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The Reduction of Stress Concentration by Tapering Threads*

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Abstract

For bolted joints failures usually happen at the root of the first bolt thread where the maximum stress concentration occurs. Previously several methods were proposed to reduce the stress concentration through improving bolts and nuts profile. Among those methods, tapering threads have been widely used in mechanical structures. Those types of threads are called CD bolts, which were proposed by Nishida as an effective method for stress reduction. Several experimental studies indicated that CD bolts have higher fatigue strength although little FEM analyses are available. In this study, therefore, the bolted joints with tapered threads are analyzed with the finite element method, and stress reduction effect of CD bolts is discussed with varying geometrical conditions. The reduction of the stress concentration is realized by tapering bolt threads. Then, it is found that the stress reduction is notable when the height of bolt threads is reduced significantly near the bolt head and the nut is closer to the bolt head. According to those results, optimum conditions for stress reduction are discussed. Then, it is shown that the maximum stress can be decreased by 20% compared with the cases of standard bolts and nuts.

Key words: Finite Element Method, Stress Concentration, Machine Element, Fixing Element

1. Introduction

For bolted joints failures usually happen at the root of the first bolt thread where the stress concentration is the largest. In order to prevent those failures, a new shape of bolt was developed by improving fatigue strength. The new method proposed by Nishida was named CD bolt, standing for "Critical Design for Fracture". The stress concentration is reduced because the heights of threads of the bolt are decreased gradually [(1)-(3)]. Experimental results show that CD bolts have higher fatigue strength, and therefore, they have been widely used in several fields [(4)-(6)]. However, detailed analytical research has not been given until now mainly because computers were not developed well when CD bolts were invented.

In this paper, therefore, based on the proposal by Nishida, the bolted joint with tapered threads will be analyzed with the finite element method, and stress reduction effect of CD bolts will be discussed under several geometrical conditions. Then the optimum shape of CD bolt will be decided. Moreover, the effect of nut position on the stress reduction will be discussed, and the best method for stress reduction will be clarified.

2. Analysis method and model

2.1 Analysis method

In this paper, we will employ threaded fastener involving an M12x1.75 (JIS) thread, with a cylindrical clamped member whose inner radius, outer radius, and thickness are 13, 50, 35mm, respectively. The analysis models are simplified and shown in Figure 1. In order to study the stress concentration conveniently, the numbers are given at the roots of threads as shown in Fig.1. There are 8 pitches of nut and 11 pitches of bolt. The normal bolt and nut are shown in Fig. 1(a).

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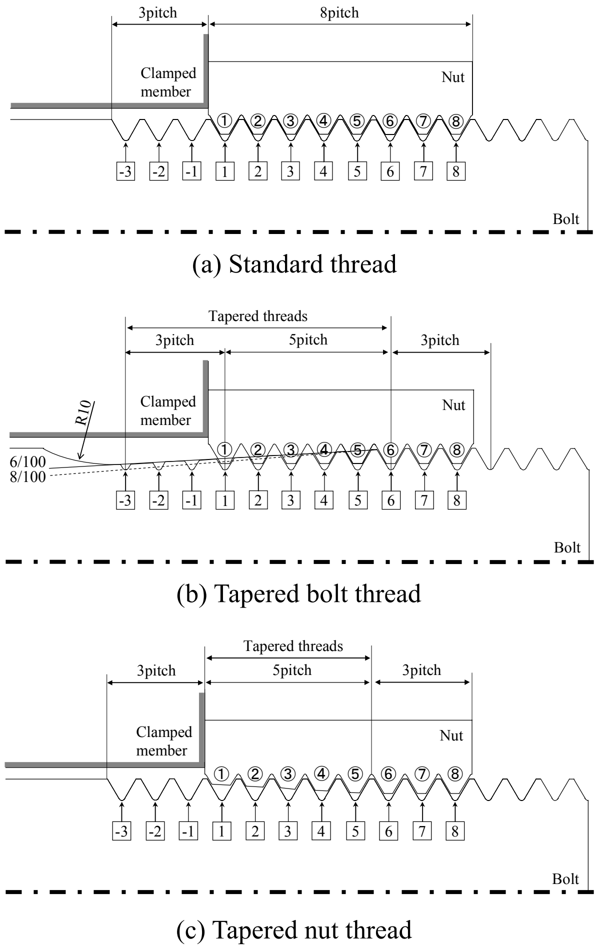
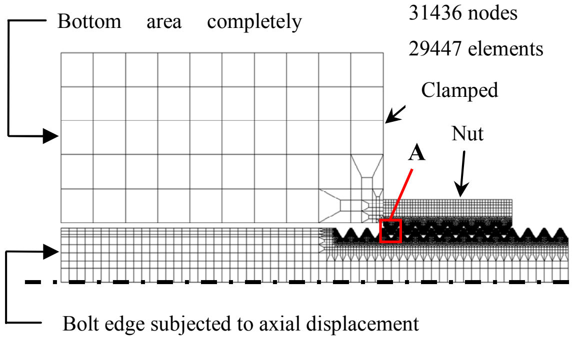


