

ANALYTICAL STUDY ON SHAPE EFFECT OF FRICTION-TYPE BOLTED JOINTS

By Fumio NAGASHIMA*

Shape effect on partial slip behavior and load partition behavior in the friction-type butt joint is computed by using nonlinear discrete models. In the past studies, partial slip behavior of the friction-type joint, as compared with the bearing-type one, is regarded as insignificant because it exerts no significant effect on the major slip load. For the establishment of a more reasonable, economical and synthetic joint design, however, it is necessary to investigate these behaviors. In addition to this study, the relationship between fatigue stress and partial slip stress is investigated. The result shows the possibility that the defacement of the frictional surface at the edge bolt has one of the important effects upon the fatigue strength, as well as the stress concentration behavior. According to this assumption, an attempt has been made for prediction of the relative fatigue strength of the joints from partial slip stress of the edge bolt.

Keyword : joint design, shape effect, fatigue.

1. INTRODUCTION

The frictional resistance characteristics of joints are affected by various factors. The influence exerted by the factors among them such as the cross-sectional dimensions of plates, joint length, bolt arrangement and so forth is called the "shape effect" on which numerous experimental studies have formerly made mainly with respect to the major slip load¹⁾. In most cases, however, the influence on the major slip load that is caused by a certain factor out of those of the shape is so small that it is buried in the influences that come from other factors, thus, it is assumed that shape effect rather presents itself in the load partition behavior or local partial slip behavior prior to the occurrence of the major slip.

Since the partial slip behavior should be of the nature that has very little to do with the major slip load, it has not been so seriously considered as in the case of the bearing-type joint. Moreover, it is generally difficult to clarify the relation of cause and effect experimentally as the number of factors of the shape is very large, which would have been one of the reasons why the papers discussing on this subject is scarce.

However, in the case of the friction-type joint, it is also necessary to investigate the partial slip behavior in order to establish a reasonable method for designing the joints as well as to evaluate the comprehensive load bearing performance. For these purposes, it would be an important problem to study the influence which the various shapes of the joints might exercise on the behavior of the partial slip.

The writer and his colleagues previously originated a discrete model for the purpose of analyzing the partial slip behavior of joints and got results²⁾⁻⁵⁾ satisfactory enough to explain the measured data⁶⁾ precisely. When comparison was made between the fatigue strength obtained by analyzing with this model and the results of the experiments⁷⁾, a result that looks to suggest existence of some sort of correlation

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between the fatigue strength and the partial slip load of the edge bolt was obtained. In other words, we got the impression that repeated generation of local partial slip under the continuously repeated load had deteriorated the conditions of the frictional surface, thus possibly causing the generation of the fatigue fracture.

If the fact that stress concentration behavior is affected by the partial slip is considered together with the fact that the partial slip itself becomes larger at the location where the stress concentrates, it is supposed to have an important significance for itself to get thorough knowledge on the local partial slip behavior prior to the major slip and for estimating the fatigue strength as well.

In this paper, a series of analyses of the influence which the shapes of joints would exercise on the partial slip and on the stress distribution are undertaken by using the rigid body-spring model⁴⁾ previously reported for the joints of a single row and applying the newly developed parabolic isoparametric finite element-shear spring model to the joints of staggered holes.

2. ON THE CORRELATION BETWEEN THE STATIC SLIP CHARACTERISTICS AND FATIGUE STRENGTH OF JOINTS

In Fig. 1, a comparison between the range of fatigue stress σ_r (per gross area) in the friction-type butt joint fastened with high-strength bolts of F 10 T-M 22 which is shown in the literature 7) and partial slip stress σ_{ps} ($=L_{ps}/A_g$; where, L_{ps} : partial slip load at the edge bolt, A_g : gross sectional area of the joint) obtained by using the rigid body-spring model (RBSM)⁴⁾ is illustrated. The reason why the partial slip stress is calculated by analysis is that it is difficult to separate the relative displacement due to shear deformation and the displacement due to slip in the load-relative deformation relation experimentally measured, because both displacements occur continuously due to coating of anti-corrosive paint on the friction surface of the specimen. The fatigue tests are conducted for 4 cases of numbers of bolts, $n=4, 8, 12, 16$ and 15 specimens, in total.

In this diagram, 11 cases only in which failure due to fatigue happened around the edge bolt are presented. σ_r is estimated by converting the points obtained as the results of zero-to-tension fatigue tests to the strength of 2 million cycles by using the slope in the log-log scale of the designed fatigue life line⁸⁾ for the friction-type joints shown in the formula (1).

