Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Push-out Analysis on Cyclic Performance of Group Studs Shear Connector under Biaxial Load Action

Chen XU[1,2*], Kunitomo SUGIURA[2]

[1] *Graduate School of Science and Technology, Kanazawa University, Japan*
[2] *Dept. of Civil and Earth Resources Engineering, Kyoto University, Japan*
[*] *Graduate School of Science and Technology, Kanazawa University, Kanazawa, Ishikawa, Japan, 920-1192. xuchen@se.kanazawa-u.ac.jp*

ABSTRACT

The application of studs as shear connector in steel and concrete composite structures has an over 50 years history. Arranging studs in group, say group studs, is favorable in constructional perspective. Nowadays, many steel and concrete composite bridges are designed with wide transverse cantilevers and web spacing. This results to biaxial load action on group studs, comprising longitudinal shear force and transverse bending-induced action. So far, effect of such action on group studs has not been concerned intrinsically in cyclic aspect. Thus they carried out a related study by setting up strain based cyclic push-out FEM analysis and introducing multi-axial fatigue criterion. In condition of the certain introduced load actions, it showed that group studs under biaxial load action appeared better cyclic response while that under effect of residual bending-induced concrete cracks appeared reverse situation.

Keywords. Group Studs, Cyclic Performance, Biaxial Load Action, Bending-induced Concrete Cracks, Multi-axial Fatigue Criterion.

INTRODUCTION

The application of studs as shear connector in steel and concrete composite structures has an over 50 years history. Compared with other kinds of shear connectors, shear studs get economical and constructional advantages. As to the stud arrangement in structure, group arrangement is favorable in constructional perspective, for example precast concrete slab can be easily installed. On the other hand, literature information (Xu C. et al., 2012, Okada J. et al 2006, Shim C. S. et al., 2001) shows stud shear stiffness and strength would be unfavorably affected by group arrangement.

Nowadays, many composite bridges are characterized by wide transverse cantilevers and web spacing. The self-weight and relevant passing-by vehicle 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 (Xu C. et al., 2012). But concerning the cyclic aspect which is of great importance to steel and concrete composite bridges, the related research is rare.

In this sense, a related study on cyclic behavior of group studs shear connector under biaxial load action was carried out. In this study, cyclic effects of uniaxial loading action, biaxial load action and residual bending-induced concrete cracks were investigated by cyclic push-out FEM analysis with multi-axial fatigue criterion.

NUMERICAL ANALYSIS SETUP

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 assumes: 1. the fatigue life is determined by the local stress-strain response at the notch position; 2. the relationships between elastic strain and endurance and between plastic strain and endurance are linear on log-log axes; 3. Miner's rule can be used to calculate the total fatigue damage from strain history, and a fatigue crack will initiate when Miner's summation equals 1.0.

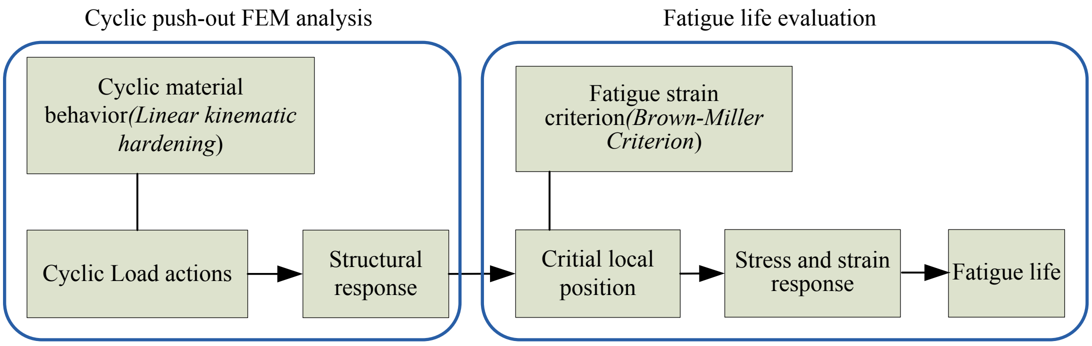


Figure1. Local stress-strain fatigue analysis procedure

The specific analysis procedure is shown in Figure 1, composed by two parts, cyclic push-out FEM analysis and fatigue strength evaluation. The FEM analysis was executed to derive stable cyclic structural response for the following fatigue strength evaluation in which the multi-axial fatigue criterion, Brown-Miller Criterion, has been introduced. In the FEM analysis, push-out FEM model was established with cyclic load actions. Based on the FEM analysis results, fatigue strength of critical local position determined by FEM analysis and fatigue criterion can be finally evaluated.

