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Slip Limit Prediction of High-Strength Bolt Joints Based on Local Approach

Chang He, Hiroshi Tamura, Hiroshi Katsuchi, Jiaqi Wang

***Abstract*—**In this study, the aim is to infer the slip limit (static friction limit) of contact interfaces in bolt friction joints by analyzing other bolt friction joints with the same contact surface but in a different shape. By using the Weibull distribution to deal with microelements on the contact surface statistically, the slip limit of a certain type of bolt joint was predicted from other types of bolt joint with the same contact surface. As a result, this research succeeded in predicting the slip limit of bolt joins with different numbers of contact surfaces and with different numbers of bolt rows.

***Keywords*—**Bolt joints, slip coefficient, finite element method, Weibull distribution.

I. Introduction

THE bolt friction joints are widely used in steel structures. The slip coefficient is often used to evaluate the loading capacity of bolt friction joints and it is only decided by the contact surface specification like 0.45 for inorganic zinc rich painted (usually abbreviated as IOZ) surface and 0.4 for blasted surface in design. However, experimentally obtained slip coefficients μ have dispersion even when made by the same contact surface specification. It could be considered that the micro surface condition is ununiform for many reasons, for example, the spatial dispersion in one surface [1], the number of contact surfaces [2], bolt columns [3] and so on. Experimental results showed that the slip coefficient of a double-lap bolt joints is slightly higher than that of a single-lap bolt joints both in IOZ and blasted surface [2], and slip coefficients also varied when numbers of bolt columns changed [3]. Based on these issues, not only the contact surface specification but also many other reasons should be considered in real situation so that we can get a rational slip limit considering relationships between local stress and dispersion of micro surface condition. To achieve that, computational simulation could be considered because it provides detailed local stresses in contact surfaces and may efficiently save experimental cost at the same time.

This research focuses on the slip coefficients of different kinds of bolted joints with the same contact surface specification. The aim of this research is to find a local-approach-based rational method to predict slip limit of many types of different high-strength bolt joints from experimentally obtained slip coefficients of one type of joint with the same contact surface specification.

This research firstly speculates the slip limit of single-lap bolt joints from double-lap bolt joints and secondly speculates the slip limit of multi-rows bolt joints from 2-rows bolt joints.

II. Experiment

A. Subject Description

Fig. 1 shows the geometry of experimental specimens, and Table I shows their specifications. P2-15 and B2-10 (PB) are 2-face friction joint, the former with inorganic zinc and the latter with blasted specimens. P1-15 and B1-10 (PB) are 1-face friction joint, the former with inorganic zinc and the latter with blasted specimens [2]. A structural steel SM490Y was used for the base plate and connecting plate of the specimens, and F10T high-strength bolts (nominal diameter M22, length beneath the head 90 mm) were used. For the anchorage side, a higher bolt axial force was introduced so that the main slip would precede on the slip side where the bolt axial force was controlled.

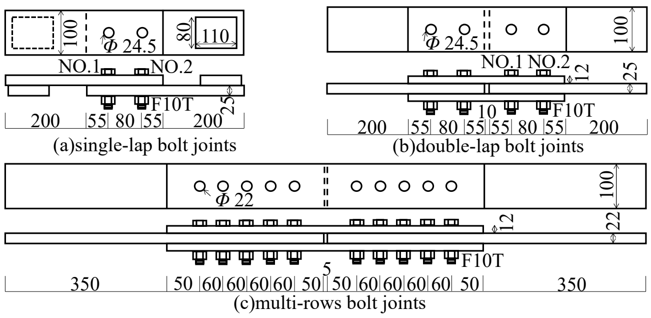


Fig. 1 Experimental specimens

TABLE I
Specifications of Experimental Specimens

Specimen name	Contact surface	Number of contact surfaces	Rows of bolts	Ratio of slip/yield strength	Number of specimens
P1-15	IOZ	1	2	0.31	3
P2-15	IOZ	2	2	0.61	3
B1-10	Blast	1	2	0.24	3
B2-10	Blast	2	2	0.49	3
MB-20-2-12	Blast	2	2	0.8	2
MB-20-3-12	Blast	2	3	1.2	2
MB-20-4-12	Blast	2	4	1.6	2
MB-20-5-12	Blast	2	5	2.0	2

MB20-2~5-12 (MB) are specimens of 1 column 2-rows to 5-rows friction joints with blasted contact surfaces. SS41 was used for the base plate and connecting plates of the specimens,

C. He is with Department of Civil Engineering, Yokohama National University, Yokohama, Japan (corresponding author, e-mail: he-chang-wd@ynu.jp).