$(\sigma_r)^5 m = \text{Const.} \dots\dots\dots (1)$

where, σ_r : stress range (kgf/mm²), m : no. of cycles.

If the case of $n=16$ in which σ_r takes low value is excluded, it looks like the relation between σ_r and σ_{ps} is approximately linear. Thus, as a result of the linear regression analysis, formula (2-a) is obtained:

$\sigma_r = 12.8 + 0.339 \sigma_{ps} \dots\dots\dots (2-a)$

The correlation coefficient for this case is 0.962, when all the data are included, the recurrence formula becomes the following and it gives a correlation coefficient of 0.919:

$\sigma_r = 11.5 + 0.376 \sigma_{ps} \dots\dots\dots (2-b)$

The intersection of the regression line with the ordinate or the constant value of the recurrence formula is assumed to show a value close to the fatigue strength of a plate having holes and the upper limit of a recurrence formula would be the fatigue strength of a flat plate with a full cross section. In the diagram, rank A and rank C out of the fundamental range of the allowable fatigue stress in the Standard Specifications for Railway Bridges⁹⁾ (hereinafter, abbreviated as Specifications) are shown

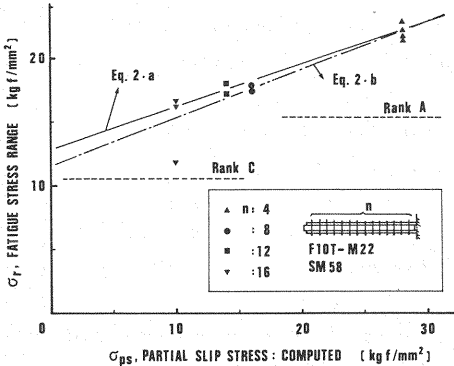


Fig.1 Relationship between experimental fatigue stress range (2.0×10^6 cycles) with partial slip stress of the edge bolt computed by RBSM.

as broken lines just for guidance. The results mentioned in the above can be endorsed by (i) and (ii) below : (i) There is an example⁽¹⁰⁾ in which a report is made based upon the results of the fatigue test that defacement of the friction surface caused by repeated generation of the partial slip under the action of high contact pressure may affect the fatigue life of the joint and (ii) while Tajima⁽¹⁾ made an investigation on the relation between the fatigue strength and "average slip stress", the writer investigated the relation between the fatigue strength and the "partial (minimum) slip load" at the edge bolt using the same data as his and obtained results which look to imply that correlation is stronger than the result obtained by the former.

On the other hand, an attempt to investigate the relation between the fatigue strength and the stress concentration adjacent to a hole experimentally has been undertaken.

At the present stage of development, the mechanism through which the fatigue failure of a friction-type fastener takes place has not yet been established, but two possible causes mentioned above are mainly suspected. As an example in which the fatigue fracture started at the corner of the hole was reported⁽¹⁰⁾, it is highly probable that two causes are working in conjunction with each other.

In view of the facts as mentioned above, it has become necessary to obtain more concrete knowledge on the slip behavior prior to the major slip^{(11), (12)}, which had not been seriously considered for frictiontype joints in the past, as it has little to do with the major slip load.

3. COMPUTER SIMULATION MODELS FOR SLIPPING PROBLEM OF THE BUTT JOINTS

(1) Rigid body-spring model (RBSM)

A discrete model (RBSM) for inelastic analysis in the slipping problem of friction-type butt joints was developed and shown in reference 4). The analytical solutions were verified by comparing them with the results of test of 18 joints fastened with M30 bolts and 3 joints fastened with M24 bolts.

An outline of this discretization method by using the RBSM is as follows. Because of the symmetricity of butt joints, only a quarter of a joint is considered. The quarter is, then, divided into a number of finite discrete joint units by an imaginary X - Y plane at the bolt axis. A joint unit is assumed to consist of four half rigid bodies connected by two elongation springs k_e and a shear spring k_s (Fig. 2(a)). The displacements of the centroids of rigid bodies in (i) unit, $w_{BP}^{(i)}$ and $w_{SP}^{(i)}$ (suffix BP and SP means a base plate as the inner plate and a splice plate as the outer one, respectively) are unknown variables in this method. As the number of units is larger by 2 than the number of bolts, the total number of degree-of-freedom is only twice the number of bolts when the four end conditions are considered. Elongation-spring constant k_e has the same quantity as the elongation stiffness of the plate having a bolt hole. Shear spring k_s has nonlinear properties in which the shear force S , when it reaches critical shear force S^* , holds the same value of critical one (Fig. 2(b)). As the loading increases, the thickness of the plates decreases with Poisson's ratio ν . Accordingly, bolt tension N and critical shear force S^* vary as

