Modal Experiments and Finite Element Analysis of the Bolted Structure Considering Interface Stiffness and Prtension

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Abstract: *It is particularly important to evaluate natural frequencies and natural modes of the structure of bolted joints to avoid the failures of the structure due to the resonance. The vibration characteristics of bolted structures are closely connected to surface roughness of contact interfaces, the magnitude of pretension of the bolts and the number of clamping bolts. In this paper, the effect of the factors above on the natural frequencies of bolted structures is systematically investigated by experiments. Then, the finite element method is applied to analyze the effect. Finally, the numerical method is validated by experimental measurements of the natural frequencies.*

Key words: surface roughness; pretension; natural frequency; FEM; bolted structures

1 Introduction

For some reasons, few studies have been devoted to elucidating the natural frequencies of bolted joints. Most researchers are interested in detecting joint imperfections, evaluating bolted clamping force variations due to vibration forces, and suppressing the resonance. However, when designing machinery and structures, it is particularly important to evaluate natural frequencies of bolted joints in service condition with practical accuracy to avoid the failure due to resonance. Recently the finite element method has been applied extensively to analysis of vibration problems of complex structures. Bolts used to connected parts are often simplified as beam elements or combination spring elements and then both end nodes of the elements are coupled with nodes of clamped parts along bolt holes [1~3]. However, it is premature to say that the numerical method has been established without considering surface roughness at the interface and axial bolt force.

In this paper, as a first step, modal impact experiments are conducted to examine the effect of surface roughness, axial bolt force and multiple bolts on natural frequencies of bolted joints. Second, the interface stiffness and contact pressure are evaluated. Then the finite element method (FEM) is applied to analyze the natural frequencies and the vibration modes of the bolted joints. At last, the validity of the proposed numerical method is demonstrated by comparing the natural frequencies of bolted joints with experimental results.

1.1 Test specimens of bolted structures

The test specimen is composed of two plates which are clamped with $M16$ bolts. The size of the two plates is the same, as shown in Figure 1. The surface roughness is different for each plate. R_{som}, which is the sum of maximum height roughness of the mating surfaces, is adopted to quantitatively evaluate the interface stiffness. Measured values of R_{som} are 25 μm and 50 μm, respectively. The clamping bolts can be mounted to bolt hole positions 1, 2, 3, 4, 5, 6 separately.

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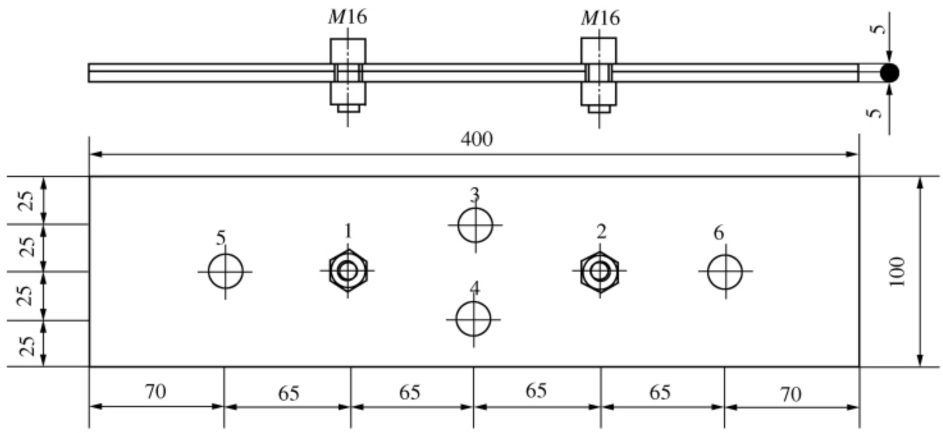

Figure 1 Configuration of bolted joints model

1.2 Experimental setup and measuements

The experimental setup is shown in Figure 2. Specimens are suspended with two elastic ropes. An accelerometer is stuck to the surface of the plates. Axial bolt pretension is carried out by using a torque spanner. A measuring instrument produced by LMS international is used to measure the natural frequencies directly. Impact excitation is implemented by a special hammer. First, two $M16$ bolts at positions 1, 2 are installed. Axial bolt force is increased from 0 to 48 kN gradually. The condition of axial force $F_b = 0$ corresponds to "hand tight". Second, from positions 3 to 6, bolts are installed in ones. All axial bolt forces are the same as 48 kN.