H. Tamura, H. Katsuchi, and J. Wang are with Department of Civil Engineering, Yokohama National University, Yokohama, Japan (e-mail: tamura-hiroshi-jg@ynu.ac.jp, katsuchi@ynu.ac.jp, wang-jiaqi-nf@ynu.ac.jp).

and F10T high-strength bolts (nominal diameter M20, length beneath the head 85 mm) were used and tightened to standard bolt tension (nominal value 18.2 t) on the sliding side [3]. The ratio of slip/yield strength smaller than 1 means the sliding behavior of bolted joints will occur before the yielding of base board in design, otherwise the opposite.

B. Experimental Methods and Results

In the slip capacity experiment of specimens PB, the bolt axial force was measured by strain gauges attached to the bolt shaft on the slip side immediately before loading, the average strain on the front and back of the base plate was measured by strain gauges attached to the front and back of the base plate during the test, the amount of slip was measured by a clip gauge attached to the first bolt position on the slip side, and the load was measured by the load cell of the testing machine. A tensile load was applied at a loading rate of approximately 2 kN/s until the main slip occurred.

In the slip capacity experiment of specimens MB, a 100-ton universal testing machine was used to apply a monotonic tensile force to the specimens. The average elongation of the joints of the specimens and the axial force of each bolt were measured with a strain gage during the force application. Strain gauges were also attached to the shaft of the base plate, the base plate of the first bolt, and the connecting plate of the n-th bolt to measure the axial strain.

TABLE II
THE RESULTS OF THE SLIP CAPACITY TEST

Specimen name		NO.1 bolt load [kN]	NO.2 bolt load [kN]	Average bolt load [kN]	Slip resistance [kN]	μ	Average μ
P1-15	-1	223	233	228	256	0.561	0.543
	-2	230	215	222.5	236	0.530	
	-3	217	231	224	241	0.538	
P2-15	-1	219	213	216	460	0.532	0.516
	-2	212	208	210	430	0.512	
	-3	221	226	223.5	450	0.503	
B1-10	-1	221	220	220.5	314	0.712	0.658
	-2	230	223	226.5	271	0.598	
	-3	229	225	227	302	0.665	
B2-10	-1	229	220	224.5	574	0.639	0.602
	-2	226	220	223	521	0.584	
	-3	227	215	221	516	0.584	
MB-20-2-12	-1			181.6	521	0.718	0.670
	-2			181.2	451	0.622	
MB-20-3-12	-1			184.1	570	0.516	0.518
	-2			185.0	576	0.519	
MB-20-4-12	-1			183.8	635	0.432	0.431
	-2			179.8	620	0.431	
MB-20-5-12	-1			181.3	658	0.366	0.368
	-2			182.2	674	0.370	

The results of the slip capacity test are shown in Table II. In PB experiment, the bolt axial force immediately prior to the test decreased significantly with the passage of time of more than one month after bolting. The coefficient of slip tended to be higher for the blasted specimens, and both the IOZ and blasted specimens showed a slightly higher coefficient of slip for the specimens with single-lap bolt joints. The bending strain (the difference in strain between the front and back of the base plate divided by two) at the onset of main slip (when the slip capacity is reached) was about 1000 μ for the specimens with single-lap bolt joints. In the MB experiment, the axial force variation during the experiment was measured with strain gauges at the bolt heads.

III. ANALYSIS CONDITIONS

A model that reproduces the behavior of each test piece up to the occurrence of main slip was created and using high static friction coefficient to fix slip displacement of the joint contact surface (using commercial software Abaqus 2020).

