules and rules for buildings. 2004.

6) Feldmann M., Gesella H., Leffer A. The cyclic load-slip behavior of headed studs under non static service loads-experimental studies and analytical descriptions. Composite construction in steel and concrete V, ASCE, 2006.

7) JTG D62-2004. Code for design of highway reinforced concrete and prestressed concrete bridges and culverts, Beijing: China Communication Press, 2004. [in Chinese].

8) Code for design of concrete structures, GB50010-2002. Ministry of housing and urban-rural development of China, 2002. [in Chinese].

9) Brown M. W., Miller K. J. A theory of fatigue under multiaxial strain conditions. Proceedings of the institution of mechanical engineers, June 187:745-755, 1973.

10) Xu C., Sugiura K. FEM analysis on failure development of group studs shear connector under effects of concrete strength and stud dimension. Engineering failure analysis, 2013. Doi: 10.1016/j.engfailanal.2013.02.023

11) Zhao S. B. Design of fatigue resistance. China Machine Press, ISBN 7111035747, 1994. [in Chinese].

12) Xu C. Static and fatigue strength of group studs shear connector under biaxial loading action. Doctoral dissertation, Kyoto University, Kyoto, Japan. 2012.