FEM Model Setup

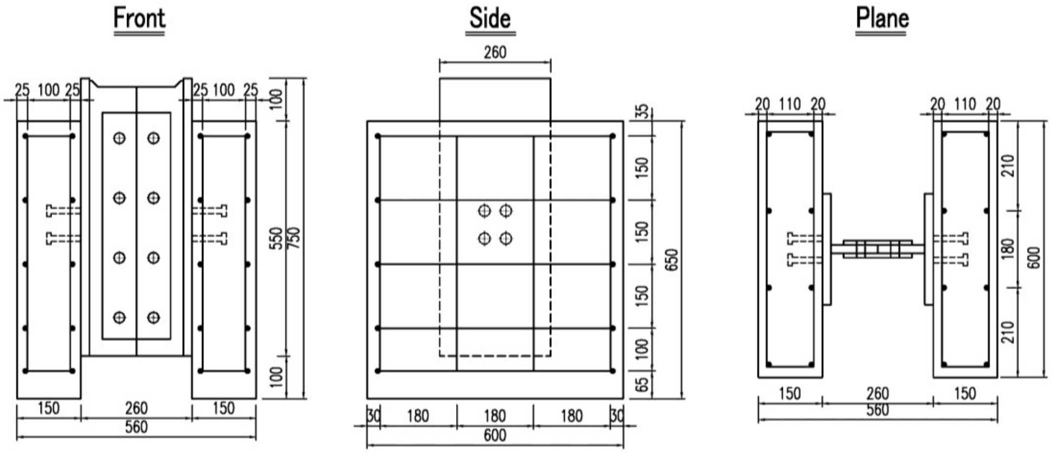


Figure 2. Dimension of push-out model

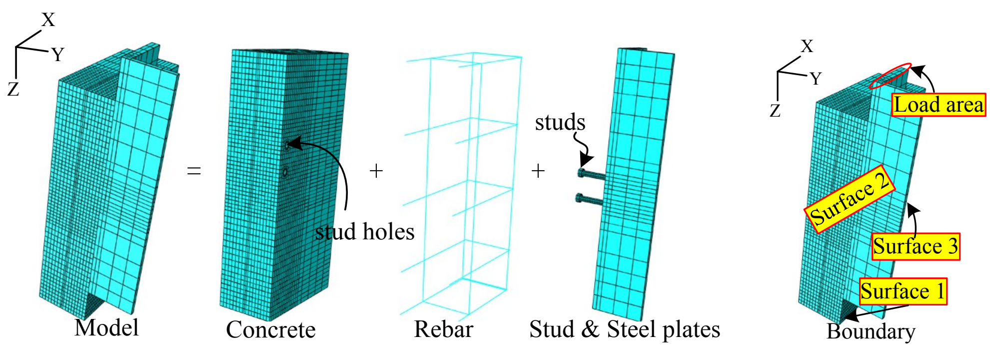


Figure 3. Parametric FEM push-out model

A total of 3 FEM push-out models were involved in the cyclic analysis, labeled with FA, FAB and FAC with different loading actions. They will be introduced in detail in section of load actions. The dimension of FEM push-out model with group studs is shown in Figure 2, mainly based on (Eurocode4, 2004). In the model, two equivalent steel concrete composite beams respectively with four embedded studs are assembled by gasket plates and high strength bolts. 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 one fourth of push-out specimen was simulated in three-dimensional FEM model in ABAQUS. As shown in Figure 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, as shown in Figure 3 also, the bottom concrete surface, designated as surface 1, is restrained from moving in all three directions. The symmetry boundary condition is applied to the surface 2 and surface 3. Surface 2 is taken as symmetric in X axis indicating all nodes located on this surface should be constrained from moving in X direction. Surface 3 is taken as symmetric in Y direction, which means all nodes belonging to this surface should be constrained in Y direction. The nodes of reinforcement element are tied to related nodes of concrete elements.

