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EXPERIMENTAL EVALUATION OF FATIGUE LIFE IN ELASTICALLY BENDED DOUBLE-LAP BOLTED JOINT

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ABSTRACT–Double-lap bolted joints have been widely applied for connecting parts in various industries owing to their structural stability and ease of manufacturing. When double-lap bolted joints are under loading, the section that sustains the load by friction between the surfaces of the components fastened by the bolt is called the frictional mode, which is before the load is transmitted to the bearing surface of the bolt. The clamping force decreases owing to cyclic loads even in the frictional mode, therefore, it is necessary to understand the fatigue characteristics in this section. We performed fatigue tests according to the initial clamping force and magnitude of cyclic load in the frictional mode for a special type of joint called an elastically bended double-lap bolted joint. The compressive strain generated in the clamped part between the double-laps was measured during the fatigue test to obtain the continuous behavior of the clamping force. Basically, the clamping force decreased as the cycles of the load increased, however, the rate of the decrease varied according to the test phase. The test phase was divided into four stages by analyzing the behavior of clamping force, and an appropriate method for calculating the fatigue life was established.

KEY WORDS : Bolted joint, Tightening torque, Clamping force, Fatigue life

1. INTRODUCTION

With the increasing complexity of mechanical assemblies, modular and integrated system technologies have emerged (Gershenson, 2003). However, the use of joints for connecting parts is still prevalent (Kweon *et al*., 2006; Cho *et al*., 2009; Wagle and Kato, 2009). Lap joints are widely used in the joints of structures exposed to external loads because of their ease of manufacturing and excellent resistance to twisting and bending of the overlapped part. Among the types of lap joints, the bolted lap joint is generally preferred owing to its easy assembly and dismantling, convenient maintenance, and moderately low cost (Zaki *et al*., 2010; Ghorbani *et al*., 2016; Yang *et al*., 2016; Yu *et al*., 2018). Additionally, bolted lap joints have superior tensile and fatigue strengths compared to rivet or pin joints (Al-Bahkali, 2011; Esmaeili *et al*., 2014).

However, fatigue failure frequently occurs in bolted lap joints owing to cyclic shear loads. In the case of a single-lap bolted joint subjected to a shear load, secondary bending occurs owing to its asymmetric structure (Ekh *et al*., 2005; Ekh and Schön, 2005; Wang *et al*., 2016; Zhao *et al*., 2016). Secondary bending causes stress concentration around the bolt hole and significantly reduces the fatigue life. Therefore, the double-lap bolted joint is preferred for connecting parts exposed to cyclic shear loads. In the double-lap bolted joint, a member that delivers a load is located between the laps and fixed by a bolt penetrating the parts. By tightening the bolt, a compressive force is applied to the double lap, creating friction on the contact surface between the laps and member. Figure 1 shows the failure stages of the double-lap bolted joint due to the static load. The load from the member is initially transmitted to the double-lap joint by friction, and a slip between the double lap and member occurs when the critical load is reached. After the slip, the bolt makes contact with the bolt hole on the double lap, leading to failure of the bolt, bolt hole, or double lap. In Figure 1, based on the slip occurrence, Stage 1 is called the frictional mode, and Stages 3 ~ 5 are called the bearing mode (Minguez and Vogwell, 2006).

Studies were conducted to evaluate the fatigue life and failure behavior of double-lap bolted joints. Shankar and Dhamari (2002) experimentally investigated the failure pattern of a double-lap bolted joint made of aluminum alloy 7075. An increase in the initial clamping force increased the fatigue life. However, when the clamping force exceeded a certain value, a fretting fatigue mode occurred, and the fatigue life did not increase further. Furthermore, Esmaeili *et al*. (2014) studied the fatigue life of double-lap bolted