Fig.1 Profile of bolted joint (○: Thread number, □: Root number)

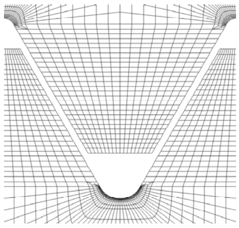
Based on the instruction reducing the height of the threads gradually (2), the tapered bolt is shown in Fig. 1(b) and the tapered nut is shown in Fig. 1(c). Here, the gradient of the taper is 6/100. The heights of 5 pitches are reduced gradually and the other 3 pitches are normal (4). And in Fig. 1(b), there is a gentle circle (R=10mm) between the tapering thread and the bolt head. Similarly, in Fig. 1(c) the heights of nut threads are reduced gradually.

2.2 Axi-symmetric model

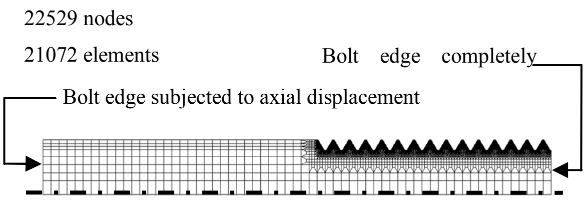
The axi-symmetric models of the normal bolt and nut are shown in Figure 2. The lead angle 2.7° of M12 may be ignored because of minute. The tolerance class is 6H/6g, and the radius ρ is assumed as ρ/p=0.1 at the root of the thread with the pitch of the thread p. The coefficients of friction 0.15 are assumed for all contact surfaces. The Young's modulus is assumed as 205GPa and Poisson's ratio is 0.3 for bolt, nut, and clamped member. In this study, elastic analysis is performed. As shown in Fig. 2(a), the clamped member is fixed and the head of bolt is subjected to bolt axial force (40kN). In order to study the stress concentration in detail, the elements of the root are divided into smaller as shown in Fig. 2(b). In Fig. 2(c), the element model of bolt is shown to study the screw thread of bolts under simple tension. The head of the bolt is subjected to the force 40kN and the other edge is fixed. From the comparison between the results of Fig. 3(a) and Fig.3(c) the deference between the bolt axial tension due to nut and simple bolt tension can be clarified. The element model of the tapering bolt is shown in Fig. 3(a), and the element model of the tapering nut model is shown in Fig. 3(b). The boundary conditions of Fig.3 are the same of the ones of Fig 2.



