Effect of Clamping Force of Double Nuts on Fatigue Strength of Bolted Connection*

By Ken TERAO***, Tadashi KANEKO***, Eiichi SUZUKI†, Juichiro MASAKI‡‡, Masao MIZUNO+++

In this study, effect of the clamping force of double nuts on fatigue strength of bolted connection was investigated under the conditions of clamping in elastic and plastic regions and also in the case of applying pre-load torque to bolt. The results are as follows: From a standpoint of fatigue strength, it is by the optimum clamping method of double nuts that both lower and upper nuts can be clamped with the same clamping torque. Upper nut (lock nut) of double nuts not only prevents a relaxation of bolted connection but also gives an effect on the clamping force and fatigue strength of it. When a bolt is clamped in plastic region, fatigue strength of bolted connection is improved. Fatigue strength of bolted connection depends on the total clamping force of double nuts.

1. Introduction

Bolted connection is a most popular connective mechanism because of easiness for disassembling and clamping operation. Though the importance of clamping force is recognized, criterion on strength of bolted connection has not yet been established. A clamping force equal to 70 percent of yield load of bolt is recommended by the Japanese Standards Association(1), and at present the apparent safety factor is overestimated to prevent a fatigue fracture. It has become very important in recent years to improve fatigue strength of bolted connection, and for this purpose, many studies on shape, stress concentration, machining method and clamping force are pursued steadily. In recent papers, studies on clamping in plastic region are also made (2)(3). In this paper, effect of clamping force and clamping method of double nuts on fatigue strength of bolted connection is investigated. In advancing the standpoint of preventing a relaxation of clamped connection, it is the original role to be played by double nuts, and from the standpoint of improving fatigue strength, fatigue tests of bolted connection are performed under various ratios of clamping force of upper and lower nuts. The fatigue tests are performed under the conditions of clamping in elastic region and in plastic region, and also in the case of a pre-load torque being given to bolt. Further, the relation between clamping force and clamping torque is determined, and the optimum clamping ratio of double nuts is found. Lastly, the relation between clamping force and fatigue strength is discussed on the basis of experimental results.

Fatigue strength of bolt is usually expressed in terms of internal force. But, this study is concerned with a comparison test, and the relation between clamping force and allowable external load amplitude is most important. So, in this paper, we take external load as the fundamental value. In the fatigue tests of bolted connection, contact plane of connection would be partially separated by a large external load amplitude. But, in the present study, clamping force of bolted connection always remains been throughout the test.

2. Experimental equipment and test piece

2.1 Experimental equipment

Equipment for fatigue test of bolted connection is shown in Fig.1. Main equipment is a Hairh type (tension and compression) fatigue testing machine (allowable load: ± 1 ton, 50 KHz), and the measuring apparatus is arranged as Fig.1. Bolted connection including a jig (jointed parts) is shown in Fig.2. Material of this jig is SOM3, and each thickness of jointed parts that are clamped is 14 mm (total thickness is 28 mm). We put a ring chain in space between load cell and bolted connection to avoid influence of eccentricity.

2.2 Test piece

Test piece bolt is a rolled thread (coarse screw) and material of it is S45C. Heat treatment, shape and size, mechanical properties, and chemical composition of the test piece are shown in Fig.3.

3. Experimental method

3.1 Clamping method of double nuts

Condition of clamping by double nuts is

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other hand, as lower nut is lastly turned back, clamping force should be decreased finally and also fatigue strength should be decreased rapidly. For the above reason, this clamping method is not adopted in this experiment. From a standpoint of fatigue strength, first we clamp lower nut with a target torque and then clamp upper nut with the target torque.