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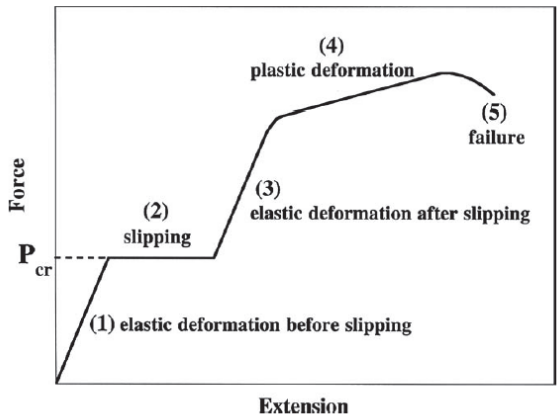


Figure 1. Behavior of a lap joint under loading (Minguez and Vogwell, 2006).

joints according to the tightening torque. They experimentally confirmed that the fatigue strength improved as the tightening torque applied to the bolt increased and proved that the compressive load around the bolt hole reduced the cracking stress using finite element analysis. When lubrication was applied between the double lap and member, the fatigue life was reduced (Chakherlou *et al*., 2011). The reduced friction between the parts promoted the bearing mode, in which the load was directly transferred to the bolt hole.

According to the literature, the complete failure point corresponding to Stage 5, shown in Figure 1, was calculated as the fatigue life of the double-lap bolted joint. However, in the sliding state after slipping, the displacement of parts causes problems in position control, which can lead to damage and accidents in mechanical systems (Wu and Tung, 2002; Spencer *et al*., 2015; Alinia and Guler, 2017; Zare and Allen, 2021). Therefore, it is necessary to understand the fatigue characteristics in the friction mode in which the double-lap bolted joint fully maintains the fastening function. In this study, a special double-lap bolted joint, as shown in Figure 2, was selected as the test specimen. There is a gap between the double lap and member before tightening, and the double lap is elastically bended by tightening to contact and fix the member. This model is defined as an elastically bended double-lap bolted joint, which is designed to be a fixed connections instead of a hinge for load transmission in the automobiles, ships, and construction structures. To the best of our knowledge, a quantitative evaluation of the fatigue life of similar models has not been conducted previously.

In this study, fatigue tests according to cyclic shear load and initial clamping force were performed on an elastically bended double-lap bolted joint. The main purpose was to establish a method to calculate fatigue life that is appropriate for this model through the analysis of clamping force behavior in the frictional mode.

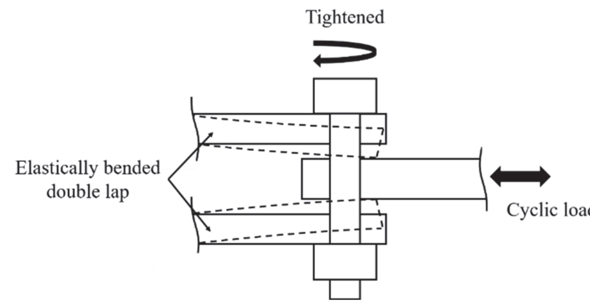


Figure 2. Diagram of elastically bended double lap bolted joint.

2. EXPERIMENTAL SET-UP

2.1. Specimen Preparation

A combination of an actual part with an elastically bended double-lap bolted joint structure was selected as the test specimen. The double lap and loaded member were made of structural steel, and a steel bush was assembled inside the member. M14 steel bolts and nuts were used for the assembly, as shown in Figure 3.

2.2. Condition of the Fatigue Test

Figure 4 shows the constructed test system to perform fatigue tests under cyclic shear loads. The structure with the double lap was fixed to the test bed, and the load was applied using an INSTRON hydraulic tester. The range and period of the cyclic load was selected in consideration of the actual operating environment of the part; the magnitude of the tensile-compressive cyclic load (R = - 1) was 2.94, 3.43, 4.41, and 5.40 kN (300, 350, 450, and 550 kgf), and the load was applied at a frequency of 3 Hz. To determine the behavior of clamping force in the frictional mode, fatigue tests were performed by applying a tightening torque of less than 100 N·m. The torque was adjusted until the clamping force drastically decreased owing to slip. Table 1 summarizes the cyclic load and tightening torque applied in the fatigue test.