Fig. 2 shows an analytical model that reproduces the 1/2 region of the PB specimen and the 1/8 region of the MB specimen, in consideration of symmetry. Reduced integral first-order solid elements were used throughout the analysis. The contact surfaces were reproduced as flat surfaces with no surface roughness or coating. For the PB specimen model, the elements were divided to the thickness of 5 mm for base and connecting plate, and the circumference of the bolt holes was divided into small sections with a length of 3.5 mm. For MB specimen it was 4 mm for thickness and 2.5 mm for area near to bolt holes. Fig. 3 shows the element partitioning around the bolt holes in multi-rows bolt joints as an example test model. In the contact analysis, the base plate, connecting plate, and fasteners (bolts, nuts, and washers integrated together) were mobilized as independent elastic bodies with uniform material properties (Young's modulus 200 GPa, Poisson's ratio 0.3), and contact conditions were applied to the interface between the base plate and connecting plate (contact surface of the joint) and between the connecting plate and the washer portion.

The static friction coefficients for the PB and MB joints surfaces were set to 20 and 30, respectively. This is determined by the specific situation of each specimen, in order to make the coefficient of friction of each element less than the set value at the moment of sliding, which means no relative sliding will occur. Using a higher coefficient of static friction, a similar solution will be obtained, but it will be more difficult to obtain the convergence solution.

The contact determination is based on the penalty and extended Lagrange methods. Local slip is determined by the maximum frictional shear stress, which is determined by the contact pressure and the static friction coefficient.

The displacement was fixed at the end of the fixed base plate and the initial axial force during the test based on Table II was imposed at the bolt axial part by Abaqus bolt load. The loading was then reproduced by applying a joint axial tension-forcing displacement to the end of the base plate on the slip side. Since this is a boundary nonlinear problem with contact conditions, it was solved statically as a sequential analysis with the maximum forced displacement increment set to 1/100 of the maximum forced displacement.