$$S^* = \mu N = \mu \left\{ N_{in} - \frac{A_B E_B}{t_0} \frac{\nu (\bar{\sigma}_z^{BP} t_{BP} + 2 \bar{\sigma}_z^{SP} t_{SP})}{E} \right\} \dots \dots \dots (3)$$

where μ : friction factor, N_{in} : initial bolt tension, t_0 : initial thickness under no loadings, A_B : equivalent cross-section area of the bolt, E_B : elastic modulus of the bolt, E : elastic modulus of the plate, $\bar{\sigma}_z^j$ ($j=BP$ or SP): longitudinal average stress ($\bar{\sigma}_z^j = (\sigma_z^j + {}^{(i+1)}\sigma_z^j)/2$) calculated by internal stresses of the plates shown in Fig. 2(c), and t_j : thickness of the base plate or splice plate.

Figure 2(b) shows the relation between shear force S and relative displacement, $\beta = w_{BP} - w_{SP}$, under cyclic loading which reverses at β_{rev1}^* and β_{rev2}^* . On path B~C or D~E, the joint unit is in a state of slipping. Linear relationship between shear force and relative displacement is no longer valid once partial slip occurs. To obtain the equilibrium position of the nonlinear system, the direct iteration method is used.

material of the plates are assumed in advance, and the sectional areas are designed referring to the ratio of major slip stress σ_{ms} to yielding stress σ_y at the net sectional area of the joints (stress ratio : $\kappa = \sigma_{ms} / \sigma_y$) and the fullness ratio ρ ($= A_n / A_g$: where A_n : net sectional area, A_g : gross sectional area).

Figure 4 (a) shows the procedure for designing in which priority is given to the fullness ratio. In case of designing with priority given to the plate thickness, the procedure is obtained by replacing the portion of the diagram surrounded by broken lines with Fig. 4 (b). For all the specimens for the numerical experiments, the major slip stress is taken nearly same as the yielding stress of the net sectional area ($\kappa = 0.9 \sim 1.0$), except for the case of investigating the effect of κ , and in that sense, the design is deemed to be well-balanced.

The net area required is calculated from slip coefficient μ' , designed bolt tension N and others, and in the case of the joint with double shear it is given by the following formula.

$$A_n = 2 \mu' N n / (\kappa \sigma_y) \quad (4)$$

Therefore, if the slip coefficient is underestimated, it might result in an insufficient sectional area. In this formula, the actual measured value as it is should be used.

When cyclic load is applied to the joint and an examination of the fatigue strength is required, the sectional area of the structural member is to be determined almost completely by fatigue strength. Accordingly, in such a case, the cross section is said to be well-balanced when it is so designed that the major slip stress and the fatigue stress for the gross area are equal. In Para. 7 of Chapter 5, this method is used in designing the cross section.

As the value of the friction factor, $\mu = 0.45 \sim 0.60$ is used. The Poisson's ratio of the material of the joint is assumed to be 0.3 throughout all cases.

5. EFFECT OF SHAPE OF BUTT JOINT ON SLIP BEHAVIOR

(1) Effect of pitch length

Taking the joints with the number of bolts $n=6$ (F 10 T-M 22, $\kappa=0.9$, $\rho=0.7$, $\mu=0.60$), an investigation is made for three cases of pitch l_e : namely, $l_e=75, 112.5, 150$ mm. Figure 5 (a) shows the partial slip or the major slip load (L_{ps} , L_{ms}) and in Fig. 5 (b), the value of the shear-stress concentration factors at the position of each bolt immediately after the partial slip occurred at the edge bolt are shown.

Against the partial slip, the smaller pitch is more advantageous and it provides the most desirable pattern with regard to stress concentration as well. However, a variation in the pitch affects the major slip load very little. In the models of the numerical experiment, the size of pitch is related to the stiffness for elongation and the larger the pitch becomes, the lower the stiffness for elongation becomes. A fall in rigidity against elongation, namely a relative increase in the stiffness of shear spring increases the relative displacement between the base plate and the splice plates and causes a drop in the partial slip load.

From these facts, it looks better to keep the pitch of the bolts as small as possible and avoid choosing too large a value which is beyond necessity.