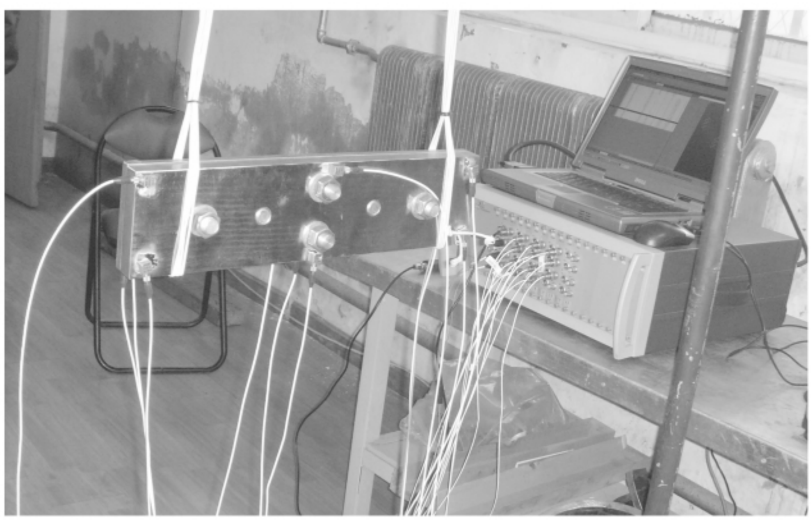

Figure 2 Setup for modal experiments

1.3 Experimental results

Figure 3 shows the effects of axial bolt force on the first three orders of modal frequencies of the specimens, excluding modal frequencies of rigid body. All natural frequencies increase with the increment of axial bolt force. At the beginning period the change is obvious. In the second half there is no radical change. The values of natural frequencies approach to a constant. The specimen with smaller surface roughness generates higher natural frequencies than the one with larger surface roughness. Figure 4 shows that natural frequencies of specimens also increase as the clamping bolts are added. When the bolts were installed to position 3 and position 4, respectively, the change of the natural frequencies is insignificant. However, when they are installed to position 5 and position 6, respectively, the increment of natural frequencies is obvious. It is clear that the distance between the latter and position 1 or position 2 is larger than that between the former and position 1 or position 2. The experimental results are summarized as follows.

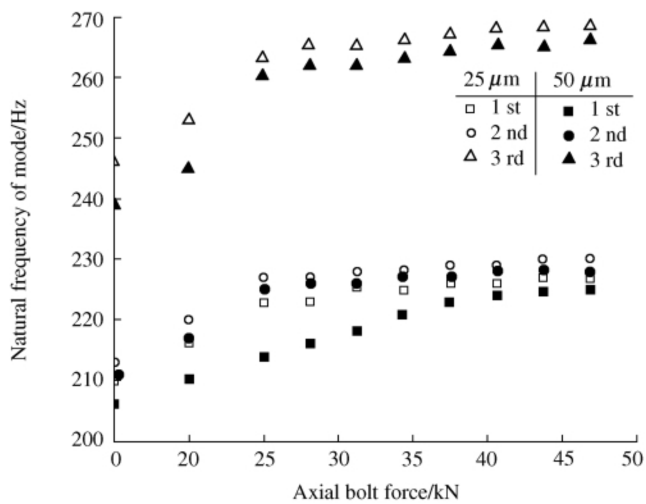

Figure 3 Experimental results of natural frequency with increment of axial bolt force

