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Static and Fatigue Strength of Studs

Résistance statique et à la fatigue de goujons

Tragwiderstand und Ermüdungsfestigkeit von Dübeln

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SUMMARY

Through a multi-variable linear regression analysis on the static push-out test data of numerous results, a refined equation for the prediction of the static strength was derived. For the fatigue data, the same multi-variable regression analysis was also carried to find parameters influencing the strength. As a result, a new expression to obtain the fatigue strength of studs was derived.

RÉSUMÉ

Une équation raffinée destinée à prévoir la résistance statique a été déduite d'une analyse par régression linéaire à plusieurs variables à partir des données de nombreux résultats de l'essai statique. Au sujet des données de la fatigue, la même analyse par régression linéaire à plusieurs variables a été retenue en vue de trouver les paramètres ayant une influence sur la résistance. Une nouvelle expression présumant de la résistance à la fatigue des goujons a été déduite de ce résultat.

ZUSAMMENFASSUNG

Mit Hilfe einer multilinearen Regressionsanalyse von zahlreichen Ausstossversuchen wurde eine verfeinerte Gleichung zur Bestimmung des Tragwiderstandes ermittelt. Dasselbe wurde für die Ermündungsfestigkeit gemacht, woraus eine neue Beziehung für diese Bemessung resultierte.

1. INTRODUCTION

In composite structures, the stud shear connectors are the key elements to secure appropriate composite action between steel and concrete. In Japan, changing the current allowable stress design method into a limit state design method is one of the urgent problems to be solved. Therefore, the authors have investigated the existing design strengths and the experimental characteristic values of studs, especially the static ultimate strengths and the fatigue strengths of studs. As the results, it was very difficult to find out reasonable design strengths or formulae about studs. Therefore, the authors have gathered many experimental results/1-6/ and have carried out multi-variable linear regression analysis on those data to find out reasonable equations about the static and fatigue strengths of studs.

2. ORDINARY EXPRESSIONS FOR THE STRENGTHS OF STUDS

Table 1 is the list of the main ordinary expressions about static ultimate strengths of studs. As clear, those equations are mutually different, especially in the number and function of influence factors to the strengths.
On the other hand, fatigue strengths of studs are generally expressed by S-N relations, where S is the shearing stress range and N is the number of cycles. Figure 1 is a S-N diagram plotting all gather data by the same method. The triangular plots are the data by Fisher and the dots are the data by other researchers including the authors'. The deference between those two groups seems to be due to the difference of specimen. That is, only Fisher has used the specimens having single slab on the one side of H-shape steel and the other researchers are

Investigation	Expression method	Relation
Slutter and Driscoll(1965)	Equation	$Q_u = A \cdot d_s^2 \sqrt{f_{cu}}$; $(h_s/d_s \geqq 4.2)$
	〃	$Q_u = B \cdot d_s \cdot h_s \sqrt{f_{cu}}$; $(h_s/d_s \leqq 4.2)$
Menzies (1971)	Diagram	$Q_u - f_{cu}$ Relation
Ollgaard, Slutter and Fisher(1971)	Equation	$Q_u/A_s = C \cdot \sqrt{f_{cu} \cdot E_c}$
Hawkins (1973)	Equation	$Q_u = D \cdot A_s \cdot \frac{\sqrt{f_{cu}} \cdot f_{su}}{\sqrt{d_s}}$
Roik (1982)	Diagram	$Q_u/d_s^2 - f_{cu}$ Relation
	Equation	$Q_u \leqq E \cdot d_s^2 \cdot f_{su}$

Where, Q_u:Ultimate strength of a stud, d_s:Diameter of stud, h_s:Height of stud, f_{su}:Tensile strength of stud, f_{cu}:Concrete cylinder strength, A_s:Cross-sectional area of shank of stud, E_c:Modulus of elasticity of concrete, A, B, C, D, E:Constant.