(2) Effect of the slip stress ratio (κ)

Effect of ratio of the stress working within the joint when the major slip takes place to yielding stress for

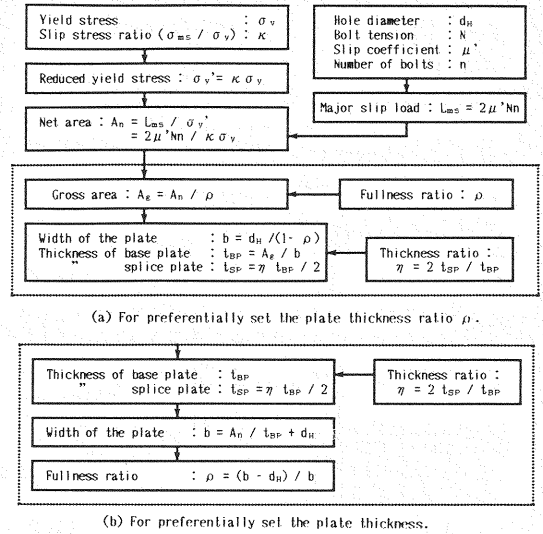


Fig. 4 Procedure to design the test specimens of the joints.

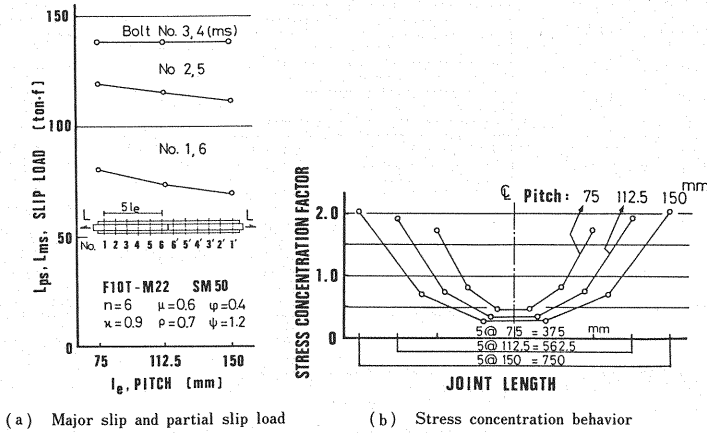


Fig. 5 Effect of pitch length.

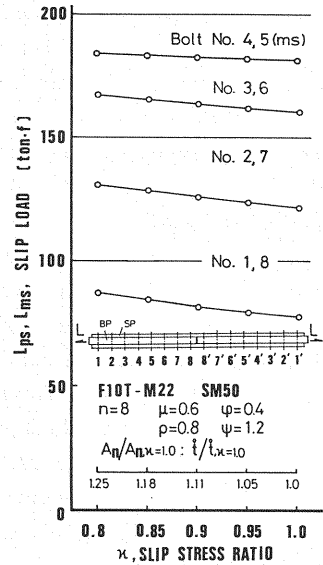


Fig. 6 Effect of lip stress ratio χ ($=\sigma_{ms}/\sigma_y$) on the slip loads.

the net area ($\chi=\sigma_{ms}/\sigma_y$); namely, the “slip stress ratio” is investigated regarding the joints with the number of bolts $n=8$ (F 10 T-M 22, $\rho=0.8$, $\mu=0.60$, $l_e=75$ mm). The difference in the slip-stress ratio comes out as the difference in the sectional area or thickness of the joint plate, if the other factors are fixed. In Fig. 6, the major slip load (L_{ms}) and partial slip load (L_{ps}) are compred for the joints of 5 kinds with $\chi=0.8\sim 1.0$ (the width of the member is made constant at 125 mm). The scale in the diagram indicates the sectional area ratio, in which sectional area is represented as 1.0 when $\chi=1.0$.

Although the sectional area or the plate thickness in case of $\chi=0.8$ is 25 % larger than in the case of $\chi=1.0$, the major slip load remains almost unchanged (1~2 % increase). However, the partial slip load at the edge bolt increases. Therefore, while the slip stress ratio χ may affect the partial slip load slightly, little effect on the major slip load is observed and it is known that even if the sectional area is made larger beyond the least value required its increasing effect on the major slip load is very small.