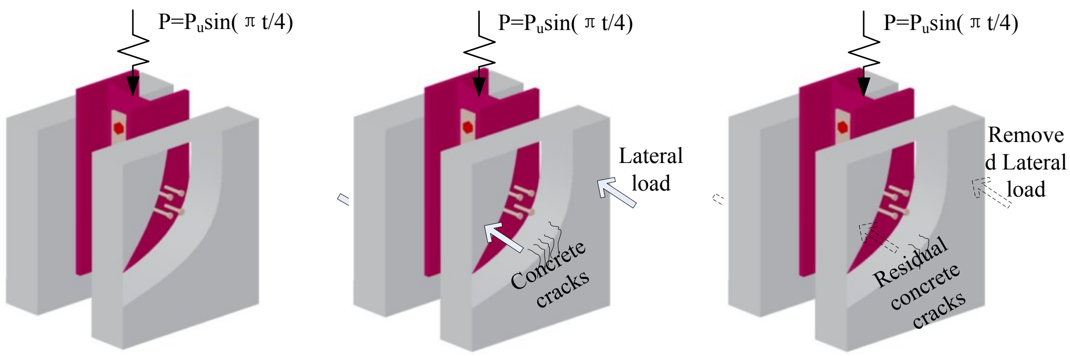
The interlayer surfaces between steel flanges and concrete slabs and between stud shafts and surrounding concrete were simulated by contact pair algorithm. Contact interaction properties of these two kinds of interlayer were assumed equivalent. The normal behavior consisted of a "hard" contact pressure-over closure relationship. As to tangential behavior, penalty frictional formulation was used. The interlayer friction coefficient was assumed 0.3. Moreover, contact surfaces of steel flange and stud shaft were initially selected as master surface while concrete contact surfaces were the slave surfaces.

Load Actions

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.



Ⅰ.Uniaxial action   Ⅱ.Biaxial action   Ⅲ. Residual bending-induced concrete cracks

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

Table 1 lists the models and related load actions which have been depicted in Figure 4 as well. The load procedures are specified in Table 2. The vertical cyclic push load was displacement controlled based on some results of experiment on full scale composite girder under wheel loading, which showed that the interlayer slip amplitude kept almost constant (Feldmann M. et al., 2006). In this analysis, analyzed cyclic performance was considered stable when variations of stress strain amplitudes become less than 10%. And 4 push load cycles was found to be enough for this. Figure 5 shows the detail cyclic push loading history. Lateral loads, 36kN, inducing estimated maximum concrete crack width of 0.15mm in terms of (JTG D62-2004, 2004), were applied on cyclic push-out models under biaxial load action (FAB) or with residual bending-induced concrete cracks (FAC). The specific displacement controlled cyclic push load amplitudes were from static stud stiffness proportion among the models FA, FAB and FAC. Due to effect of different loading actions, it is 1:1.15:0.95(C. Xu et al., 2012). Thus, compared with a 0.2mm cyclic displacement action on FA, a 0.17 mm cyclic displacement action and a 0.21mm cyclic displacement action were applied on FAB and FAC.

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	removed
3	continued	continued	continued	started	None

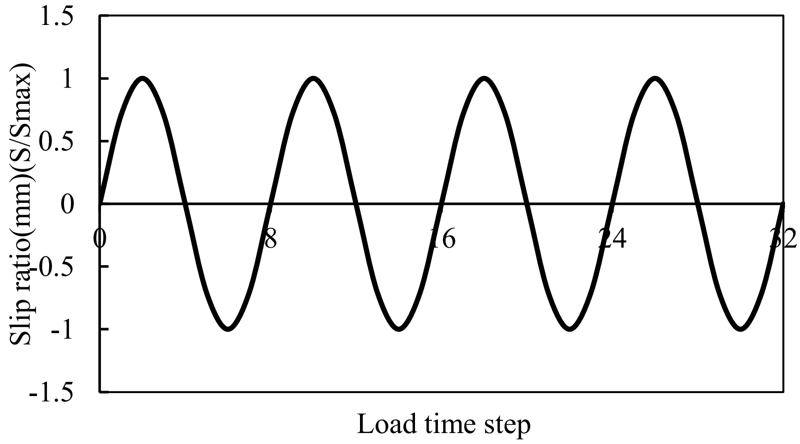
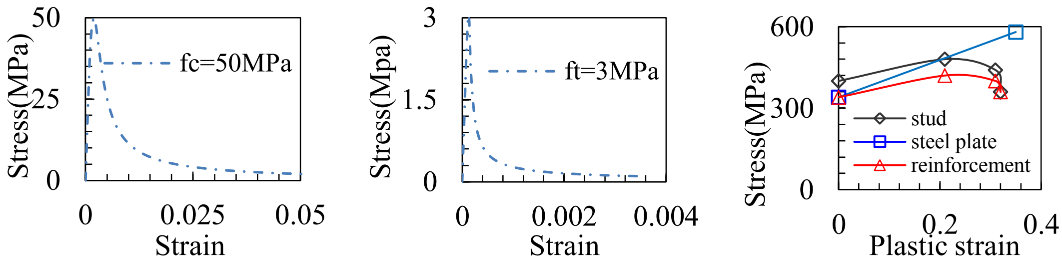