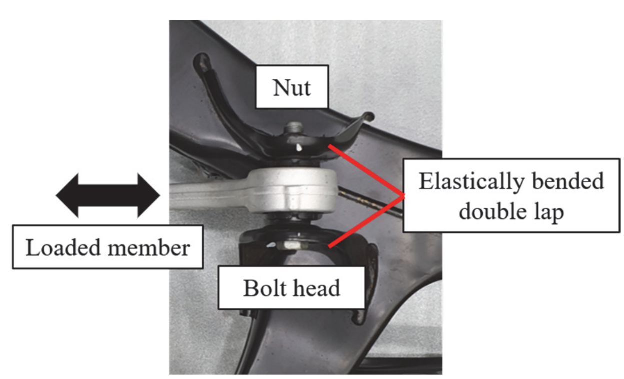


Figure 3. Elastically bended double lap bolted joint.

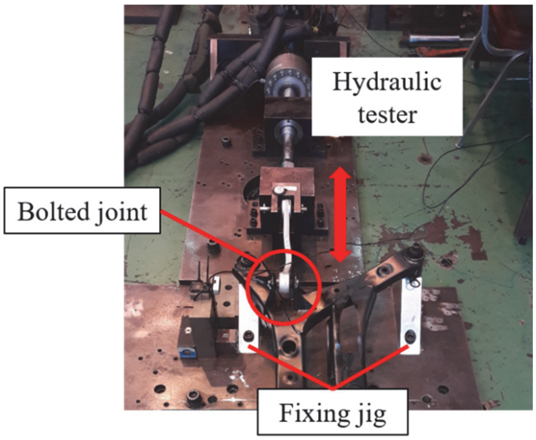


Figure 4. Fatigue test system.

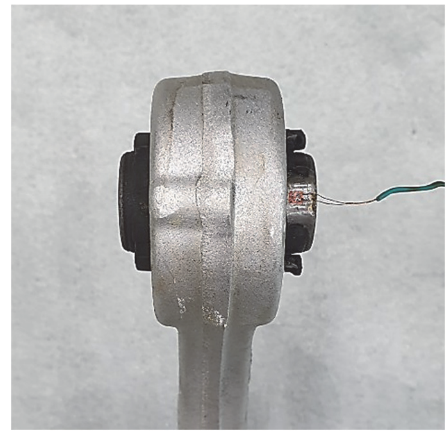


Figure 5. Bush with strain gage attached.

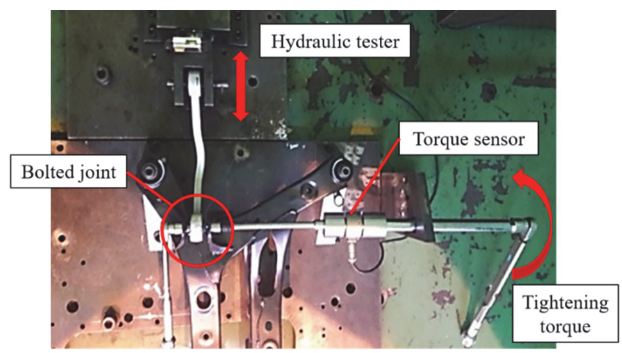


Figure 6. Applying tightening torque to the bolted joint.

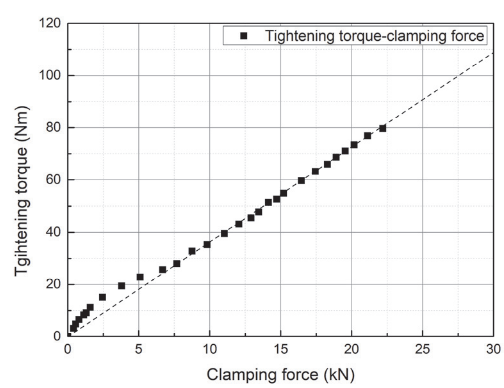


Figure 7. Tightening torque-clamping force relationship.