Table 1 Ordinary expressions for ultimate strengths of studs

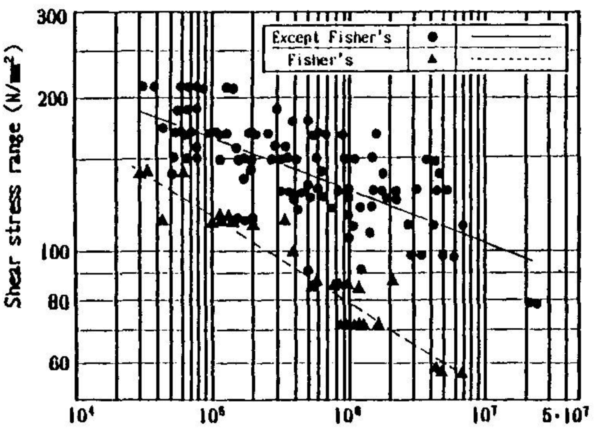

Fig.1 S-N relations

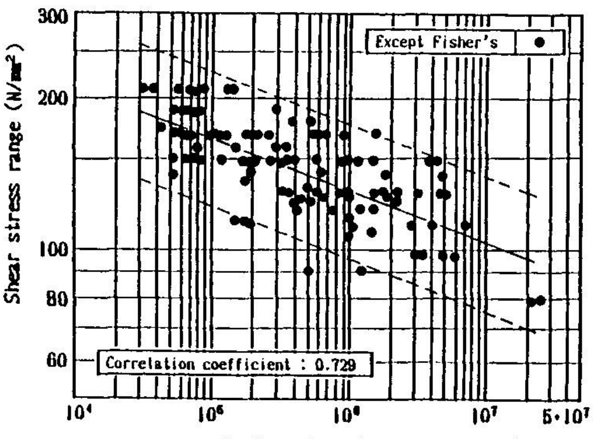

Fig.2 S-N relations

adopting the specimens having double slabs on the both sides of H-shape steel. As the results, Fisher's data are plotted around the lower bound of the other data. The deviation seems to be generation of tensile axial force in the stud due to such eccentric specimen. Figure 2 is a S-N diagram plotting the data except Fisher's. From the plots, scattering of data seems to be very large. Essentially, the fatigue strengths of studs can be presumed to have many influence factors such as diameter, height and tensile stress of the stud and properties of concrete. Therefore, the above mentioned simple expression by shear stress only seems to be a cause of the scattering of the fatigue data.

3. STATISTICAL ANALYSIS

To derive rational expressions for the static and fatigue strengths of studs, multi-variable linear regression analysis were carried out using the almost data in the world. The numbers of data are shown in Table 2, which were only the data from the specimens having two slabs on the both flanges of H-shape steel and having slabs made of normal-density concrete. The basic statistics of all the test data are shown in the Table 2.

3.1 Static Ultimate Strength

As can be supposed from Table 1, the ultimate strength of studs seems to be expressed as Eq.(1) having various parameters of specimens,

$$Q_u = \alpha \cdot d_s^{a} \cdot h_s^{b} \cdot f_{su}^{c} \cdot f_{cu}^{d} \qquad (1)$$

where, d_s:diameter of the shank of a stud, h_s:height of a stud, f_{su}:Tensile strength of a stud, f_{cu}:Ultimate compressive stress of concrete.

By the regression analysis, the coefficients for every variables were obtained as shown in Table 3. Where, T-values are used for judging the significance of the variables. When the T-value being less than 2.0, the variable has not so much influence to Q_u. In the case of T-value being greater than 4.0, the variable can not neglect and becomes a particular influencing factor. From the T-values in Table 3, the variables of d_s, h_s and f_{cu} seem to be the important influence factors for the static strength of studs. The factor of f_{su} can be recognized to be not

Test	No. of data	Data	Mean	C.O.V. (%)	Min.	Max.
Static	179	d_s (mm)	18.777	13.58	13	32
		h_s (mm)	89.944	20.51	51	214
		f_{su} (N/mm²)	490.84	11.97	348.88	620.046
		f_{cu} (N/mm²)	31.255	26.08	13.622	61.936
Fatigue	145	d_s (mm)	18.628	9.66	13	22
		h_s (mm)	90.235	16.67	60	102
		f_{su} (N/mm²)	454.06	9.96	406.70	620.046
		f_{cu} (N/mm²)	32.842	17.88	21.266	47.530

Where, d_s:Diameter of stud, h_s:Height of stud, f_{su}:Tensile strength of stud material, f_{cu}:Concrete cylinder strength, C.O.V.:Coefficient of Variation.