<table>
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<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
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<tr>
<td>0.44</td>
<td>0.24</td>
<td>0.077</td>
<td>0.029</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
<td>0.1</td>
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Tensile stress: Hardness HHL Heat treatment: Vacuum annealing
62 Kg/mm²: 42.7 830°C (2 hours)

Fig.3 Test piece

3.2 Clamping ratio of double nuts
Clamping torque (double nuts: upper and lower nuts) and clamping ratio are shown in Tables 1-3. (The marks in Fig.5,6,7, 8,14,15 follow Tables 1-3.)

3.3 Method of fatigue test
Test piece bolts are clamped by torque wrench according to Tables 1-3. Clamping torque (target torque) is T=60 Kgcm and T=90 Kgcm. Washers (diameter: 20 mm, thickness: 2 mm) are applied in jointed parts (bolt side and nut side) to prevent a deformation of jig caused by friction. Further, lubricating oil is given to the contact plane (head of bolt and both faces of nuts) and screw to prevent a scattering of clamping force. Under above condition, bolted connection is set in the Haigh type fatigue testing machine. Fatigue test is made under partly pulsating load (constant mean external load [Fpm] is 400 Kg). We take the value of the external load as the fatigue limit, when number of load cycles reaches $2 \times 10^6$. 

shown in Fig.4 (1 is upper nut and 2 is lower nut). In ordinary circumstance, first, two nuts are put (clamped) on a bolt, and then using two wrenches, upper nut is fixed and lower nut is turned back in reverse direction until two nuts contact tightly. Thereby two nuts are compressed on contact plane to each other. The merit of this clamping method is that it can prevent relaxation of bolted connection, but on the
According to these results, under the condition of clamping in elastic region, it is best for fatigue strength to clamp upper nut and also lower nut with the same target torque.

The results of fatigue tests under the value of target clamping torque, 90 Kgcm, are shown in Fig.6 (refer to Table 2). At a value of clamping torque, 90 Kgcm, bolts are in plastic region (refer to Fig.13). In Fig.6, the value of allowable external load amplitude becomes lower in order of their magnitudes, C,B,A,D,E. These results are in the same tendency as Fig.5. Further, the higher the clamping force of lower nut and also upper nut, the better the value of allowable external load amplitude is. And the optimum clamping method of double nuts is that of C. So, under the condition of clamping in plastic region, it is best for fatigue strength to clamp upper and lower nuts with the same target torque.

<table>
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<tr>
<th>Clamping method</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<tr>
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<td>X</td>
<td>O</td>
<td>◆</td>
<td>O</td>
<td>△</td>
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<tr>
<td>Clamping torque (Kgcm)</td>
<td>Upper</td>
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<td>48</td>
<td>60</td>
<td>60</td>
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<tr>
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<td>nut</td>
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<td>(80%)</td>
<td>(100%)</td>
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<tr>
<td></td>
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<td>nut</td>
<td>(100%)</td>
<td>(100%)</td>
<td>(100%)</td>
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<tbody>
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<tr>
<td>Clamping torque (Kgcm)</td>
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<td>54</td>
<td>72</td>
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<tr>
<td></td>
<td>Lower</td>
<td>90</td>
<td>90</td>
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<td>(100%)</td>
<td>(100%)</td>
<td>(100%)</td>
<td>(80%)</td>
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</table>

4. Effect of double nuts on fatigue strength of bolted connection

The results of fatigue tests in the case of a clamping (target) torque of 60 Kgcm are shown in Fig.5 (refer to Table 1). At the value of clamping torque, 60 Kgcm, bolts are in elastic region (refer to Fig.13). From Fig.5, it is clear that the value of allowable external load amplitude (fatigue limit) becomes lower in order of their magnitudes, C,B,A,D,E. The allowable external load amplitude is the larger (better), the higher the clamping force of lower nut (in order of their magnitudes, C,D,E). And under the condition of clamping force of lower nut being constant, the higher the clamping force of upper nut, the better the allowable external load amplitude is (in order of their magnitudes, C,B,A). When the value of clamping torque is 60 Kgcm, the optimum clamping method of double nuts is that of C.
Comparing Fig.6 with Fig.5, the value of allowable external load amplitude in Fig.6 is far better (35%~70%) than the value in Fig.5. From these results, it is clear that clamping in plastic region is better for fatigue strength of bolted connection.