(a) Bolted joint

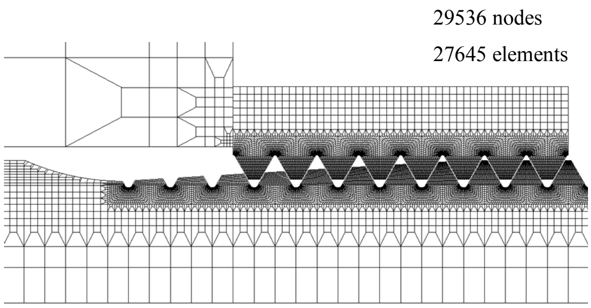


(b) Detail of A

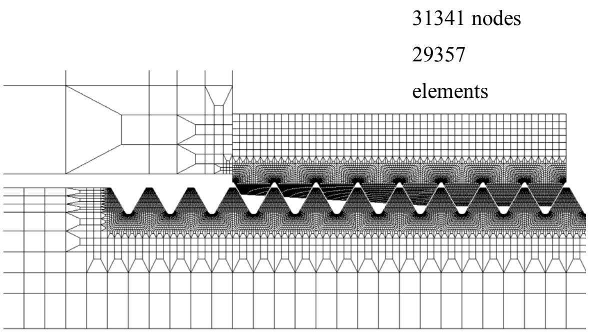


(c) Single bolt under tension

Fig. 2 Axi-symmetric model having standard thread

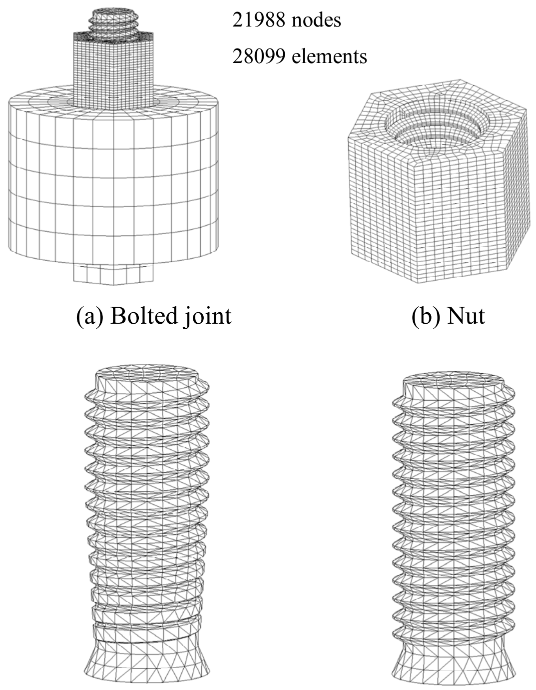


(a) Tapered bolt thread



(b) Tapered nut thread

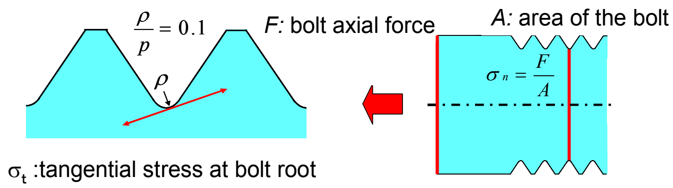
Fig.3 Axi-symmetric model of tapered thread



(a) Bolted joint (b) Nut

(c) Tapered threads (d) Standard threads

Fig.4 Three-dimensional finite element model



(a)Definition of σ_{tmax} (b)Definition of σ_n

Fig. 5 Definition of K_t

2.3 Three-dimensional model

In order to simulate the fastening processes more closely to the real bolt and nut, 3D model is also considered. In Fig. 4, the following models are shown; (a) bolted joint model of taped thread, (b) nut model, (c) tapered thread model, and (d) normal thread model. In the boundary condition, the fastened plate is completely contained, and the nut is rotated to produce bolt axial force 40kN. For the clamped member, inner radius, outer radius, and thickness are 13, 50, and 35 mm respectively. The fasten force 40kN are assumed while the nut is rotated. The tolerance class is 6H/6g, and the radius ρ of the root of the thread is not considered because the stress concentration is not evaluated by 3-D model. Both the coefficients of friction between threads and between the bearing surfaces are 0.15. The Young's modulus and Poisson's ratio of all materials (bolt, nut, and clamped member) are 205GPa and 0.3 respectively. In this study, the elastic analysis is performed.

3. Results and discussion

3.1 Stress reduction effect by tapering threads

In this study, the stress concentration at the root of thread is mainly discussed by using the stress concentration factor K_t defined by Equation (1).

$$K_t = \frac{\sigma_{t\max}}{\sigma_n} \quad (1)$$

Here, σ_{tmax} is the maximum tangential stress appearing at each bolt root as shown in Fig. 5(a), and σ_n is equal to the total bolt axial force (40kN) divided by the area of the bolt (A=72.25mm^2) as shown in Fig. 5(b). It should be noted that total bolt axial force is always used for No.2 – No.8 threads in order to compare the stress at each root although total bolt axial force is carried by the threads from No.1 to No.8 (see Fig.1). The stress concentration factors at each thread root are shown in Fig. 6. The maximum stress concentration always happens at the first root for normal bolt, tapered bolt, and tapered nut. It is seen that the tapering bolt can reduce the stress concentration by 8%. The stress reduction can be observed also at the threads at -3, -2, -1 since the tapered profile is connected to circular arc profile smoothly as shown in Fig.1 (b). On the other hand, it is seen that the tapering nut cannot reduce the stress concentration at No.1 thread as shown in Fig. 6.