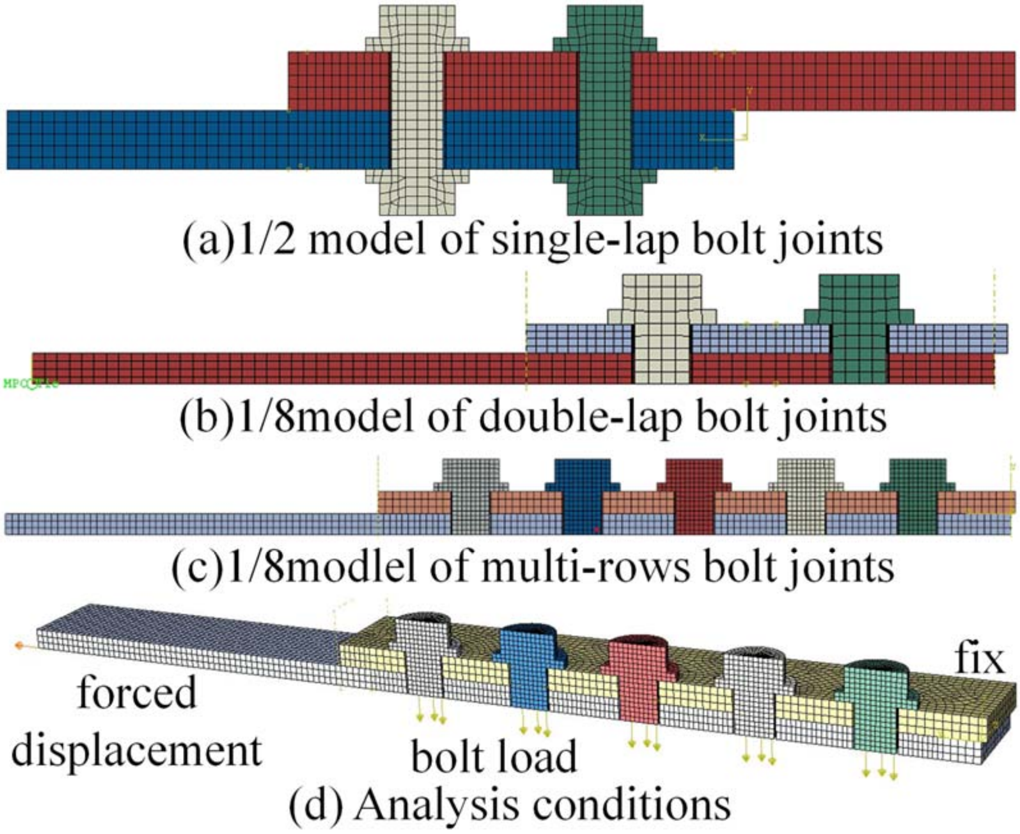


Fig. 2 Analysis models

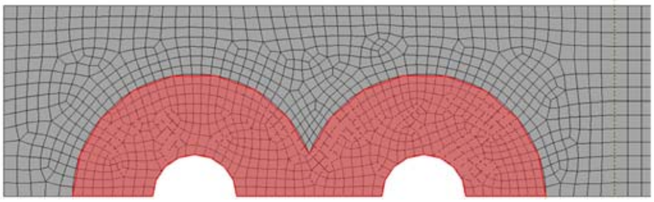


Fig. 3 Mesh near the bolt holes

IV. Method

A. Hypothesis

Main slip in high-strength bolt joints is a slip that propagates instantaneously across a single or multiple contact surfaces and generates large relative displacements between steel plates, often resulting in a sudden decrease in the axial stiffness of the joint. In joints that exhibit a well-defined slip resistance point, the initiation of principal slip causes the axial stiffness of the joint to instantaneously turn negative and the relative displacement between the steel plates to increase rapidly.

Although the mechanism of occurrence of such principal slip is not always clear, this study assumes that it is an unstable phenomenon in which loss of shear stiffness and localized slip occur in a chain model starting from a microscopic region where a certain limit state is first reached on the joint surface (starting point) and propagate to the surrounding area. The main slip is assumed to originate from the region of high frictional shear stress.

This study focuses on whether a limit state for local slip is established at the assumed onset point. Coulomb's law is assumed as the local limit state. Coulomb's law states that (1) holds for the maximum value of frictional shear stress $\tau_{\mathrm{interface}}$ transmitted by a small surface area.

$$\max(\tau_{\mathrm{interface}}) = \mu p_{\mathrm{interface}} \quad (1)$$

where μ and $p_{\mathrm{interface}}$ are respectively the static friction coefficient and the contact pressure of the small surface area. From (1), we can assume $\tau_{\mathrm{interface}}/p_{\mathrm{interface}}$ as the driving parameter for the generation of localized slip. Present study applies local approach to consider this local trigger introducing two parameters, stress ratio and Weibull stress ratio, as described later.

B. Stress Ratio

This study investigates the possibility of estimating the occurrence of local slip based on the stress values evaluated at the integration points of finite elements in order to investigate a method to evaluate the limit of principal slip occurrence from a simple finite element analysis. The $\tau_{\mathrm{interface}}/p_{\mathrm{interface}}$ (the stress ratio) is defined for a small surface area, which is the ratio of the shear stressτ_{IP} to the direct stress σ_{IP} evaluated at the integration point of the finite element forming the surface layer.

$$\rho = \tau_{\mathrm{IP}}/\sigma_{\mathrm{IP}} \quad (2)$$

Equation (2) focuses on the maximum stress ratio at the onset of slip resistance around the bolt holes of the contact surface, and examine whether the maximum stress ratio can be used to evaluate the main slip onset limit state.

If the contact surfaces are finished in the same way, the stress ratios at the slip limit should match. In other words, in the case of PB specimen, the stress ratio of the slip limit of the single-lap bolt joints should match the stress ratio of the slip limit of the double-lap bolt joints. In MB specimen, the stress ratio of the slip limit of the 345-rows joints should match the stress ratio of the slip limit of the 2-row joints.