5. Effect of double nuts on fatigue strength when pre-load torque is given to bolt

Pre-load torque is given to bolt by torque wrench easily. First, bolted connection is clamped in plastic region at $T = 90$ Kgcm by lower nut (pre-load torque is given to bolt), then lower nut is loosened by wrench (load is removed). And then, bolted connection is clamped by lower nut with the target torque (60 Kgcm) and further, it is clamped by upper nut at various ratios. Clamping ratio of double nuts and clamping force are shown in Table 3. The results of fatigue tests under above condition are shown in Fig.7. The value of allowable external load amplitude becomes lower in order of their magnitudes, C, B, A, D. This is the same tendency as Fig.5 and Fig.6. The value of allowable external load amplitude in Fig.7 is improved over the value in Fig.6. These results are worth noting.

The results of a series of fatigue tests are summarized in Fig.8 (a: pre-load torque is 90 Kgcm and target clamping torque is 60 Kgcm; b: target clamping torque is 90 Kgcm, c: target clamping torque is 60 Kgcm). From Fig.8, it is seen that the value of allowable external load amplitude in the case of given pre-load torque, (a), is most improved. From above results, clamping in plastic region and clamping after pre-load torque to bolt will be an effective means to improve fatigue strength of bolted connection.

In a series of experiments, bolts and nuts are not damaged when they are clamped in plastic region, and bolts and nuts can be dismantled easily. These results seem to change the traditional theory and consideration that upper limit of clamping force is the yield load of bolt.

The test piece bolts are ruptured by fatigue tests at the position of incomplete thread (16%), and at the position of edge of lower nut (84%). Pictures of ruptured bolts are shown in Fig.9. The data that we adopt in these fatigue tests are all on the case of the rupture position of bolt being at the edge of lower nut (upper picture of Fig.9).

6. Clamping torque and clamping force of double nuts

6.1 Experimental method
To know the real roles played by lower nut and upper nut, the relation between clamping force and clamping torque of double nuts is investigated. Using a cylinder (jig) made of steel (outside diameter is 20 mm, inside diameter is 6.5 mm, height is 28 mm), compression test and clamping test of bolt are performed. First, the cylinder on which three strain gages are placed is clamped by lower nut (target clamping torque is $T = 54$, 72, 90 Kgcm), and then it is clamped by upper nut (target clamping torque $T = 90$ Kgcm). On the other hand, compression test of the cylinder by a universal testing machine is made. From above two experimental results, the relation between
clamping force and clamping torque is elucidated. In these experiments, test piece bolt, torque wrench and lubricating oil are the same as on previous fatigue tests.

6.2 Experimental results
In the case when lower nut is clamped up to \( T = 50 \) Kgcm and then upper nut is clamped up to \( T = 90 \) Kgcm, the relation between clamping torque and clamping force of double nuts is as shown in Fig.10. In the same way, the relation between clamping torque and force in the case when torque of lower nut is \( T = 72 \) Kgcm and then, torque of upper nut is \( T = 90 \) Kgcm, is shown in Fig.11. Figure 12 shows the case of lower nut being clamped up to 90 Kgcm and upper nut clamped up to 90 Kgcm. From Figs.10~12, it is clear that clamping torque of lower nut plays an important role for clamping force, and further, clamping force is also slightly increased by upper nut. This fact will be able to explain the results of previous fatigue tests. Upper nut not only prevents relaxation of bolted connection but also gives an effect on clamping force and fatigue strength.

