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Numerical Simulation for Self-Loosening Phenomenon Analysis of Bolt Joint under Vibration

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***Abstract*—**In this paper, the finite element method (FEM) is utilized to simulate the comprehensive process including tightening, releasing and self-loosening of a bolt joint under transverse vibration. Following to the accurate geometry of helical threads, an absolutely hexahedral meshing is implemented. The accuracy of simulation process is verified and validated by comparison with the experimental results on clamping force-vibration relationship, which shows the sufficient correlation. Further analysis with different amplitude and frequency of transverse vibration is done to determine the dominant factor inducing the failure.

***Keywords*—**Bolt self-loosening, contact state, FEM, transverse vibration.

I. Introduction

THE bolt joint is a very popular engineering component used in many industrial fields as a result of outstanding features such as low cost, easy installation. However, one of the most severe problems of bolt is self-loosening phenomenon under vibration, which leads to unwanted failure of machines and structures especially in harsh working conditions. Many experiments had been implemented to analysis the bolt self-loosening phenomenon. However, experimental methods are expensive, time consuming and hard for parameterization. Besides that, experiments are not able to give the insight information of process. Numerical methods have been becoming popular as the result of rapidly development of hardware and software capabilities. FEM effectively analyzes the bolt self-loosening phenomenon under the different amplitude and frequency of vibration. However, in order to gain the reliable simulation result, some challenges have to be coped with. The first one is to model precisely the dimension of threads and then generate the unified meshing with all hexahedral elements. Fukuoka successfully proposed equations modelling the precise dimension of thread and meshing method [1]. The second mission is to define the nonlinear contact between threads, which determines to the slip between them. The final challenge is to build up the comprehensive process to simulate the loosing phenomena of bolted joints. Some studies tried to simulate the failure of bolted joint under transverse vibrations. But the process is not complete and the correlation between the simulation result and experiment result is not proven [2]-[4]. In addition, only when the reliable simulation process is completely built up are the further investigations with different parameters of transverse vibration carried out. In this research, the simulation result of clamping force matches well with the simulation result. Then the effects of both frequency and amplitude of transverse vibration are analyzed to determine the dominant factor.

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II. Three Dimensional FEM

A. Equation of Thread Cross Section Profile Dimension

The dimensions of thread profiles are followed by ISO 68, 261, 262 and 724, which creates a two-dimensional (2D) base circle, shown in Fig. 1. The base circle is divided into four sections: *B-C* (thread shank), *C-C'* (crest), *C'-B'* (thread shank) and *B'-B* (root radius). The set of points in base circle is continuously calculated by (1) then imported to three-dimensional (3D) design software Solidworks to create a plane bounded by the base circle. The plane is exported to meshing software Hypermesh to obtain the 2D meshing plane.

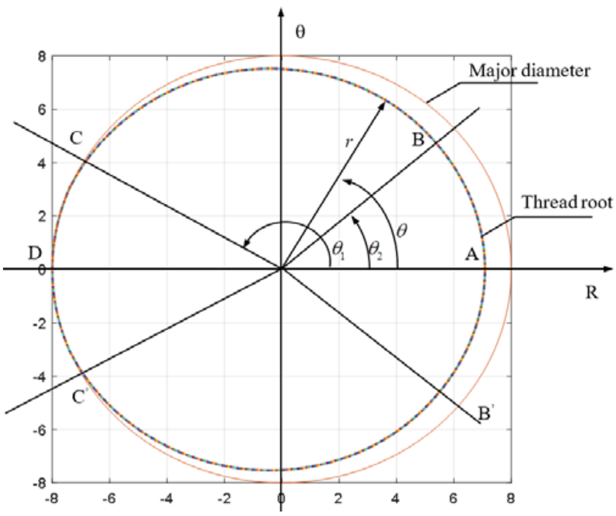

Fig. 1 Profile of the cross section of external thread

The distance between the center and a point of the base circle of the external threads smoothly varies following to the set of equation (1). The profile of internal thread also defined by the same type of equations (2) [1]:

$$r=\begin{cases}\dfrac{d}{2}-\dfrac{7}{8}H+2\rho-\sqrt{\rho^2-\dfrac{P^2}{4\pi^2}\theta^2} & (0\le\theta\le\theta_1)\\[2mm] \dfrac{H}{\pi}\theta+\dfrac{d}{2}-\dfrac{7}{8}H & (\theta_1\le\theta\le\theta_2)\\[2mm] \dfrac{d}{2} & (\theta_2\le\theta\le\pi)\end{cases} \qquad (1)$$

$$\theta_1=\frac{\sqrt{3}\pi}{P}\rho \quad \theta_2=\frac{7}{8}\pi \quad \rho\le\frac{\sqrt{3}}{12}P \quad H=\frac{\sqrt{3}}{2}P$$

where d and H represent nominal diameter and thread overlap.