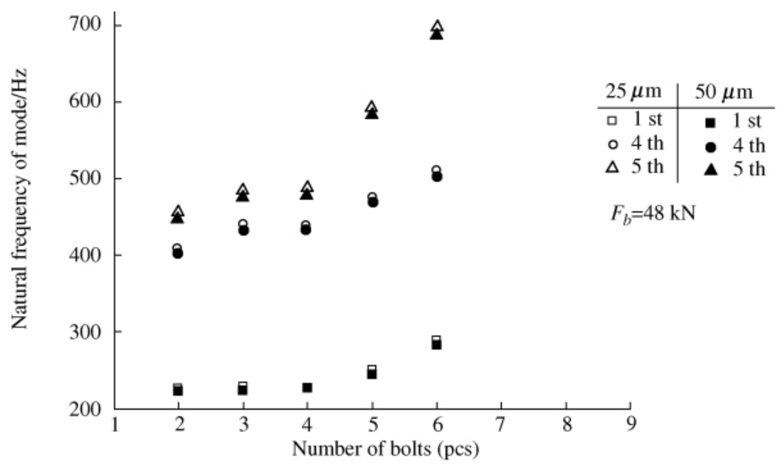

Figure 4 Experimental results of natural frequency with increment of bolts

1) Natural frequencies of the bolted structure are close to constant values beyond some amount of axial bolt force.

2) The model with smaller surface roughness produces higher natural frequencies than that of the larger.

3) The natural frequencies of the structure with bolted joints increase with the increment of the installed bolts. But the increment of natural frequencies is close to the position of mounted bolts. The larger the distance, the more obvious the effect.

2 Modal analysis of bolted structures with finite element method considering interface stiffness and preload

2.1 Evaluation of interface stiffness

The increase of natural frequencies of the bolted structure is primarily due to the crush of asperities at the mating surface when the axial bolt force is increased. The relation between interface $\delta(\mu\mathrm{m})$. and contact pressure p_n (MPa) is related to the following equation proposed by Ostrovsk [4].

$$\delta = cp_n^m \tag{1}$$

Where c and m are constants. These constants can be expressed as an equation of R_{som} proposed by Tangiguchi *et al* [5,6].

$$\begin{cases} c = 0.0674R_{som} + 0.413 \\ m = 0.0155R_{som} + 0.155 \end{cases} \tag{2}$$

The maximum value of m is set to 0.5 [7]. The spring rate in the normal direction, k_n is expressed as follows.

$$k_n = \frac{\mathrm{d}F_n}{\mathrm{d}\delta} = \frac{A}{mc}p_n^{1-m} \tag{3}$$

F_n is the normal force exerting on the mating surface, A is the contact area. Meanwhile, the spring rate in the tangential direction, k_t can be related to k_n using the below equation by Kirsanova and Back. They suggest that the surface deformation in the tangential direction, ζ, can be expressed as the product of shear stress p_t and shear compliance k_t in the tangential direction [8].

$$\zeta = k_t p_t \tag{4}$$

Back proposes an equation that links k_t to p_n in terms of constants R and s given for each material [7].

$$k_t = \frac{R}{p_n^s} \tag{5}$$

The equation for calculating k_t is derived as the product of the first derivative of p_t with respect to ζ and contact area A. Using (4) and (5), the expression for k_t is derived, and then it is related to k_n, assuming that ζ is independent of p_n.

$$k_t = \frac{cm}{R}p_n^{m+s-1} \times k_n \tag{6}$$

According to Back´s research [7], s is 0.5 and R is calculated by the following equation.

$$\frac{R}{cm} = 2(1 + \upsilon) \tag{7}$$

Where υ is Posson´s ratio. It is evident that k_n and k_t can be calculated when roughness R_{som}, contact pressure p_n and contact area A are known.

2.2 FEM model

Figure 5 shows a bolted structure composed of two plates. According to the pressure cone theory, when a bolted preload is applied, the zone (clamp solid) under compressive stress widens from the bolt head or the nut toward the interface and has the shape of a paraboloid of revolution. For the calculation, clamp and deformation solids are equated in a simplified manner and substituted in a further step by a substitutional deformation cone. In the clamping region the axial compressive stress in cross section decreases linearly outward in the radial direction [9~11]. The maximum pressure $p_{\max}$ occurs along the bolt hole, and p at the radial position of r is calculated for given bolt force F_b as follows [12]. The angle of frustum cone θ is assumed to be 30° [9].