C. Weibull Stress Ratio

The prediction accuracy of the limit of occurrence of principal slip may be improved by considering local variations in surface properties at the joint surface of a high-strength bolt joints. In this study, the Weibull stress concept, which has been used to evaluate the failure limit of brittle materials [4], is applied to the evaluation of the occurrence limit of principal slip at the joint surface. The Weibull stress is derived from the weakest link hypothesis, which posits that brittle fracture occurs in a material when the elemental volume that contains defects fails under an equivalent stress drawn from a material-specific probability distribution. Furthermore, the relationship between the applied stress and the probability of material failure adheres to a Weibull distribution [5]. In this study, the Weibull stress ratio is defined as the equivalent stress to the stress ratio for the element in the surface layer as shown in (3) to apply to the principal slip.

$$\sigma_w = \left(\sum_{i=1}^{n} \rho_i{}^m S_i\right)^{1/m} \quad (3)$$

Here, n is the number of surface finite elements in the region Ω where high shear stress is generated. The threshold Ω of shear stress is discussed in the next section. ρ_i and S_i are the stress ratio of finite elements the area of the surface. Weibull parameter m gets bigger when the dispersion in each specimens gets smaller. The Weibull stress ratio is higher when the maximum value of the stress ratio is higher and when Ω is wider. Fig. 4 illustrates the Weibull stress ratio concept. The Weibull stress ratio concept models the contact surface as a series of basic surface areas, including defects, and considers that an increase in the stress ratio induces the main slip across the entire contact surface by causing one of the basic surface areas to slip.

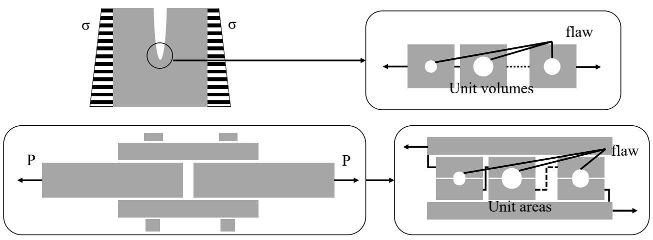


Fig. 4 Concept of Weibull stress ratio

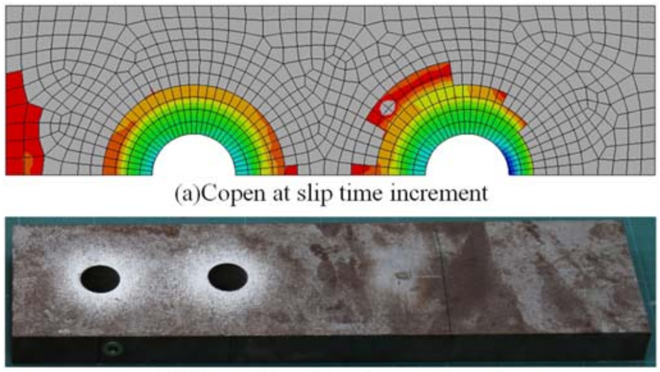
Same as the stress ratio which is mentioned in Section IV *B*, in MB specimens, the Weibull stress ratio of the slip limit of the 3,4,5-rows joints should also match the Weibull stress ratio of the slip limit of the 2-rows joints.

V. Result

A. Calculation Region

The region Ω is mainly determined by the portion of the contact surface in the resolution that is actually in contact. Some of the unstable outermost elements are removed according to the actual situation. The region Ω was calculated for multiple loads and was selected to satisfy the above conditions at any load level, although it was calculated densely around loads equivalent to the slip capacity.

Fig. 5 shows the threshold values for the direct stress σ_{IP} and the distribution of direct stresses on the joint surface at the friction force. As an example of the blasted specimen, the area Ω determined by the threshold values in the figure generally corresponds to the area of damage on the contact surface after the test, which means Copen of the element is smaller than 0.