(3) Effect of fullness ratio (ρ)

In the joint of a single row, the following relation exists among the fullness ratio ($\rho=A_n/A_g$), width of plates b and diameter of bolt holes d :

$$b=d/(1-\rho) \dots\dots\dots (5)$$

Accordingly, if the diameter of bolts to be used is given in advance, the width of plate is decided exclusively depending upon the value of ρ . The investigation is made for the specimens with the number of the bolts $n=8$, (F 10 T-M 22, $\mu=0.60$, $l_e=75$ mm, $\chi=0.9$) and five varied values of ρ over the range of $\rho=0.6\sim 0.8$ while the net sectional area being kept constant. In Fig. 7, a comparison between PS load and MS load is presented. The decreasing trend of the value of PS load can be seen as the fullness ratio gets larger, where, it is meant by the term of “large fullness ratio” that the values of the gross area and the plate thickness are relatively smaller for the same net area. In this example of analysis, the gross area for $\rho=0.8$ becomes about 87 % of that in case of $\rho=0.7$ and the plate thickness is 58 % of the value of that for ρ

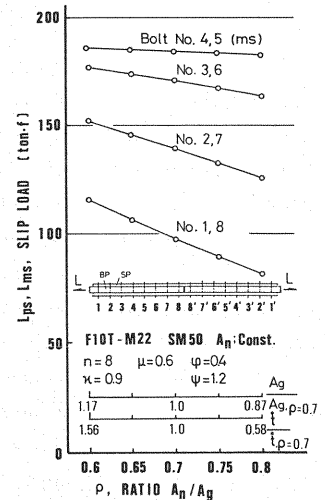


Fig. 7 Effect of ratio A_n/A_g on the slip load (A_n : const.).

≈ 0.7 . It is very difficult to investigate the effect of the plate thickness experimentally and has not been fully known yet.

The afore-mentioned results of the analysis may be interpreted that because the shearing strain energy gets larger in the case of the thicker plate compared with the case of the thinner plate, the starting time of the partial slip is slightly delayed. If particular attention is paid to this phenomenon, it looks to be preferable to made the width as small as possible, but on the other hand, if the staggered arrangement of the bolts is chosen, the length of the joint becomes larger. It must be taken into consideration that the partial slip takes place earlier on the contrary, affected by the larger length of the joint.

(4) Effect of distribution of the bolt tensions

Assuming that three types of distribution of the bolt tensions as shown in the followings are given to the joints having the same sectional area with the number of bolts $n=9$ (F 10 T-M 22, $\kappa=0.9$, $\rho=0.7$, $\mu=0.60$, $l_e=75$ mm) the numerical experiments are carried out. Namely, in the case when bolt tension N in the i -th bolt is distributed in the following patterns for the standard bolt tension $N_0=20.48$ tonf :

a) Uniform distribution

$$N=N_0, \quad i=1, 2, \dots, 9 \dots\dots\dots (6-1)$$

b) Parabolic distribution

$$N=0.9 \overset{(5)}{N}=0.9 \overset{(1)}{N}, \quad \sum_{i=1}^9 N=9 N_0 \dots\dots\dots (6-2)$$

c) Reversal parabolic distribution

$$N=0.9 \overset{(1)}{N}=N, \quad \sum_{i=1}^9 N=9 N_0 \dots\dots\dots (6-3)$$

Comparison is made with respect to PS load and MS load (Fig. 8). Since the model for analysis is of the nonlinear system, even if the total sum of the bolt tension may be equal, a difference in MS load appears though only slightly.

Type b is the most advantageous among these three against the PS load and the relation among them is represented by $b) > a) > c)$. In other words, it can be seen that the slip load is affected to a considerable extent by the axial force induced in the edge bolts. In view of the difficulty of adjusting the bolt tension during construction, the result may not be directly brought into practice, but it can be concluded that in the final confirmation of the bolt tension, those in the several bolts at the edge should be given first priority.

(5) Effect of joint length

The decreasing trend of the frictional resistance per bolt as the size of the joint gets larger (or as the number of bolts in a row increases) has been confirmed by a number of experiments. The phenomena is mainly caused by the drop in the axial force in the bolt due to a loss in the sectional area of the member in the field of tensile stress. If the pretension force that was introduced to the bolt about 10 % in excess has become equal to the required tension force due relaxation and fabrication tolerances, ratio of the reduction of the tension can be approximately expressed by the following formula :

$$\zeta = -\frac{\nu \kappa \rho}{a} \frac{A_B}{A_{Be}} \frac{A_{BP} \sigma_{zy}}{(A_{BP} + 2 A_{SP}) \sigma_{By}} \dots\dots\dots (7)$$

where, ν , κ , ρ are the Poisson's ratio, stress ratio and fullness ratio ; a is the ratio to the yield point of the material of the bolts (F 10 T : $a=0.75$) ; A_B , A_{Be} are the sectional area and the effective sectional area of the bolts ; σ_{zy} , σ_{By} are yielding stress of the member and of the bolts, respectively.