Table 2 Basic statistics of all push-out test data

Test		α	a	b	c	d	e	Multiple Correlation
Static	Coefficient	179.56	1.273	0.469	-0.190	0.525	—	0.9037
	T-values	8.8215	16.607	8.3162	2.1416	13.122	—	
Fatigue	Coefficient	159.44	1.342	0.447	-0.036	0.320	-0.104	0.9224
	T-values	6.0028	11.139	5.8046	0.2695	4.2068	13.457	

Regression analysis model: $Q_u = \alpha \cdot d_s^{a} \cdot h_s^{b} \cdot f_{su}^{c} \cdot f_{cu}^{d}$ (Static test),
$R = \alpha \cdot d_s^{a} \cdot h_s^{b} \cdot f_{su}^{c} \cdot f_{cu}^{d} \cdot N^{e}$ (Fatigue test);
Where, Q_u:Ultimate strength of a stud, R:Shear force range acting on a stud, d_s:Diameter of stud, h_s:Height of stud, f_{su}:Tensile strength of stud material, f_{cu}:Concrete cylinder strength, N:Number of cycles to failure.

Table 3 Results of logarithmic multi-variable linear regression analysis influence factor. Therefore, the strength of studs can be judged to be expressed as Eq.(2) by rounding up the each coefficient under an engineering judgment.

$$Q_u=\alpha'\cdot d_s^{1.5}\cdot h_s^{0.5}\cdot f_{cu}^{0.5} \tag{2}$$

The difference of coefficients between Eq.(2) and the results shown in Table 3 can absorb into the constant coefficient as shown by Eq.(3) using average values for each variables.

$$\alpha'=\alpha\cdot d_{sm}^{-0.227}\cdot h_{sm}^{-0.031}\cdot f_{sum}^{-0.190}\cdot f_{cum}^{0.025} \tag{3}$$

Then, Eq.(2) can be decided as Eq.(4).

$$\begin{aligned} Q_u' &= 27\cdot d_s^2\cdot\sqrt{(h_s/d_s)\cdot f_{cu}} \\ &= 34.4\cdot(\pi\cdot d_s^2/4)\cdot\sqrt{(h_s/d_s)\cdot f_{cu}} \\ &= 35\cdot A_s\cdot\sqrt{(h_s/d_s)\cdot f_{cu}} \end{aligned} \tag{4}$$

where, A_s:cross sectional area of the shank of the stud (cm^2).

Finally, in order to confirm the efficiency of Eq.(4), a linear regression analysis is carried out again using all the data. As the result, Eq.(5) was derived as the another expression for the static strength of studs. Fig.3 is a diagram to verify the fitness of the equations with the experimental data. The correlation factor of scattering raises up to 0.894 which is larger than the ones by the ordinary expressions.
Finally, Eq.(5) can be said as an appropriate equation to predict the static strengths of studs.