The load share rate at each thread is shown in Figure 7. The load share rate of the first thread is the largest of whichever the normal threads and the tapering threads. Also, the load share rates become smaller with the increase of the threads number. However, the load share rate at No.1 thread of the tapering threads is smaller than that of the normal threads. From Figure 6 and Figure 7, it is seen that the stress concentration factor of the bolt tapering threads is smaller than that of the normal threads. However, the stress concentration factor of the nut tapering thread cannot be reduced although the load share rate can be reduced. The reason can be explained in Figure 8. In Figure 8(a), both the magnitude and distance of the contact load F and d for the tapering thread are smaller than those of the normal (F<F′ and d<d′), so that the bending moment becomes smaller and the stress concentration is reduced. On the other hand, in Figure 8

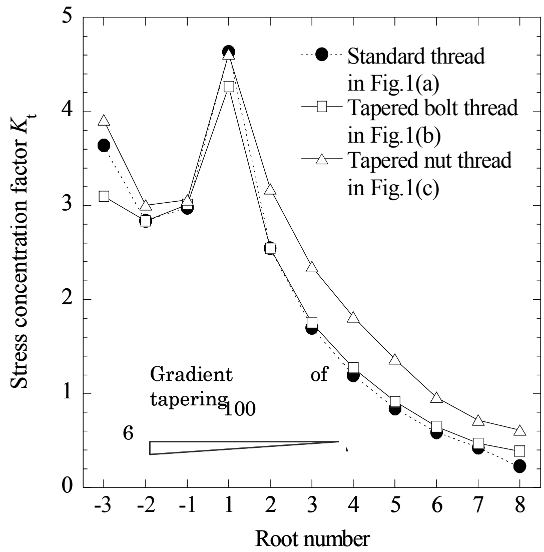


Fig. 6 Stress concentration factors K_t

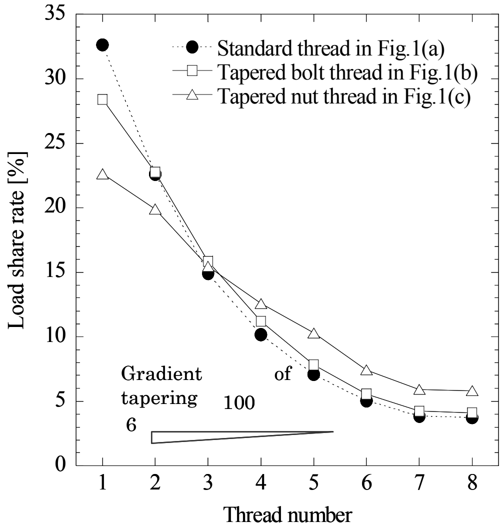


Fig. 7 Load share rate for tapering threads

(b), the magnitude of the load is smaller, but the distance of the force is longer (F<F′ but d>d′). Therefore, the bending moment cannot be decreased and the stress concentration is not reduced. That is to say, the tapering nut threads cannot reduce the stress concentration.

The load share rate for tapering threads is also shown in Figure 9 from 3D model. Here, the results of the normal bolt and the tapering bolt are compared. The result of the tapering nut is not researched because it has little effect on the stress concentration. The gradient of tapering is 6/100 and the situation of the nut and the boundary condition are same as the axi-symmetric model. It is generally known that the load share of the normal bolt is the maximum at the No.1 thread decreasing with approaching to the top of the nut. In Figure 9, the load share of the thread No.1 of the tapering bolt is less than which of the normal bolt. On the other hand, the loads share of the other threads increase. The trends of the 3D model coincide with the one of axi-symmetric. The stress concentration can be reduced by the tapering bolt, because the load share decreases.