The results of calculation by formula (7) has been verified by comparing with the results of the actual

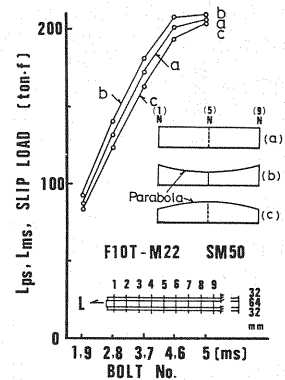


Fig. 8 Effect of distribution of the bolt tensions on the slip loads.

measurement⁶⁾. Accordingly, it is known that the ratio of the reduction in the bolt force depends upon the shape of the cross section, material and the stress ratio. Since the number of bolts is not included in formula (7), it can be concluded that there is no direct correlation between the number of bolts and the major slip load. However, it must be noted that in case of the multiple-bolt joint, reduction ratio ζ becomes larger as fullness ratio ρ tends to rise.

(6) Effect when varied section is taken by doubling the butt strap

In the friction-type joint, the stress in the base plate is transmitted to the butt strap (splice plates) by way of the friction surface step by step and about half of the stress at the middle of the joint and finally at the end of the base plate, the whole stress is transferred to the butt strap. Therefore, in the first half portion from the end of the butt strap, the stress working is only less than half of the allowable load bearing capacity of the butt strap. By reducing the sectional area down to about half for economizing the joint, a double-butt strap is able to be obtained.

If a butt strap of this type is employed, the weight of butt strap is reduced about 3/4 of conventional butt straps. In the case of the stiffening truss of the suspension bridge that needs great number of joints, this problem cannot be disregarded in view of structural weight-savings. However, as studies on this problem have not been fully carried out yet experimentally or analytically, they look to be designed with somewhat lower allowable fatigue stress compared with conventional joints for the time being.

In Fig. 9 and Fig. 10, the result of the experiment⁶⁾ and the results of the analysis with application of RBSM with respect to the intensity of stress within the butt strap and the relation of load-relative displacement are compared (the measured value is the intensity of stress at the outer surface of the butt strap and the analytical value is the internal stress re-calculated for the net area). Both values show good conformity and it can be seen that RBSM can be effectively applied to the analysis of the double butt strap.

For the joint with a double butt strap, an investigation was made by using RBSM to know how the influence due to a reduction in the sectional area of the first half portion of the butt strap emerges in the distribution behavior of the internal stress (f_{BP} , f_{SP-1} , f_{SP-2}) or the same of the transmitted frictional force (f_{r1} , f_{r2}), which gave the results as shown in Fig. 11 immediately after partial slip generated at the edge bolt. The share of the stress transmitted to each butt strap is not equal at the middle of the joint (where the base plate is cut) even when the thickness of the outer strap and that of the inner one are equal and the share of the inner butt strap is larger. The difference in the share of stress is more conspicuous when the number of bolts is smaller and tends to be relieved as the number of bolts increases.

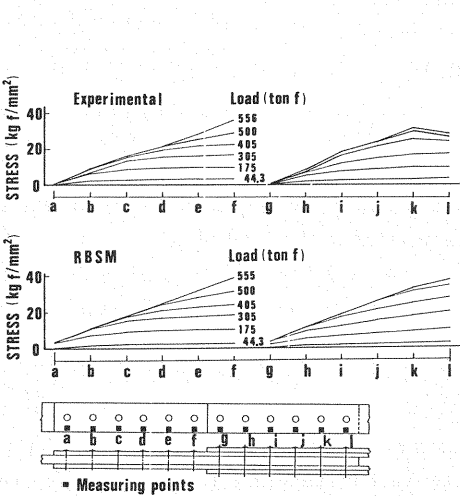


Fig. 9 Comparison of experimental and computed load partition behavior (Double-lapped joint).