Figure 5. Cyclic push load applied on FEM models

Material Constitutions and Damage Plasticity Models



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

Figure 6. Uniaxial material constitutions

Nonlinear material constitutions and damage plasticity models were introduced in the analysis. The material stress-strain relationships are shown in Figure 6. Considering the cyclic effect, kinematic linear hardening has been introduced in the constitution of stud material. On the other hand, damage plasticity models of concrete and studs have been established as well for describing the material softening processes as material modulus degradation. Normally, it comprises two parts, the damage initiation and the damage evolution (Xu C. et al., 2012, Xu C. et al., 2012a). Concrete compressive and tensile damages were respectively assumed to initiate at the peak stress states. From the initiation, the damages evolve with inelastic strains as depicted in Figure 7. As to stud, the damage initiation is governed by stress triaxiality as shown in Figure 7 (Lemaitre J. et al., 1985). For damage evolution, an exponential correlation between damage variable D and plastic displacement has been established based on (ABAQUS Documentation 2008). The exponential law parameter was 0.01 and the equivalent plastic displacement was related to dimension size of discrete elements.

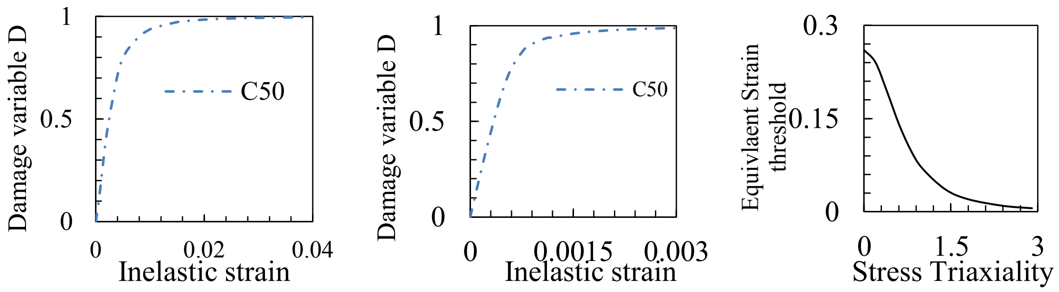


Figure 7. Uniaixal concrete damage models

Multi-axial Fatigue Criterion (Brown M. W., Miller K. J., 1973)

Structural components always bear a variety of external load actions thus leading to complex stress status. In a certain structural local position stress components keep changing and cause rotations of stress principal axes. Evaluation of local fatigue behavior under such conditions based on uniaxial fatigue analysis method is definitely unsafe, and so was born the multi-axial fatigue analysis.

The Brown-Miller criterion proposes that the maximum fatigue damage occurs on the plane which experiences the maximum shear strain amplitude as shown in Figure 8, and that the damage is a function of both this shear strain and the strain normal to this plane, as given in Eq. 1. It fits well with the fatigue damage happening to shear stud.

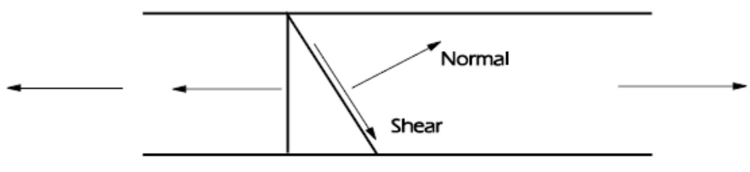


Figure 8. Maximum shear strain amplitude with strain normal to this plane

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

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. They were based on the assumption that fatigue cracks initiate on the plane with maximum shear strain. σ_{nm} is the mean normal stress on the shear plane.