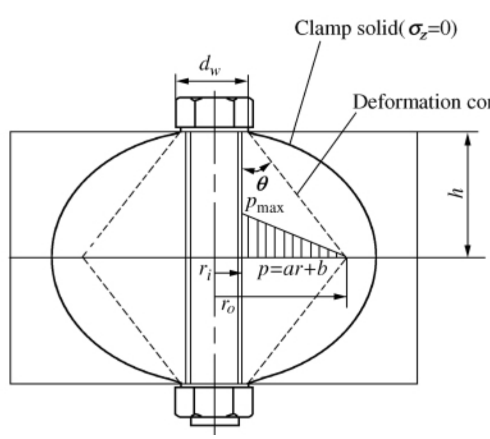

Figure 5 Clamp solid and calculation model at a bolted joint

$$p_{\max} = \frac{3F_b}{\pi(r_o^2 + r_o r_i - 2r_i^2)} \tag{8}$$

$$p_n = -\frac{p_{\max}}{r_o - r_i}(r - r_o) \tag{9}$$

$$r_o = \frac{d_w}{2} + w \cdot \tan\theta \tag{10}$$

r_o and r_i are radii of bolt hole and outer end under contact pressure. In the next finite element analysis (FEA), the magnitude of p_n at each node is calculated using (9). Contact area A in (3) is equated to the corresponding area of each contacting node. Using p_n, the spring rates, k_n and k_t which represent the interface stiffness in the normal and tangential directions, are calculated by (3) and (6). Considering the primary purpose of the present study is for calculating natural frequencies and natural modes of bolt joints, assuming the following.

1) A connection bolt is equated as a link8 element in the FE model [ANSYS is used in this paper]. All nodes in the interface between nut or bolt head and plates are coupled with end nodes of link8 element respectively [10, 11], as shown in Figure 6.

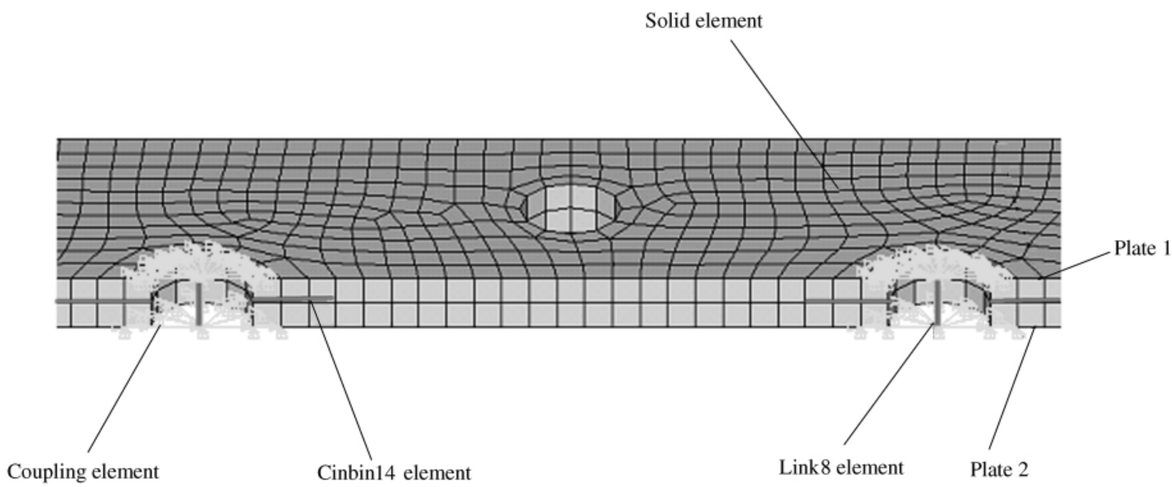

Figure 6 Finite element model of bolted joints

2) Only the interface stiffness between plates is taken into account which has the primary effect on the mode.