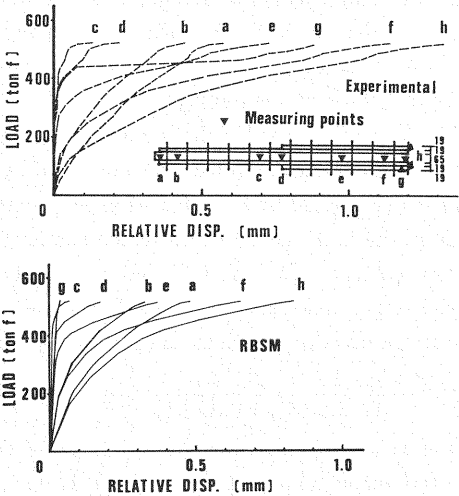


Fig. 10 Comparison of experimental and computed load-displacement relationship (Double-lapped joint).

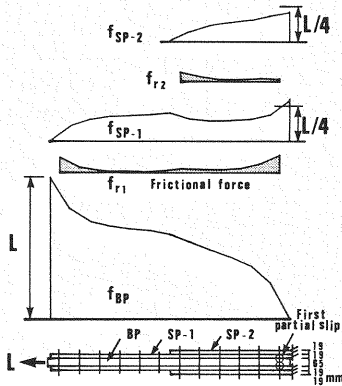


Fig. 11 Load partition behavior of double-lapped joints.

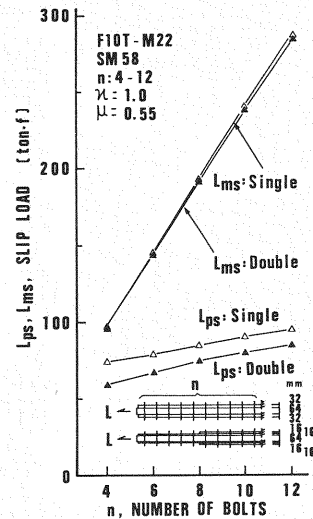


Fig. 12 Comparison of single-lapped and double-lapped joints on slip loads.

In the joint with double butt straps, since the share of stress to be borne by the inside butt strap is large in the vicinity of the edge bolt at the middle of the joint, the first partial slip occurs at this place. The value of the slip load at the time is smaller than that of an ordinary butt joint. In order to eliminate the imbalance of the shares of stress, a method to adjust the sectional areas of the outer and inner butt strap is needed. However, under the condition that the total volume of the butt straps is constant, if the sectional area of the inside butt strap is increased, the ratio of its share of stress grows while the intensity of the internal stress is improved and on the contrary, if the sectional area of the outer butt strap is increased, while the ratio of its share of stress is improved, the situation gets worse with respect to the intensity of the internal stress against expectation. After all, little is expected for the effect of adjustment of the sectional area to improve the imbalance of the shares of stress.

Another method to improve the imbalance of the shares of stress is to extend the length of the outer butt strap by several pitches. However, this method does not look to be very effective for multiple-bolt joints.

Through a comparison of single-lapped joints with double lapped joints on the slip loads, what degree of fall in the slip load should be anticipated for the joint with double-butt straps is investigated (Fig. 12). The results indicate that there is no significant difference between major slip loads of the two, although the major slip load of the joint with double-butt straps is slightly lower than that of a single one. However, a clear difference can be seen in the value of the partial slip load, which is about 10 % lower than that of the joint with a single-butt strap.

(7) Effect of arrangement of bolts

The performance of the joint when the bolts are arranged in a stagger pattern or in an irregular manner is investigated by applying the PIFES model that is introduced in section 3(2). In addition, some investigations on the fatigue strength against the zero-to-tension stress are made as well.

All specimens for the numerical experiments are the joints with triple rows and staggered holes and are classified by the number of bolts n into the cases a~e (a : $6+5+6=17$, b : $7+6+7=20$, c : $6+6+7=19$, d : $8+7+8=23$, e : $10+9+10=29$) as shown in Fig. 13. In case a, the angle of the bolt arrangement is varied using three different angles (33° , 45° , 57°) and in other cases it is fixed at 45° .

The number of bolts in case c is reduced by one, considering the case where corner cutting is necessary.

The plate thickness is unified to take 50 mm for the base plate and 25 mm for the butt strap in order to avoid the influence due to the differences in thickness. The coefficient of friction is kept constant

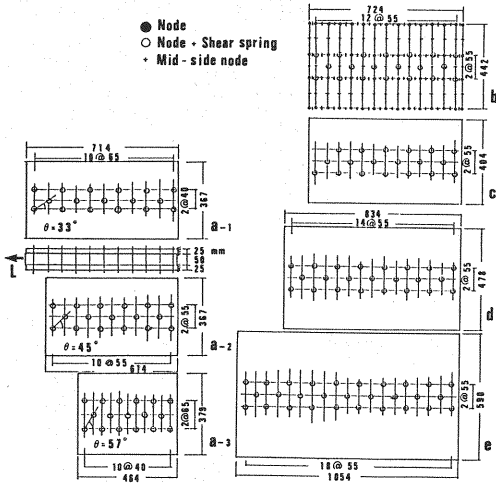


Fig. 13 Configurations and size of test specimens.