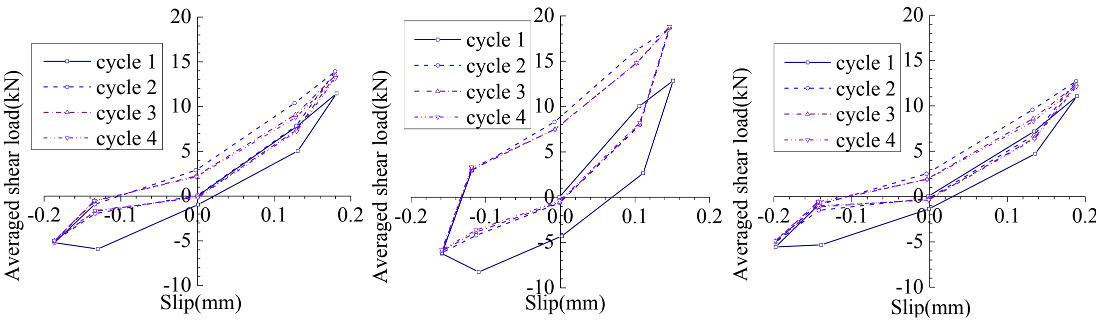
Concerning the coefficients, fatigue strength exponent b can be deduced approximately by Eq. 2 where σ_f is the true tensile strength and σ_b is the ultimate tensile strength. Regarding fatigue ductility coefficient ε_f', it is close to the value derived from the Eq. 3 where ψ is the percentage reduction of area. Moreover the value of c is suggested -0.6 for ductile material and -0.3 for high strength metal (Zhao S. B., 1994). 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 (Xu C., 2012b), ψ =70.9% can be derived. The ultimate tensile strength σ_b and fracture tensile strength have been respectively assumed 480MPa and 320MPa. And the true tensile strength σ_f can be deduced as 1103MPa. Based on these tested and assumed constants, the constants of b, c, σ_f', ε_f' can be derived, which are -0.11, -0.6, 1103MPa and 1.235. C1 and C2 were respectively equaled to 1.65 and 1.75.

$$b \approx -\frac{1}{6}\lg\left(\frac{2\sigma_f}{\sigma_b}\right) \tag{2}$$

$$\varepsilon_f' \approx \ln\left(\frac{1}{1-\psi}\right) \tag{3}$$

ANALYSIS RESULTS AND DISCUSSION

Cyclic Structure Performance



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

Figure 9. Cyclic load-slip curves

Figure 9 provides the cyclic analyzed load-slip curves. The positive averaged shear load direction is the push load direction. In Figure 9, the cyclic interlayer slip values stay in a relatively stable range due to the displacement controlled cyclic push load. 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. Moreover, the analyzed anisotropic feature is in consistence with some executed test results (Feldmann M. et al., 2006).

Critical Fatigue Position and Fatigue Strength

Generally, stud fatigue damage appears at the positions as shown in Figure 10, which are stud root (A) and stud welding collar (B) and 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 Figure 10.

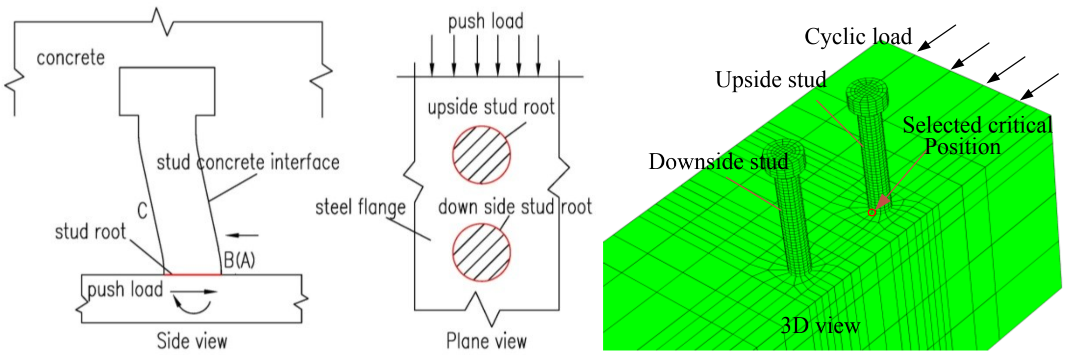
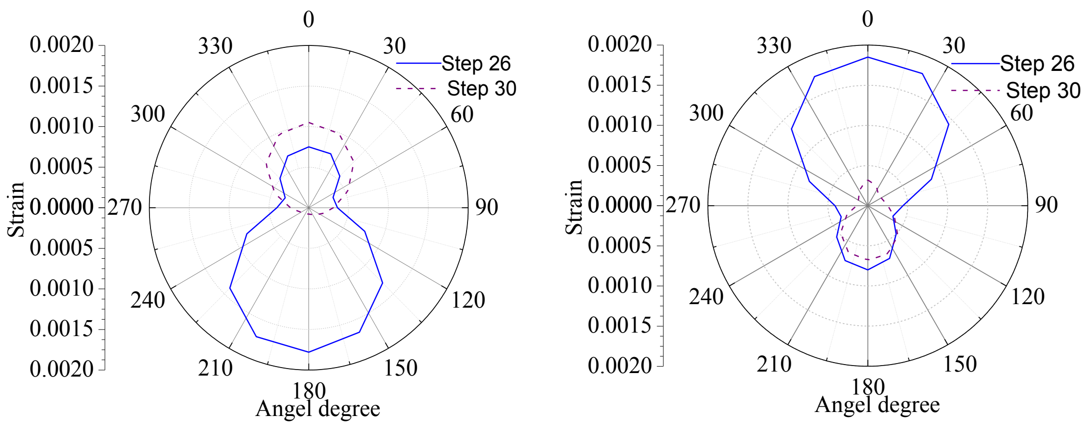