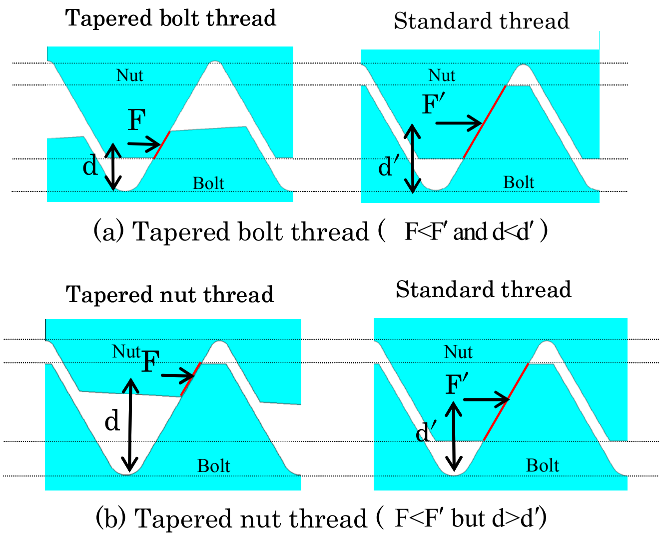


Fig. 8 Profile of tapered threads

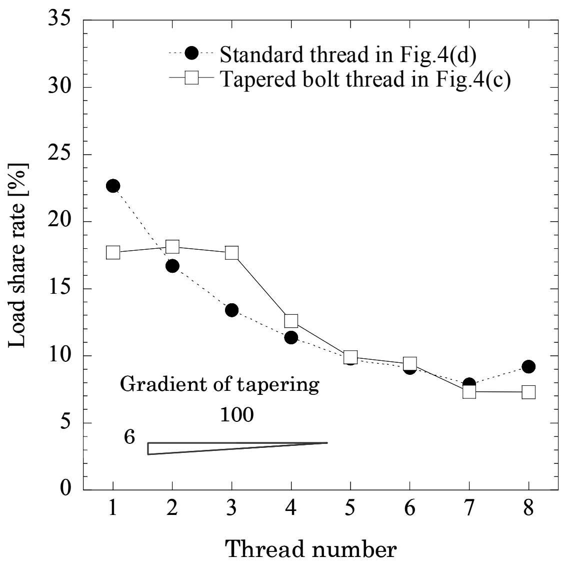


Fig. 9 Load share rate for tapering threads obtained from 3D models

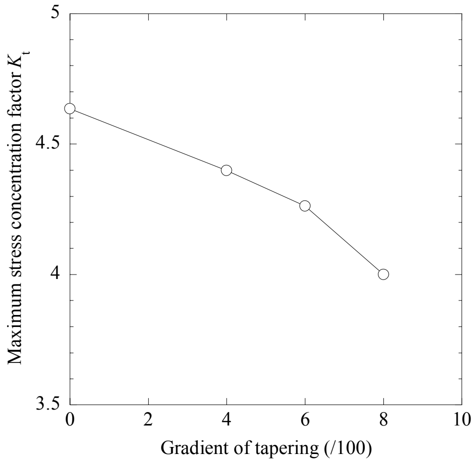


Fig.10 Relation between gradient of tapering and maximum stress concentration factor K_t

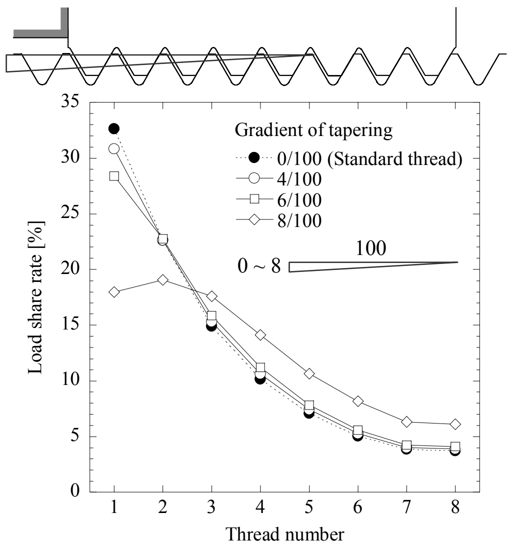


Fig.11 Relation between gradient of tapering and load share rate of mating threads

3.2 The effect of reducing stress concentration by the gradient of the tapering

Figure 10 shows the relationship between the tapering gradient and the maximum stress concentration factor K_t. When the tapering gradient is 0/100 (normal thread), 4/100, 6/100, 8/100, the maximum stress concentration factors are compared. With increasing the tapering gradient, the maximum stress concentration factor decreases. When the gradient is 8/100, Kt is reduced by 14%. Figure 11 shows the relationship between the load share rate and the tapering gradient at each thread. The load share rate of the No.1 thread decreases with increasing the tapering gradient. Decreasing the load share rate causes decreasing the stress concentration. Although the load share rate of No. 2 thread is larger than that of No.1 the stress concentration at the No.1 thread is largest when the gradient of the tapering is 8/100. This is because the total bolt axial force is applied to the cross section of No.1 and also because the compressive stress appears at the No.2 thread if No.1 thread carries some load.