Table 1. Fatigue test conditions.

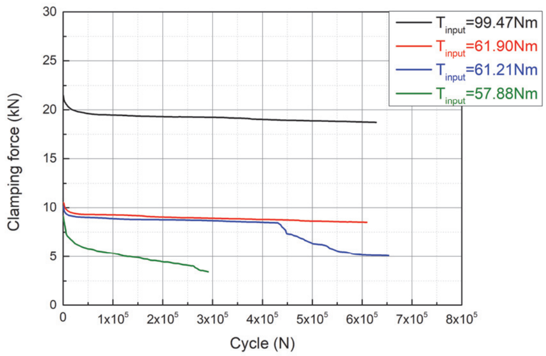
Cyclic shear load [kN (kgf)]	Tightening torque [N·m]
2.94 (300)	99.47
	61.90
	61.21
	57.88
3.43 (350)	99.67
	67.89
	65.83
	61.80
4.41 (450)	90.74
	64.06
	50.52
5.40 (550)	99.67
	69.65
	49.83

2.3. Clamping Force Measurement

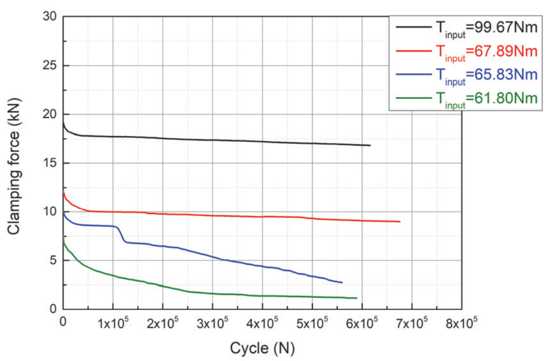
Methods to measure the clamping force of bolts include processing bolts and installing strain gauges or using ultrasonic equipment (Jhang *et al*., 2006; Pitrakkos and Tizani, 2013). The method of processing bolts was excluded because of concerns about test errors due to deformation of the bolts, and a steel bush included in the loaded member was used as a substitute. A compressive load was generated on the bush when the members were fastened between the double laps. The strain in the bush due to this compressive load was measured, as shown in Figure 5. In addition, Figure 6 shows a member with a strain gauge installed on the bolted joint, when a torque was applied using a wrench with a torque sensor attached. The elastic modulus of the bush was 204,000 MPa, and the relationship between the tightening torque and clamping force was determined, as shown in Figure 7, using Equation (1) based on Hooke's strain–stress law (Chakherlou *et al*., 2011; Esmaeili *et al*., 2014)

$$F_{\text{Clamping}} = E_{bush} A_{bush} \varepsilon_{bush} \quad (1)$$

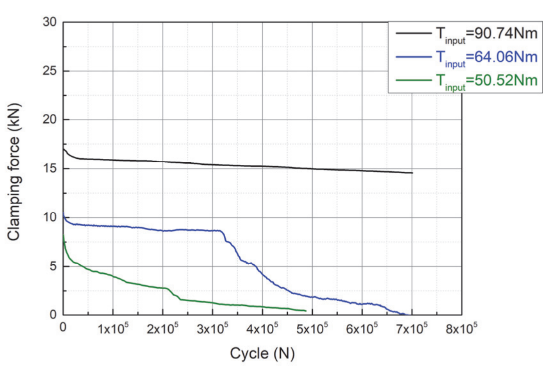
The strain of the bush was continuously measured during the fatigue tests. Finally, clamping force-cycle graphs were derived by converting the strain into a clamping force.