$$Q_u=30\cdot A_s\cdot\sqrt{(h_s/d_s)\cdot f_{cu}}+10000 \tag{5}$$

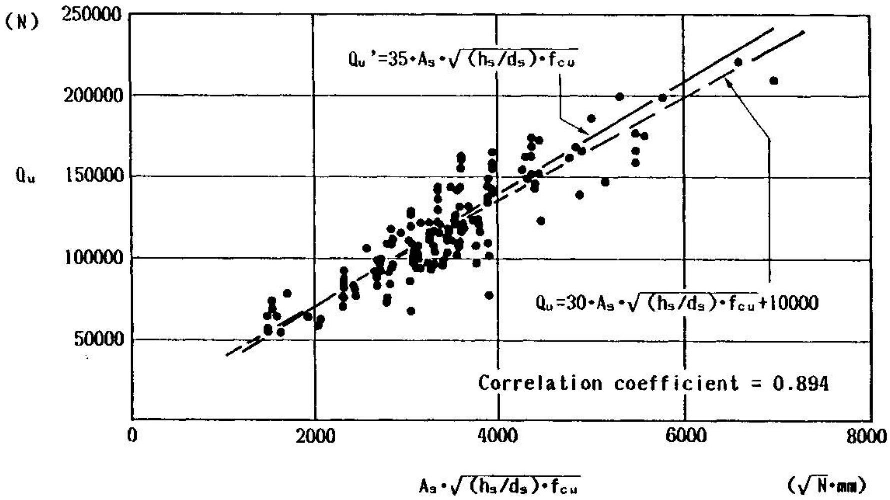

Fig.3 Q_u-$A_s\cdot\sqrt{(h_s/d_s)\cdot f_{cu}}$ relation

3.2 Fatigue strengths of studs

As described in Chapter 2, S-N curves of studs seem not to be appropriate to predict the fatigue strengths. Not only of diameter of a stud but also the height of the stud and concrete strength surrounding the stud will have some influences on the fatigue strength of the stud. Therefore, by establishing the idea that the strength can be expressed with various parameters as Eq.(6), same multi-variable regression analyses were carried out with 114 test data including the authors' data of 69.

$$R=\alpha \cdot d_s^{a} \cdot h_s^{b} \cdot f_{su}^{c} \cdot f_{cu}^{d} \cdot N^{e} \quad (6)$$

where, R:shear force range acting on a stud,
N:number of cycles up to the fatigue failure of the stud.

The regression analysis has given Eq.(7)

$$R=159.4 \cdot d_s^{1.342} \cdot h_s^{0.447} \cdot f_{su}^{-0.036} \cdot f_{cu}^{0.320} \cdot N^{-0.104} \quad (7)$$

From the meaning of T-value, stud height h_s and concrete strength f_{cu} can not make into constant values. They seem to be the important influence parameters to predict the fatigue strengths of studs.
Here the authors found an interesting thing that the influence parameters are same to the ones of static strength and the right article can be express with only N by mixing Eqs.(4) and (7). Then, by divide Eq.(7) by Eq.(4), Eq.(8) can be obtained.

$$R/Q_u'=5.904 \cdot d_s^{-0.158} \cdot h_s^{-0.053} \cdot f_{su}^{-0.036} \cdot f_{cu}^{-0.180} \cdot N^{-0.104} \quad (8)$$

As seen in Eq.(8), the exponential parts of d_s, h_s, f_{su} and f_{cu} still remain, but those are very little. Therefore, those remains can be changed into constant numbers by using each mean values. That is, it is clear that Eq.(8) can be simplified into Eq.(9).

$$R/Q_u'=1.251 \cdot N^{-0.104} \quad (9)$$

To find out the constant coefficient before N, the regression analysis was again carried out and Eq.(10) was obtained.

$$R/Q_u'=1.250 \cdot N^{-0.104} \quad (10)$$

By the way, the final equation for static strengths of studs was given by Eq.(5). Therefore, to unify the expression for static strength, Q_u' in Eq.(10) should be changed into Q_u by Eq.(5). The change seems to be a minor. But to get rigorous coefficients, the same regression analysis using R/Q_u-N relation was again carried out. Finally, the following equation was derived.

$$R/Q_u=1.28 \cdot N^{-0.105} \quad (11)$$

Fig.4 is a diagram to proof the fitness of Eq.(11). The correlation coefficient was increased to 0.795. In Fig.4, the test results by beam specimens are also shown with the sign of circles. The fact that the results are distributing around the equation can be said as a good proof that the equation is applicable to predict the fatigue strengths of studs in beams.

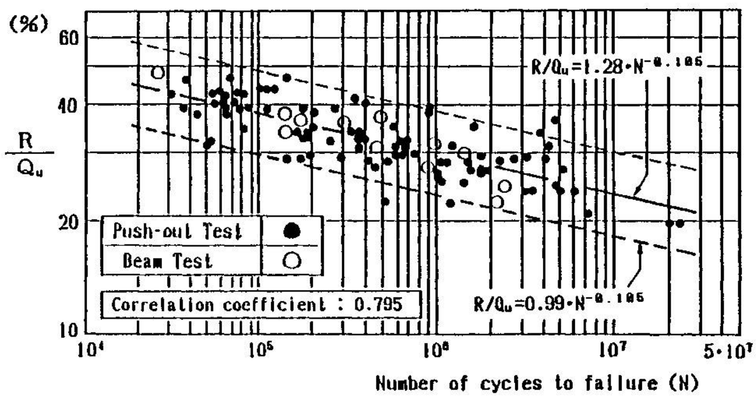

Fig.4 R/Q_u-N relations

In order to confirm in detail the validity of the new expression by R/Q_u-N relation, the fitness between the equation and experimental data was checked and compared with the fitness by the ordinary S-N expression. The examples of the results are shown in Figs.5-8. Figs.5 and 6, and 7 and 8 are comparative, respectively. As clear from those comparisons, the new expression for the fatigue strengths of studs can be said a reasonable and unified one than the ordinary expression by the S-N relation.