3.3 The effect of reducing stress concentration by the nut position

The nut position shown in Fig.1 is defined as position 0. The position -1 is defined as where 1 pitch toward the head of the bolt, and the position 1 is defined as where 1 pitch reverse to the head of the bolt. Those nut positions are shown in Fig. 12. Figure 13 shows the relationship between the maximum stress concentration factor K_t and the nut position. The stress concentration factor K_t decreases if the nut moves to the reverse side of the bolt head. It is seen that the nut position affects stress reduction. The relation between nut position and load share rate of mating threads is shown in Fig. 14. The load share rate becomes smaller when the nut moves to the reverse side of the bolt head. It is found that the nut should be placed as close to the head of the bolt to reduce the stress.

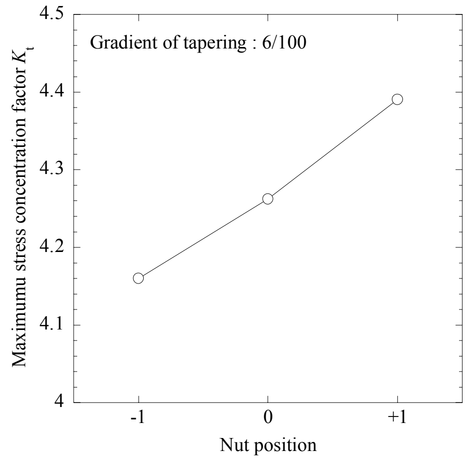


Fig.12 Relation between nut position and maximum stress concentration factor K_t

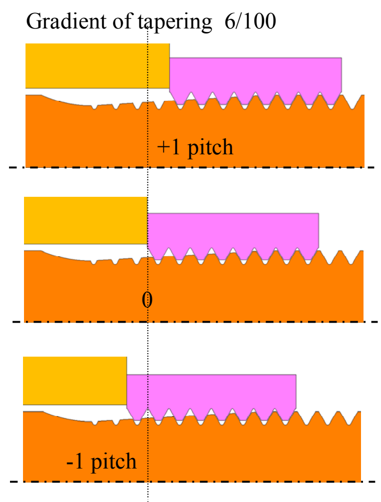


Fig.13 Nut position

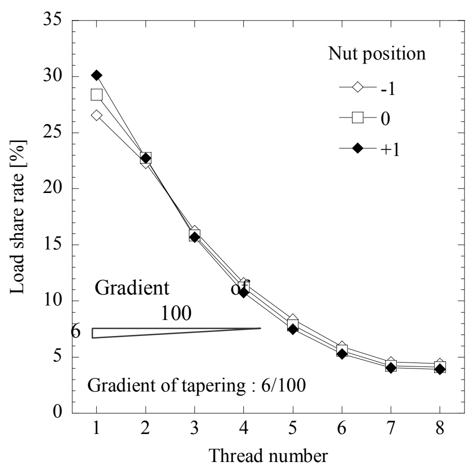


Fig.14 Relation between nut position and load share rate of mating threads

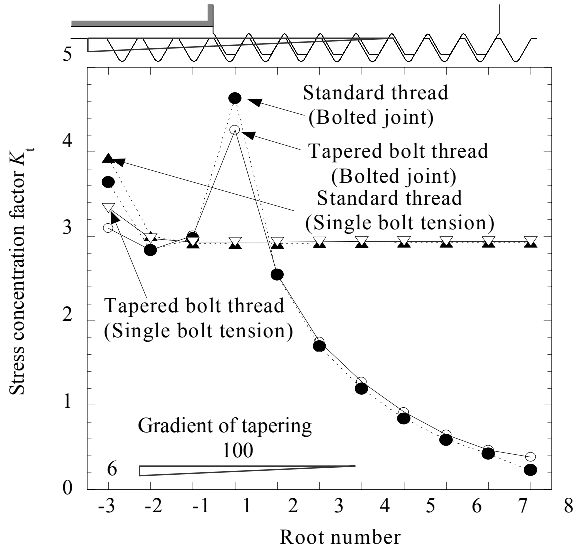


Fig.15 Stress concentration factors K_t for bolted joint and single bolt under tension