Figure 10. Positions under fatigue investigation



(a) Max. Principal strain-upside (b)Min. Principal strain-upside

Figure 11. Maximum principal strain distributions along stud root

Figure 11 shows the maximum and minimum principal strains distributed along upside stud root outline as depicted in Figure 10 at the 26th and 30th load steps, corresponding to the final cyclic load peak and valley. 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. For visualization, it was depicted in Figure 10 as well.

Table 3. Fatigue evaluations

Model	$\Delta\gamma_{max}/2$	$\Delta\varepsilon_n/2$	$\sigma_{n,mean}$	N_f
FA	0.00109	0.0004	10.065	1.2×10^8
FAB	0.00098	0.000315	18.75	2.4×10^8
FAC	0.00118	0.00041	11.58	5.4×10^7

In terms of Figure 10 and 11, the related cyclic strain characteristics are listed in Table 3. The symbol of "△" denotes the cyclic ranges. According to Eq. 1, the fatigue lives of FA, FAB and FAC under such cyclic load actions are respectively 1.2×10^8 cycles, 2.4×10^8 cycles and 5.4×10^7 cycles. This shows group studs under biaxial load action appeared better cyclic response while that under effect of residual bending-induced concrete cracks appeared reverse situation. It is noteworthy that this summation is based on the certain introduced displacement controlled cyclic push load action and biaxial induced actions. Systematic analysis and load controlled aspect will be studied in future.

CONCLUSTIONS

Influences of biaxial load action and residual bending-induced concrete cracks on fatigue performance of group studs were analyzed. The following conclusions can be drawn from the present study.

Local strain fatigue analysis method with multi-axial fatigue criterion was introduced. Through FEM analysis results, critical local position, cyclic maximum shear strain range, related normal strain range and mean value of normal stress were derived and the cyclic response and fatigue lives related to each kind of load actions were investigated and discussed.

Generally, it can be found that, in condition of the certain introduced cyclic push load action, group studs under biaxial load action appeared better cyclic response while that under effect of residual bending-induced concrete cracks appeared reverse situation. However, this summation was limited to the certain introduced displacement controlled (strain based) cyclic push load action and biaxial induced actions. More systematic study and the load controlled (stress based) cyclic performance will be studied in future.

REFERENCES

ABAQUS Documentation 2008, version 6.8.1. Dassault system, USA,.
Brown M. W., Miller K. J. (1973). "A theory of fatigue under multiaxial strain conditions."

Proceedings of the institution of mechanical engineers, June 187:745-755.

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

Feldmann M., Gesella H., Leffer A. (2006). "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.*

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

Lemaitre J. (1985). "A continuous damage mechanics model for ductile fracture." *Journal of engineering materials and technology,* Jan., v107/83.

Okada J., Yoda T., Lebet J.P. (2006). "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.

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

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

Xu C., Sugiura K. (2012a) "Parametric push-out analysis on group studs shear connector under effects of bending-induced concrete cracks and concrete strength." *Journal of constructional steel research*, under review.

XU C. (2102b). "Static and fatigue strength of group studs shear connector under biaxial loading action." *Doctoral dissertation,* Kyoto University, Kyoto, Japan.

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