(a)Copen at slip time increment

(b)Base plate after slip experiment

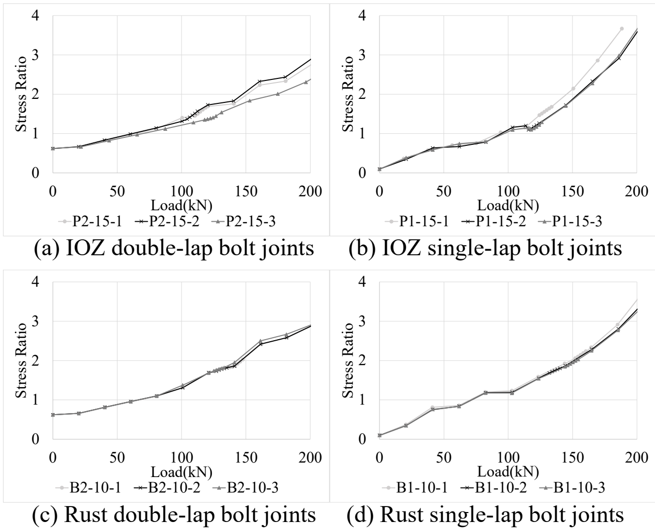
Fig. 5 Result for B2-10-1

B. Varying Numbers of Contracting Surface Prediction by Stress Ration

Fig. 6 shows the relationship between the maximum value of stress ratio ρ and load in the region Ω obtained from the analysis results. Single/double-lap bolt joints specimens are shown separately for each contact surface specification. The maximum stress ratio increases monotonically with load in all specimens, and the location of the point of maximum stress ratio at the load value equivalent to slip capacity is close to each other among the three specimens of the same type, indicating that the slip capacity and the slip coefficient of the specimens can be estimated from the maximum stress ratio. For the specimens with double-lap bolt joints, it is shown that the prediction of the main slip limit can be obtained.

C. Varying Numbers of Contact Surface Prediction by Weibull Stress Ratio

Fig. 7 shows the relationship between the Weibull stress ratio ρ_w and load in the region Ω obtained from the analysis results. Same with the maximum stress ratio, the Weibull stress ratio ρ_w monotonically increases with load. This indicates that the slip capacity as well as the slip coefficient could be estimate by the Weibull stress ratio ρ_w. For the specimens with double-lap bolt joints, it is shown that the prediction of the main slip limit can be obtained.



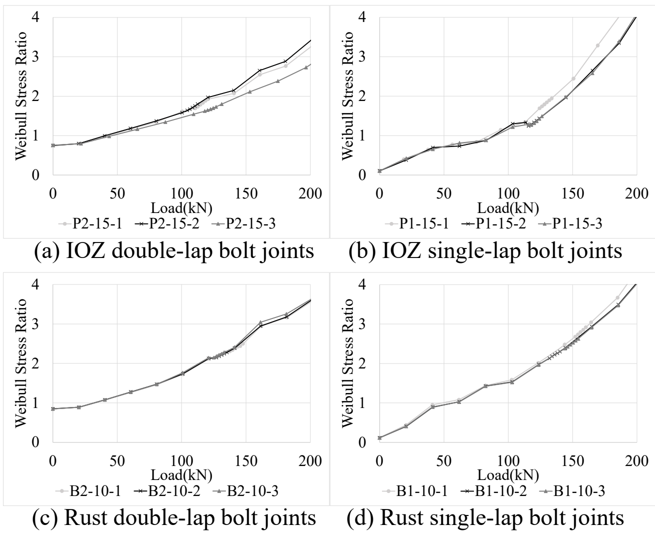
(a) IOZ double-lap bolt joints (b) IOZ single-lap bolt joints

(c) Rust double-lap bolt joints (d) Rust single-lap bolt joints

Fig. 6 Stress ratio results for different numbers of surfaces

TABLE III
PREDICTION RESULT IN DIFFERENT NUMBERS OF CONTACT SURFACE BY USING STRESS RATIONS

Specimen name	Limit value of stress ratio	Estimated slip Reaction force [kN]	Estimated slip coefficient	Estimation error	Average error
P1-15-1		124	0.454	-2.87%	
P1-15-2	1.468	132	0.595	12.17%	6.28%
P1-15-3		132	0.591	9.84%	
B1-10-1		133	0.606	-14.90%	
B1-10-2	1.829	142	0.628	5.00%	-4.82%
B1-10-3		144	0.635	-4.56%	



(a) IOZ double-lap bolt joints (b) IOZ single-lap bolt joints

(c) Rust double-lap bolt joints (d) Rust single-lap bolt joints

Fig. 7 Weibull stress ratio results for different numbers of surfaces

Based on the average of the Weibull stress ratios at the slip capacity points for the specimens with double-lap bolt joints, the critical maximum stress ratios for a principal slip for the IOZ and blasted specimens were, respectively, 1.721 and 2.285 for the analysis.