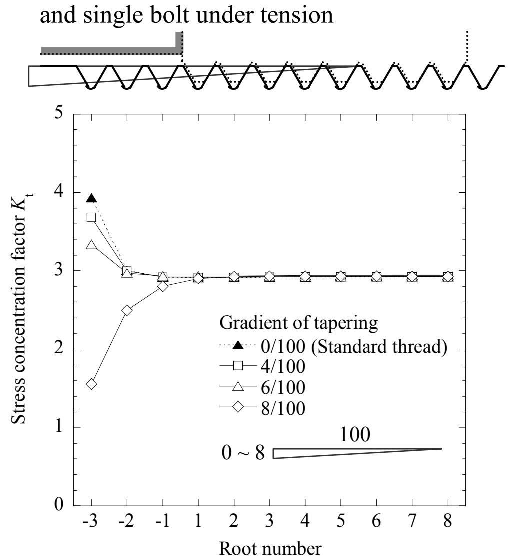


Fig.16 Relation between gradient of tapering and stress concentration factors K_t of single bolt under tension

4. Methods of the reducing stress concentration

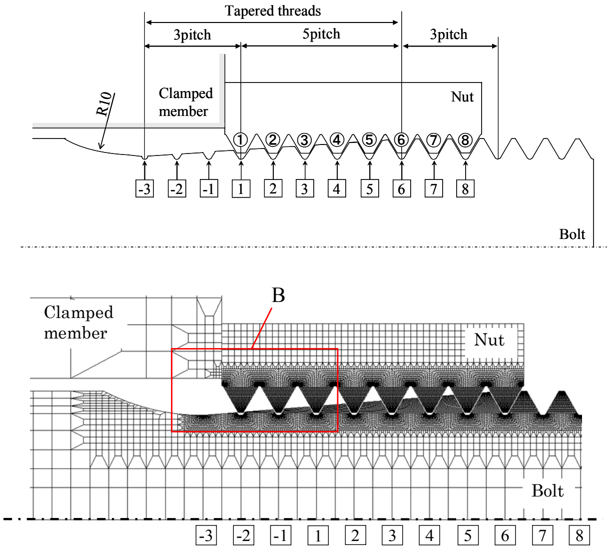
4.1 The cause of reducing stress concentration by the tapering threads

In order to find out the mechanism of stress concentration for bolted joint, a single bolt under tension is also considered as shown in Fig.15[(7)]. Here, the nut with the tapering threads is not investigated because stress reduction cannot be observed. From the comparison between the results of the bolted joint and the normal bolt, it is notable that the maximum stress appears only at the No.-3 root for the single bolt under tension. On the other hand, for the bolted joint it is seen that the maximum stress appears at the No.1 root as well as at the No.-3. It should be noted that the bolt axial force does not change at the cross sections from No.-3 to No.1. Although the total bolt axial force is carried by the contact threads from No.1 to No.8, the stress at the No.1 is larger than that of No.-1. It may be concluded that the stress concentration due to bolted joint is affected by the bending of the thread as the well as bolt axial tensile force.

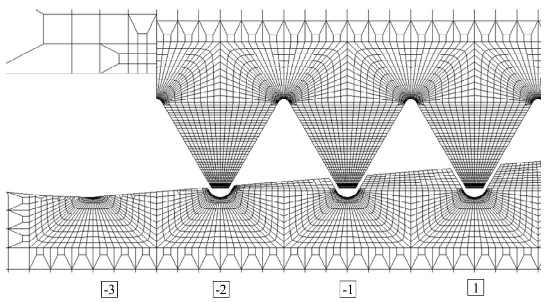
As shown in Fig.15, the stress reduction due to tapering threads is very small at the No.1 thread for the single bolt under tension. Therefore the significant stress reduction observed for bolted joint at the No.1 thread can be regarded as a reduction of bending stress instead of a reduction of tensile stress.