3) The preloads of bolts are applied by the decreasing temperature method [14, 15]. It is described as the following equation.

$$\Delta T = -\left(\frac{F_b}{\alpha E A_b} + \frac{F_b}{\alpha l c_p}\right) \tag{11}$$

ΔT is the reduction of temperature, α is the coefficient of expansion, E is Young's modulus of bolts, A_b is cross-section of bolts, l is length of the bolt, c_p is the stiffness of connected structures. ΔT is loaded to link8 elements.

Figure 6 illustrates the FEA model. A pair of nodes, placed on the mating surfaces of two plates, is connected by three springs (combin14 element). Two of them are in the tangential direction. One is in the normal direction.

3 Numerical results

3.1 Effects of surface roughness, axial bolt force and the numeber of tightening bolts

Figure 7 shows the numerical results of the plates connected by two bolts. Natural frequencies of the plates are increased with increment of axial bolt force. Figure 8 indicates that change trend of natural frequencies is same as the experimental results when the number of the pretension bolts is added.

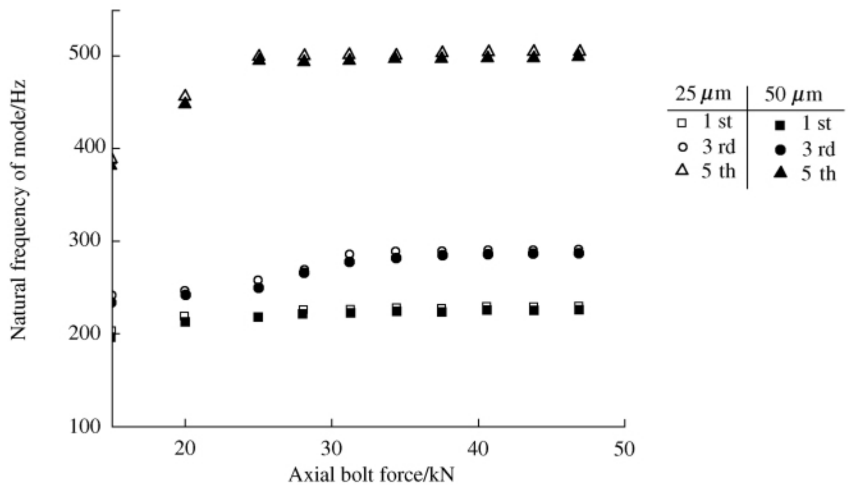

Figure 7 Numerical results of natural frequency with increment of axial bolt force

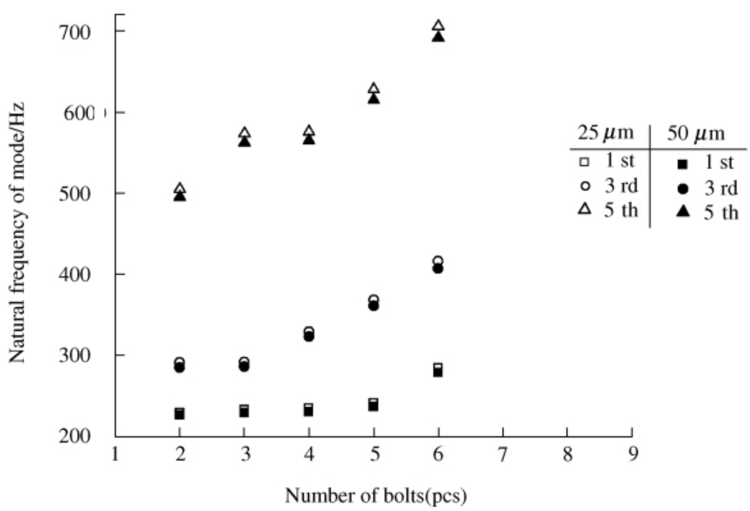

Figure 8 Numerical results of natural frequencies with increment of bolts

3.2 Comparison of experimental and numerical results

Figure 9 shows the compares of numerical and experimental results when the axial bolt force is increased, where the R_{som} is set to be 25 μm. Figure 10 compares the results as the number of mounting bolts is increased. The results indicate that FEM could well evaluate the effects of axial bolt force, surface roughness, bolt position and number of bolts on the magnitude of natural frequencies of bolted joints.