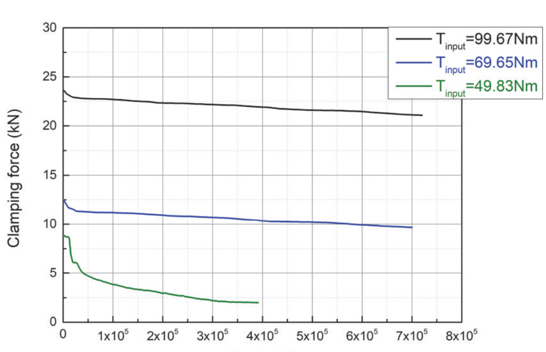
(a) Cyclic load: 2.94 kN



(b) Cyclic load: 3.43 kN



(c) Cyclic load: 4.41 kN



(d) Cyclic load: 5.40 kN

Figure 8. Clamping force-cycle graphs.

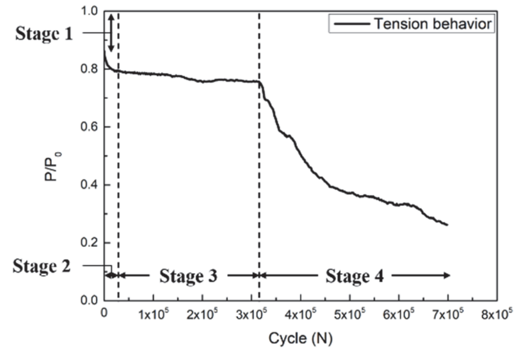


Figure 9. Behavior of the clamping force under cyclic shear load.

3. FATIGUE TEST RESULTS

3.1. Behavior of Clamping Force

Figure 8 shows the clamping force-cycle graphs versus the cyclic shear load and tightening torque. In addition, behavior of the clamping force fraction (%) on the initial clamping force P_0 was divided into four stages, as shown in Figure 9.

In Stage 1, the clamping force is reduced owing to stress relaxation before the start of the fatigue test. Stage 2 is a stabilization section in which the clamping force rapidly decreases immediately after the start of the fatigue test. In Stage 3, the clamping force gradually decreases with a constant slope. Finally, in Stage 4, the clamping force decreases rapidly again, when the clamping force is below a certain value, showing the separation of parts by slipping.

3.2. Type of Failure

After the fatigue test, abrasion occurred on the surface where the double lap and member contacted, as shown in Figure 10, and no failure around the bolt hole was found. Therefore, the fatigue tests were performed in the frictional

Figure 10. State of the lap surface after fatigue tests.

mode and the result data are regarding to the hole edge of the double lap members. Furthermore, the clamping force decreased owing to slip between parts, not failure of parts.

4. ANALYSIS

4.1. Stage 1: Stress Relaxation

The clamping force started to decrease immediately after tightening, and the fatigue test was not started until the clamping force became constant. Stress relaxation occurs in all parts fixed by the clamping force of the bolted joint, and a combination of stress relaxation reduces the clamping force. This stress relaxation is affected by internal factors, such as material and shape, as well as external factors, such as pressure and temperature (Alkelani *et al*., 2008; Liao *et al*., 2019). Tendo *et al*. (2001) experimentally investigated the amount of reduction in clamping force due to stress relaxation in terms of the material and heat treatment of the bolted member. In the case of carbon steel, most of the reduction in clamping force due to stress relaxation occurs within a few hours after tightening. Similarly, in this study, the time required for stress relaxation was confirmed to be approximately 30 min, and the reduction ratio of the clamping force due to stress relaxation in terms of the tightening torque is shown in Figure 11; the range is 1.96 to 5.46 %, and the average value is 3.71 %. After tightening, the stabilization of the contact surface between the double lap and member and the restoring force of elastically bended double lap are considered to influence the reduction of clamping force due to stress relaxation.