4.2 The methods of reducing stress concentration by the tapering threads

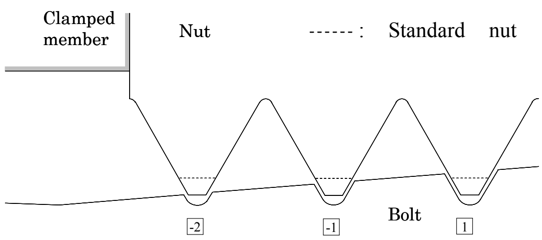
In the preceding section, it is found that the stress due to bending at the No.1 thread may be reduced by tapering thread although the stress due to tension cannot be reduced. Consequently, to reduce the stress more, the stress due to tension should be reduced. In Fig.16 the relationship between the tapering gradient and stress concentration factors K_t are shown for single bolt under tension. When the tapering gradient is 4/100 and 6/100, the stress at each thread root does not change very much. However, when the gradient is 8/100, the stress decreases significantly at the roots of No.-3, No,-2, and No.-1. Therefore it may be



(a) FEM mesh around mating threads



(b) Detail of B



(c) Nut threads profile

Fig.17 Nut threads height where nut position is -2

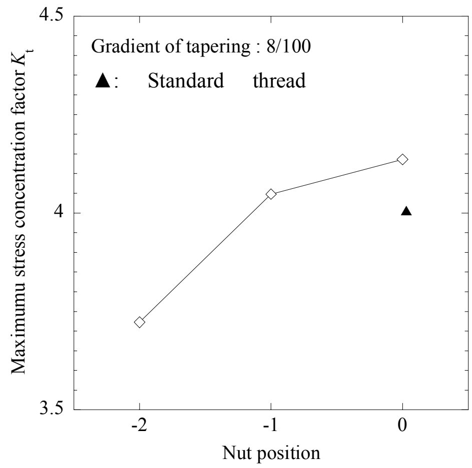


Fig.18 Effect of nut position on maximum stress concentration factor K_t

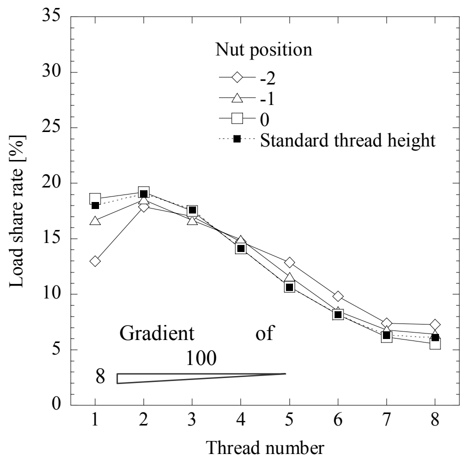


Fig.19 Effect of nut position on load share rate of mating threads

concluded that the stress concentration can be reduced by increasing the gradient of tapering and also placing the nut toward the head of the bolt.

The study model is designed according to Japanese Industrial Standard (JIS). If the nut is placed toward the head of the bolt when the gradient is 8/100, it is seen that the No.-2 bolt thread cannot meet the nut thread as shown in Fig. 17(c). In order to contact the nut thread, the height of the bolt thread is increased exceeding the instruction of JIS. The position of the nut shown in Fig. 1 is defined as position 0. When the nut moves by 1 pitch toward the head of the bolt, the position is called -1. When the nut moves by 2 pitches toward the head of the bolt, the position is called -2. As shown in Fig.17, in order to meet the nut for position -2, the height of the bolt thread is increased by 1.2 times. The effect of nut position on the maximum stress concentration factor K_t is shown in Fig.18 when the gradient is 8/100. In addition, the stress concentration of the normal height is also shown in Fig18 for the position 0. When the height of the thread increases, the stress concentration becomes larger. However, the maximum stress concentration K_t increases by placing the nut toward the head of bolt. For the position -2, the stress concentration reduces by 20%. The effect of nut position on load share rate of mating threads is shown in Fig.19. The load share of the No.1 thread decreases when the nut moves to the head of the bolt. It may be concluded that the stress concentration can be reduced by decreasing the load share.

From this study, to improve the stress reduction it is effective to place the nut toward the head of the bolt where the bolt thread height is very small but contact the nut slightly.

5. Conclusions

CD bolts, which are proposed to reduce stress concentration, are studied with FEM in this paper. Moreover, the various conditions are investigated in order to improve the ease capability of stress concentration. And the following conclusions are drawn.

(1) M12x1.75 (JIS) threaded fastener are employed. When the gradient tapering is 8/100, the stress concentration decreases 14%.

(2) Nut with the tapering threads can not reduce the stress concentration. The moment at the first thread becomes lager with decreases of height of nut threads.

(3) When the nut position moves to the head of the bolt and the height of bolt thread is lower, the stress concentration can be reduced larger. In this study, the stress concentration can be reduced by 20%.

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