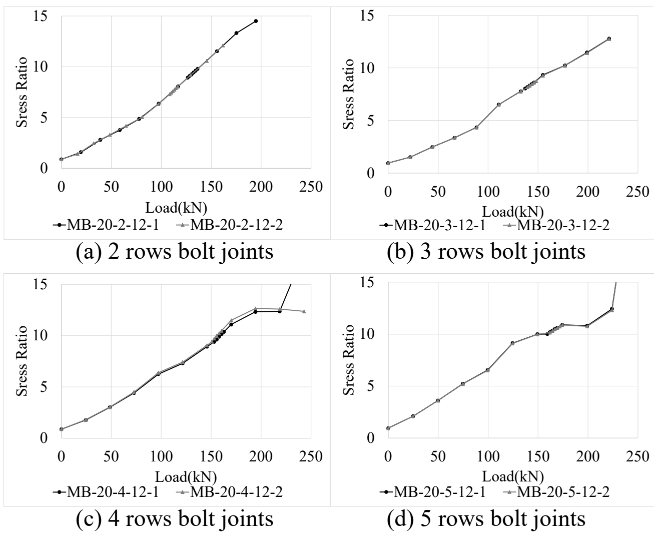
Table IV presents the slip capacity and slip coefficient obtained from the Weibull stress ratios at the occurrence of slip capacity for the double-lap bolted joints and the identified critical Weibull stress ratio for the single-lap bolted joints, as outlined in Section IV *C*.

TABLE IV
PREDICTION RESULT IN DIFFERENT NUMBERS OF CONTACT SURFACE BY USING WEIBULL STRESS RATIONS

Specimen name	Limit value of Weibull stress ratio	Estimated slip Reaction force [kN]	Estimated slip coefficient	Estimation error	Average error
P1-15-1		125	0.549	-2.14%	
P1-15-2	1.721	133	0.600	13.05%	6.92%
P1-15-3		132	0.591	9.84%	
B1-10-1		133	0.606	-14.90%	
B1-10-2	2.285	140	0.619	3.48%	-6.24%
B1-10-3		140	0.617	-7.29%	

D. Varying Numbers of Bolt Joints Prediction by Stress Ratio

Fig. 8 shows the relationship between the maximum value of stress ratio ρ and load in the region Ω obtained from the analysis results. Single/double-lap bolt joint specimens are shown separately for each contact surface specification. The maximum stress ratio increases monotonically with load in all specimens, and the location of the point of maximum stress ratio at the load value equivalent to slip capacity is close to each other among the three specimens of the same type, indicating that the slip capacity and the slip coefficient of the specimens can be estimated from the maximum stress ratio. For the specimens with double-lap bolt joints, it is shown that the prediction of the main slip limit can be obtained.



(a) 2 rows bolt joints (b) 3 rows bolt joints

(c) 4 rows bolt joints (d) 5 rows bolt joints

Fig. 8 Stress ratio results for different numbers of bolts

Based on the average of the maximum stress ratios at the slip capacity points for the specimens with double-lap bolt joints, the critical maximum stress ratios for principal slip for 2-row bolt joints specimens is 8.505 for the analysis.

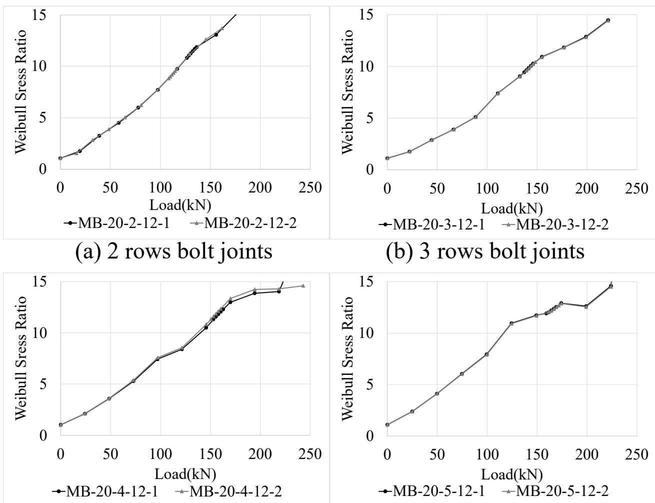
According to Section IV *B*, the slip capacity and slip coefficient estimated from the maximum stress ratios at the moment of slip capacity happen for the 2-rows bolted joints and the identified critical maximum stress ratio of the 3-rows, 4-rows, 5-rows bolted joints are shown in Table V.