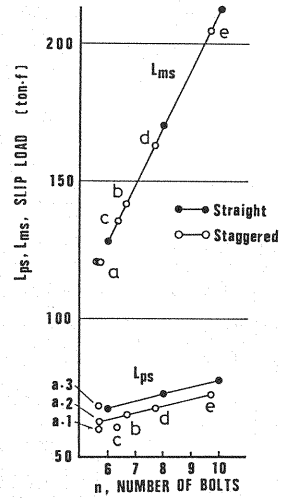


Fig. 14 Comparison of straight-pattern joint and staggered-pattern joint on slip loads.

throughout all the specimens at 0.55.

In Fig. 14, major slip load L_{ms} and partial slip load L_{ps} at the edge bolt obtained as a result of the numerical experiments on specimens a~e are presented on the abscissa of $\bar{n}$ which is the simple mean number of bolts obtained by dividing the total number of bolts by the number of rows. In the diagram, ● mark shows the slip load of the joint of a single row ($n=\bar{n}=6, 7, 8, 9, 10$). When the values of slip load are re-arranged by the use of $\bar{n}$, with respect to major slip load L_{ms} of the both, good agreement can be seen. However there looks to be some differences in partial slip load L_{ps} and in case of the staggered arrangement, the value becomes low. These differences are nearly all of the same order throughout all cases and if re-arranged by the number of bolts that is obtained by deducting 2 from $\bar{n}$, they correspond to the values in the cases of a single row.

In case a, the length of the joint varies as the angle of the bolt arrangement differs and is affected by it, differences in the values of the partial slip loads come out. The short joint with the angle of bolt arrangement $\theta=57^\circ$ has the value of L_{ps} equivalent to the single row joint. In case c where the number of the edge bolts is less, the L_{ps} value drops even further.

For the fatigue strength of the friction-type joints, the standards of the three ranks A (no. of bolts; 1~4), A' (5~15) and C (16 and above) are established in the Specifications in accordance of the number of bolts. However, in the case of the staggered arrangement, if the number of staggers is deemed to be the number of bolts as it is, it would be too many. Otherwise, for using the simple mean number of bolts $\bar{n}$ as it is, some reluctance is felt. In these circumstances, an estimation of the relative fatigue life of the joints has made from the results of the numerical experiments mentioned above, under the assumption that there is a correlation as described in Chapter 2 between the partial slip at the edge bolt and the fatigue strength. The results are summarized as follows:

It can be concluded that in the design of the fatigue of joints with staggered holes, the equivalent number of bolts for distinction of the rank may be replaced with "the largest value of the number of bolts included in a row". However, in the cases when the length of joint becomes very long due to the small angle of arrangement or when the number of the edge bolts is made smaller, a certain number should be added to the above-mentioned value.

Since the experiemntal studies on the joints with staggered holes have not been sufficiently carried out up to now, the above has yet to be satisfactorily confirmed. More accumulated results due to experimental studies in this field is greatly needed.

6. CONCLUDING REMARKS

This study was undertaken to analytically investigate the influences that the shape effect of the joint exerts on the partial slip behavior through a series of numerical experiments. The results can be used as the data for establishing the more rational method for designing taking the advantage of the characteristics of the friction-type joints and also to provide references when the specimens for the tensile slip test, fatigue test etc, of joints are manufactured.

As a result of the comparison made between the results of the fatigue tests of joints under zero-to-tension stress and the numerical experiments, there looks to be a nearly linear correlation between these two. From these facts, the writer is under the impression that estimation of the relative fatigue strength would be made possible. Taking into consideration the fact that the failure of the joints has mostly occurred at the location of the edge bolt, experimental studies on this subject should be carried out.

Among the other factors that are considered to have influences on the slip behavior of joints, there are :

- i) Unevenness of the friction surface,
- ii) Effect of anti-corrosive paint coated on the friction surface,
- iii) Leaning of the center line of the bolt toward the hole wall or eccentricity,
- iv) Other problematic factors including human errors, etc.

These are all subjects of study left to be carried in the future.

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