From Figs.10~12, the coefficient of torque (\( \alpha \)) becomes 0.34, using the following equation: \( \alpha = \frac{T}{P_v d} \) (\( T \): clamping torque, \( P_v \): clamping force, \( d \): nominal diameter of thread). This value of \( \alpha \) is very similar to the experimental results obtained by Yamamoto (\( \alpha = 0.30 \sim 0.33 \)). The relation between angle of rotation of lower nut and clamping force is shown in Fig.13. It is clear that the yield load of bolt by clamping is 400 Kg and after yield the clamping force increases.
7. Total clamping force of double nuts and allowable external load amplitude

Total clamping force of double nuts in the case of clamping torque of 90 Kgc.m is shown in Fig.14. And also in the case of clamping torque of 90 Kgc.m, the relation between total clamping force of double nuts and allowable external load amplitude is shown in Fig.15 (refer to Table 2). The larger the total clamping force, the better the allowable external load amplitude is, and fatigue strength of bolted connection depends only on the value of clamping force. This interesting experimental results are worth noting.

Fig.14 Total clamping force of double nuts and clamping method (Refer to Table 2)

T=90 Kgc.m

Fig.15 Total clamping force of double nuts and allowable external load amplitude (Refer to Table 2)

T=90 Kgc.m

8. Consideration

The relation between clamping force and allowable external load amplitude under the condition of clamping in elastic and plastic regions is considered qualitatively as follows. Figure 16 shows the relation between external load and internal force under the condition of clamping in elastic region. In Fig.16, critical load (HK) is intermediate between maximum external load and minimum external load. (The maximum value of internal force becomes just the same as the maximum value of external load, and the minimum value of internal force is larger than the minimum value of external load in Fig.16.) In above condition, with an increased clamping force, the minimum internal force will increase and internal force amplitude will decrease. (HK is clamping force.) From the fatigue limit diagram (Fig.17), it is found that the clearance will arise when stress amplitude decreases, under the condition of upper stress being constant.

And so, the value of external load amplitude that is equivalent to the clearance (Fig.17) can be increased. In other words, when we make increase clamping force, allowable external load amplitude becomes larger. The results of Fig.5 (T=60 Kgc.m) match above consideration.

The relation between external load and internal force under the condition of clamping in plastic region is shown in Fig.18. When critical load (Pcr) becomes larger than the minimum value of external load as in Fig.18, internal force amplitude becomes smaller than external load amplitude. (But, as the maximum value of external load is larger than critical load, the maximum value of internal force is the same as that of external load.) From above, it is clear that when initial clamping force increases, internal force amplitude of bolt will decrease. In Fig.17, it is found that when stress amplitude decreases, the clearance will arise, under the condition of upper stress being constant. And so, the value of external load amplitude that is equivalent to the clearance (Fig.17) can be increased. In other words, also under the condition of clamping in plastic region, when
This fact does not agree with usual conception that upper limit of clamping force of bolted connection is the yield load. (4) Giving pre-load torque to bolt, improves very much the fatigue strength of bolted connection. (5) Fatigue strength of bolted connection depends on total clamping force of double nuts. Upper nut plays also a role of slightly regulating the clamping force.

10. Acknowledgement

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References


9. Conclusions

(1) From a standpoint of fatigue strength, it is by the optimum clamping method of double nuts that lower nut and upper nut can be clamped with the same clamping torque. (2) Upper nut of double nuts not only prevents relaxation of bolted connection but also gives an effect on clamping force and fatigue strength. (3) When bolt is clamped in plastic region, fatigue strength of bolted connection is improved.

we increase clamping force, allowable external load amplitude becomes larger. The results of Fig. 6 (T=90 Kgm) match above consideration. This phenomenon would continue until critical load will become the same as maximum value of external load.

The conceivable reasons why allowable external load amplitude is improved in the case of given pre-load torque (Fig. 7) are as follows: (1) Contact plane of bolt and nut becomes better fit by pre-load torque. (2) Natural decrease of clamping force in fatigue test is smaller than usual (3) Compressive residual stress at root of thread is produced. (4) Influence of work hardening can not be ignored.