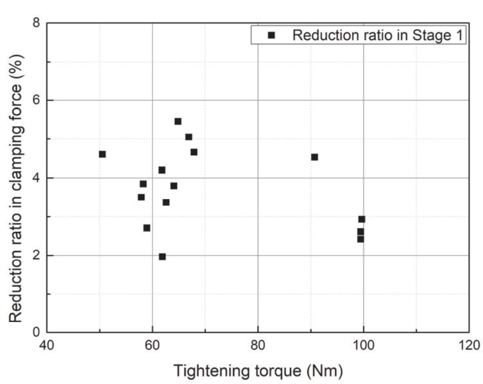


Figure 11. Reduction ratio of clamping force in Stage 1.

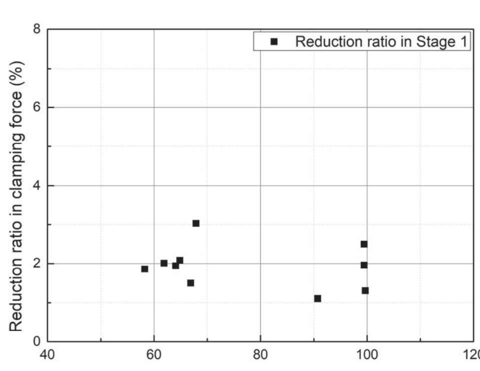


Figure 12. Reduction ratio of clamping force in Stage 2.

4.2. Stage 2: Initial Stabilization

The fatigue test was started after the stress relaxation was completed, and if the initial clamping force was sufficiently large, the clamping force rapidly decreased during the first several hundred cycles. A rapid decrease in clamping force occurs at the beginning when there is no relative rotation between the bolt and nut and during the process of redistributing the stress inside the bolt due to local repetitive plastic deformation between the fastened parts (Jiang *et al*., 2003, 2004). In the fatigue test by shear load, the clamping force decreased in the process of stabilizing the contact area between the fixed parts. Figure 12 shows the reduction ratio of clamping force in Stage 2 in terms of the tightening torque, with a range of 1.10 ~ 3.03 %, where the average value is 1.93 %. There was no correlation between the magnitude of cyclic shear load and the reduction ratio of clamping force.

4.3. Stage 3: Constant Decrease

The clamping force entered a section with a constant slope and gradually decreased because of the localized slip occurring on the contact surface between the double lap and loaded member. The decrease in the slope of clamping force was equal under the same cyclic load. Figure 13 shows the decrease in the slope of clamping force in terms of the cyclic shear load. As the cyclic load increased, the clamping force decreased more, and the cyclic load had a decreasing linear relationship with the slope.

4.4. Stage 4: Slip

While the clamping force gradually decreased, it rapidly decreased immediately after reaching the specific value for each load condition; 8.46, 8.51, 8.65, and 8.70 kN depending on the cyclic shear loads 2.94, 3.43, 4.41, and 5.40 kN. At this point, the localized slip between the double lap and loaded member turned into a complete slip, causing the part to break away. Therefore, the clamping force value for each load condition was defined as the critical force. Figure 14 shows the critical force in terms of the cyclic shear load, whereas an increase in the magnitude of load increases the critical force. In addition, the displacement data of the hydraulic tester piston were recorded during the test for the specimen in which the critical force was found under a load of 2.94 kN, as shown in Figure 15. In this test, the clamping force rapidly decreased as it entered Stage 4 in approximately 430,000 cycles, and simultaneously, the stroke of piston rapidly increased. The friction decreases between the double lap and loaded member owing to the

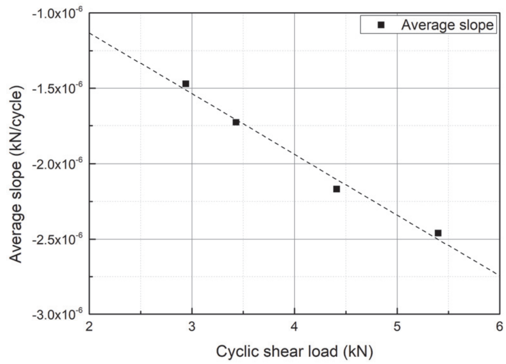


Figure 13. Average slope of clamping force decrease in terms of the cyclic shear load.