TABLE V
PREDICTION RESULT IN DIFFERENT NUMBERS OF BOLT ROWS BY USING STRESS RATIONS

Specimen name	Limit value of stress ratio	Estimated slip Reaction force [kN]	Estimated slip coefficient	Estimation error	Average error
MB-20-3-12-1	8.340	576	0.521	0.99%	0.47%
MB-20-3-12-2		576	0.519	-0.04%	
MB-20-4-12-1	9.941	564	0.384	-11.12%	-10.10%
MB-20-4-12-2		564	0.392	-9.08%	
MB-20-5-12-1	10.477	468	0.258	-28.83%	-29.68%
MB-20-5-12-2		468	0.257	-30.54%	

E. Varying Numbers of Bolt Joints Prediction by Weibull Stress Ratio

As Section V *C* mentioned, the slip capacity as well as the slip coefficient could be estimated by the Weibull stress ratio ρ_w. For the specimens with multi-rows bolted joints, it is shown that the prediction of the main slip limit can be obtained.



(a) 2 rows bolt joints (b) 3 rows bolt joints

(c) 4 rows bolt joints (d) 5 rows bolt joints

Fig. 9 Weibull stress ratio results for different numbers of bolts

TABLE VI
PREDICTION RESULT IN DIFFERENT NUMBERS OF BOLT ROWS BY USING WEIBULL STRESS RATIONS

Specimen name	Limit value of Weibull stress ratio	Estimated slip Reaction force [kN]	Estimated slip coefficient	Estimation error	Average error
MB-20-3-12-1	9.941	584	0.529	2.39%	2.18%
MB-20-3-12-2		587.6	0.529	1.97%	
MB-20-4-12-1	11.844	573.2	0.390	-9.67%	-9.38%
MB-20-4-12-2		564	0.392	-9.08%	
MB-20-5-12-1	12.351	478	0.264	-27.31%	-28.18%
MB-20-5-12-2		478	0.262	-29.05%	

Based on the average of the Weibull stress ratios at the slip capacity points for the specimens with 2-row bolts joints, the critical maximum stress ratio for principal slip is 10.315 for the analysis.

Table VI presents the slip capacity and slip coefficient obtained from the Weibull stress ratios at the occurrence of slip capacity for the 2-rows bolted joints and the identified critical Weibull stress ratio for the 3-rows, 4-rows, 5-rows bolted joints, as outlined in Section IV *C*.

VI. CONCLUSION

In this research, replacing the slip coefficient, two parameters, the stress ratio and the Weibull stress ratio, are introduced to infer slip limit of bolt joints. For each method, two prediction scenarios were considered: different numbers of contact surfaces and different numbers of bolt columns. Positive results for prediction accuracy were observed. The findings could be summarized as follows:

1) For varying numbers of contact surfaces prediction, the slip limit of single-lap bolt joints with IOZ and blasted surface was inferred from those of double-lap bolt joints. Both stress ratio and Weibull stress ratio showed a high prediction accuracy.
2) For varying numbers of joint rows prediction, the slip limit of 3-row, 4-row and 5-row bolt joints with blasted material were inferred from those of 2-row bolt joints. Both stress ratio and Weibull stress ratio showed higher prediction accuracy than slip coefficients in the prediction of 3 columns joints. On the other hand, the accuracy of both ratios were low in 4 and 5 columns joints prediction. It could be considered that the slip/yield ratio is much larger than 1 which means yield happens. Future research is needed to find out explanations to the different results and raise the accuracy by using plastic materials in simulation.

The feasibility of the two new methods were confirmed. They could currently be applied to predict slip limits of bolt joints in different numbers of contact surfaces and joint rows. In the future, their feasibility for other situations will be researched, such as bolt joints with large eccentric or over double-laps.

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