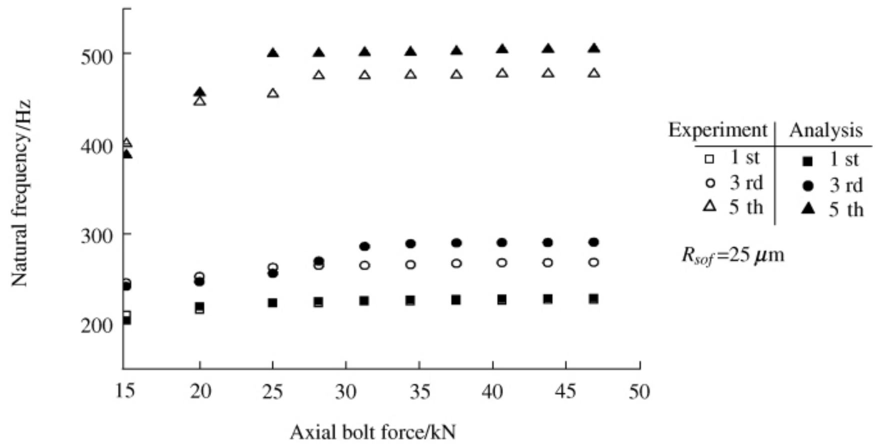

Figure 9 Comparison of experimental and numerical results of natural frequencies with increment of axial bolt force

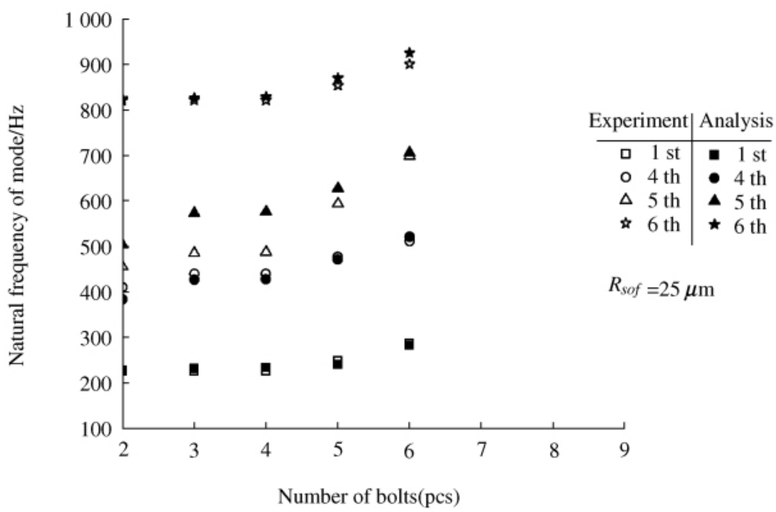

Figure 10 Comparison of experimental and numerical results of natural frequency with increment of bolts

4 Conclusions

1) The effects of surface roughness, axial bolt force, bolt position and bolt numbers on the natural frequencies of bolted structures are quantitatively examined by free mode experiments. Experiments indicate that their effect can not be ignored while considering the natural mode of bolted structures.

2) Natural frequencies of bolted structures increase with increments of axial bolt force. However, they almost reach to constants when axial bolt force is beyond a certain value.

3) Natural frequencies of bolted structures are incremental with the increment of mounted bolts, while the bolt position must be considered.

4) The validity of the FEM method is demonstrated by measuring natural frequencies of modes in this paper, which can be used to simulate the effects of surface roughness, axial bolt force and multiple bolts on natural frequencies of bolted structures.

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