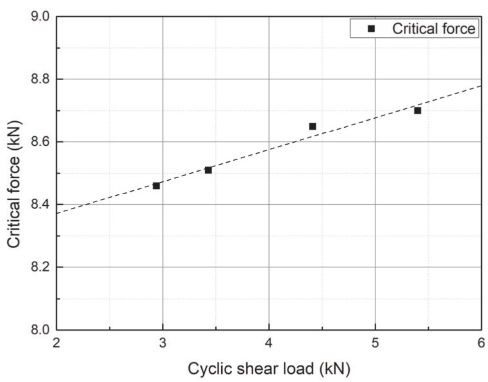


Figure 14. Critical force in terms of the cyclic shear load.

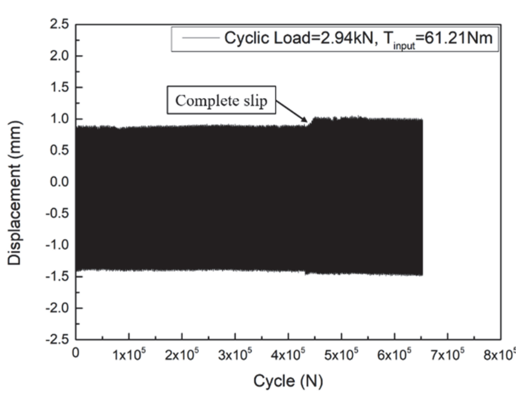


Figure 15. Piston displacement-cycle graph.

cyclic shear load. Finally, the piston stroke increases owing to the separation of parts.

4.5. Fatigue Life Calculation

Based on the clamping force behavior analysis, a method for calculating the fatigue life of the elastically bended double-lap bolted joint was established, as shown in Figure 16. Under the same load, the decrease in the slope of clamping force was constant in Stage 3 regardless of the tightening torque; therefore, the clamping force decreased with a constant slope until it reached the critical force. When the clamping force decreased below the critical force and entered Stage 4, it was considered that the function of the bolted joint was lost due to a slip between the parts. Therefore, the life when the clamping force reached the critical force was set to zero.

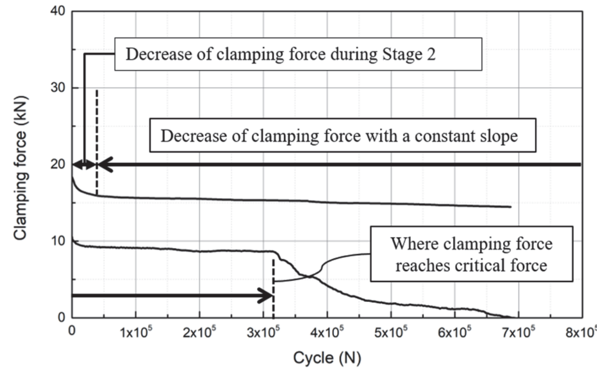


Figure 16. Calculation method of the fatigue life.

Table 2. Fatigue life according to cyclic load and torque.

Cyclic load [kN]	Average slope of clamping force decrease [kN/cycle]	Clamping force [kN]	Fatigue life [Cycle]
2.94	- 1.471(10^{-6})	19.55	7,541,199
		9.33	595,506
		9.06	404,072
		8.46	0
3.43	- 1.727(10^{-6})	17.84	5,401,913
		10.06	893,141
		8.63	63,652
		8.51	0
4.41	- 2.168(10^{-6})	16.00	3,392,630
		9.35	295,316
		8.65	0
5.40	- 2.460(10^{-6})	22.79	5,724,524
		11.34	1,071,669
		8.73	6,438