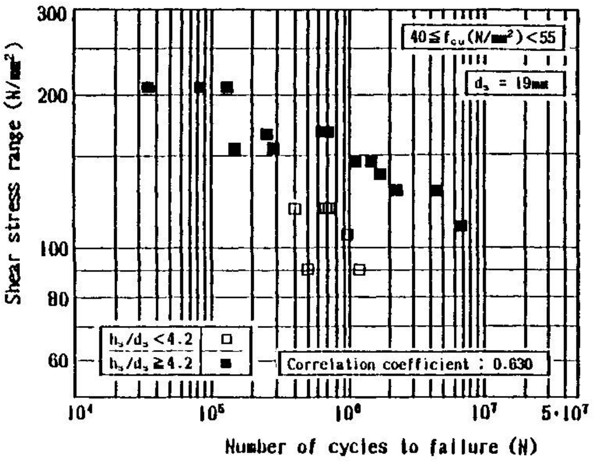

Fig.5 S-N relations

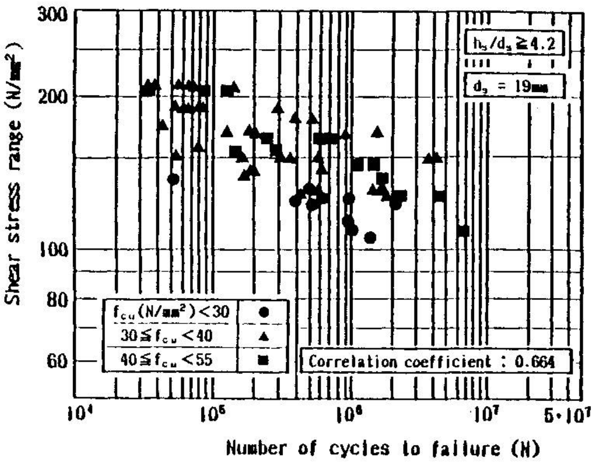

Fig.7 S-N relations

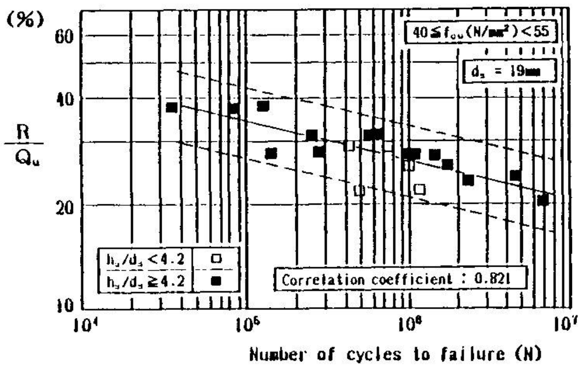

Fig.6 R/Q_u-N relations

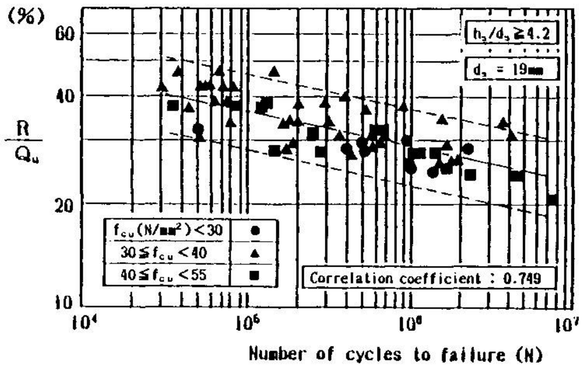

Fig.8 R/Q_u-N relations

4. CONCLUSIONS

Through the regression analysis about the experimental ultimate strengths of studs reported all over the world, a refined equation to estimate the static strength of studs was derived. Then, by the same regression analysis on the fatigue test results of studs, it was confirmed that the fatigue strengths should be related by not only the diameter of a stud but also the height of the stud and the strength of concrete. Finally, a new type of expression to predict the fatigue strength of studs could derive in the form of R/Q_u-N relation.

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