The reduction ratio of clamping force in Stages 1 and 2 is difficult to formulate because the tendency is not clear. Because the decrease in the slope of clamping force in Stage 3 is considerably small, which occupies the longest section of fatigue life, a small difference in the reduction ratio of clamping force of Stages 1 and 2 can result in a critical error in the fatigue life calculation. Therefore, the

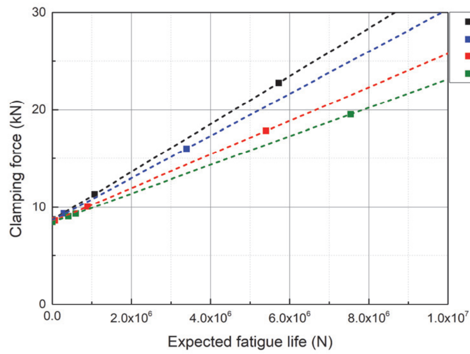


Figure 17. Fatigue life graph.

starting point of the fatigue life calculation is where the clamping force begins to decrease with a constant slope, not the initial clamping force P_0.

The slope of clamping force and fatigue life in terms of the cyclic shear load are listed in Table 2. The fatigue life in terms of the clamping force for each cyclic load is shown in Figure 17. When the clamping force increased and the load decreased, the fatigue life increased. The relationship between the clamping force, cyclic shear load, and fatigue life can be simplified as follows:

$$\mathrm{F} = 8.60 + (0.40 \times \mathrm{P} + 0.29)(10^{-6}) \times N \qquad (2)$$

$(\mathrm{F} = \text{Clamping force in kN})$

$(\mathrm{P} = \text{Cyclic shear load in kN})$

$(\mathrm{N} = \text{Fatigue life in cycles})$

By inserting the expected fatigue life of the elastically bended double-lap bolted joint into Equation (2) under a given cyclic load, the minimum required clamping force can be obtained. In addition, the initial clamping force P_0 can be calculated by inversely adding the reduction ratio of clamping force in Stages 1 and 2 to this value as follows:

$$P_{min} + P_1(\%) + P_2(\%) = P_0 \qquad (3)$$

where Pmin is the minimum clamping force required to satisfy the expected life, P_1 is the reduction ratio of clamping force due to stress relaxation, and P_2 is the reduction ratio of clamping force at the beginning of the fatigue test.

5. CONCLUSION

To evaluate the fatigue characteristics in the frictional mode for an elastically bended double-lap bolted joint, fatigue tests were performed according to the cyclic load and tightening torque. The clamping force formed on the bolted joint was measured in real time to analyze the cause of decrease of clamping force by fatigue stage. The following findings were obtained.

Before the start of the fatigue test, the clamping force decreased by 3.71 % on average because of the stress relaxation of the parts fastened by the bolted joint. During several hundred cycles of the initial fatigue test, the clamping force decreased rapidly by 1.93 % on average, and subsequently decreased slowly at a constant rate. At the same cyclic load, the reduction rate of clamping force was equal regardless of the tightening torque, and the rate of decrease increased linearly as the cyclic load increased. When the clamping force fell below a certain value, a critical force, slip occurred between the double lap and loaded member, which led to a rapid decrease in the clamping force. As the parts were separated by the slip, the piston stroke of the testing machine carrying the load also increased at this point.

The cycles from the point where the clamping force started to decrease constantly until the critical force was reached were considered as the fatigue life. In the section where the clamping force was lower than the critical force was, the cycles were excluded from the fatigue life because structural stability was not secured because of the slip between the parts. By applying the life calculation method, the prediction equation of the fatigue life was derived in terms of the clamping force and cyclic load. The clamping force that satisfies the expected fatigue life under a given cyclic load can be calculated using the derived equation. Moreover, the initial clamping force and can be determined by adding the reduction ratio of clamping force due to stress relaxation and initial stabilization of the fatigue test to this value.

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