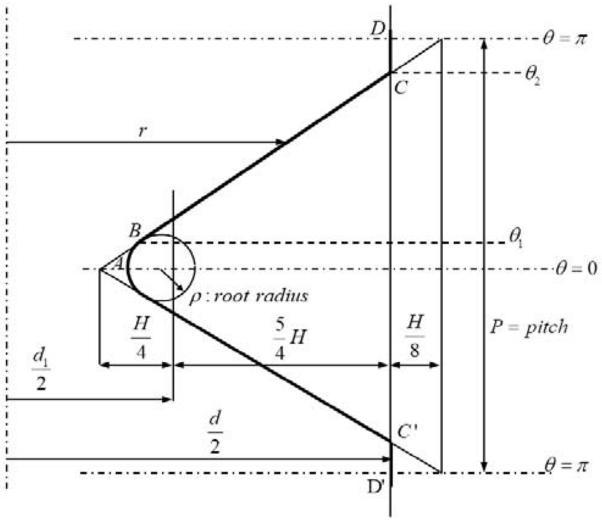

Fig. 2 Cross section of thread along the bolt axis

$$r=\begin{cases}\dfrac{d_1}{2}=\dfrac{d}{2}-\dfrac{5}{8}H & (0\le\theta\le\theta_1)\\[2mm] \dfrac{H}{\pi}\theta+\dfrac{d}{2}-\dfrac{7}{8}H & (\theta_1\le\theta\le\theta_2)\\[2mm] \dfrac{d}{2}+\dfrac{H}{8}-2\rho_n+\sqrt{\rho_n^2-\dfrac{P^2}{4\pi^2}(\pi-\theta)^2} & (\theta_2\le\theta\le\pi)\end{cases} \qquad (2)$$

$$\theta_1=\frac{\pi}{4} \quad \theta_2=\pi\left(1-\frac{\sqrt{3}\rho_n}{P}\right) \quad \rho_n\le\frac{\sqrt{3}}{24}P$$

where ρ_n is the root radius of internal thread

B. 3D Accuracy Geometry of Helical Thread

The first part needed to create is a one-pitch model. Firstly, the 2D base meshing plane is offset by the length of $P/16$ to obtain the second meshing plane. Secondly, the second meshing plane is rotated anticlockwise by an amount of $2\pi/16$ radian. The third step is to make 3D meshing slice between the 2 meshing planes. Applying these three steps again to the second meshing plane is carried out to obtain the second 3D meshing slice. One-pitch model is generated by combining 16 meshing slices. This method is utilized to create both internal and external one-pitch model.

In order to reduce to number of elements in low gradient area, the mesh refinement level is deteriorated from outside to inside for the bolt and from inside to outside for the nut. Each of mesh refinement level parts are created separately and then combined by merging the same node as Fig. 3. The same procedure is applied for create the meshing of the bolt head and body. Finally, all meshing parts are merged to generate the complete model as Fig. 4.

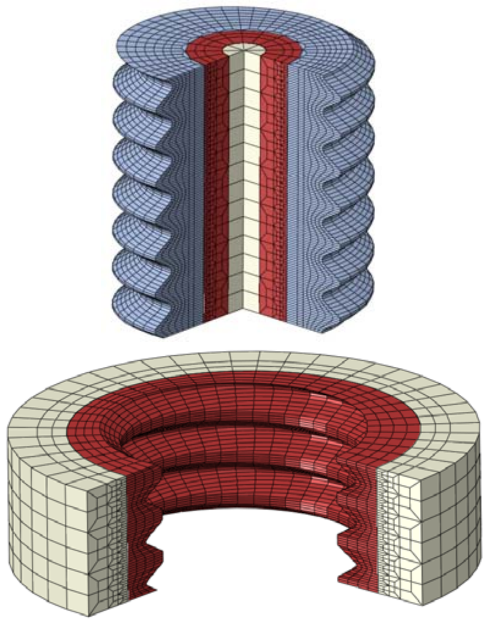

Fig. 3 Internal and external threads with different mesh refinement

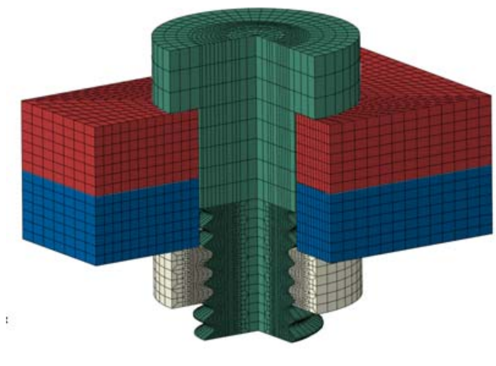

Fig. 4 The complete model of bolt and nut

III. Tightening Process Simulation

The ultimate goal of this research is to simulate the bolt self-loosening phenomenon under transverse vibration. Hence, the first mission is to complete the tightening process simulation. The reason leading to bolt self-loosening failure is the slipping between internal and external thread, so it is critical to model the accuracy dimension of threads, the contact condition with the appropriate friction coefficient between threads. Therefore, the accuracy of FEM and the contact condition is verified by the correlation between experiment and simulation results on torque-tension relationship.

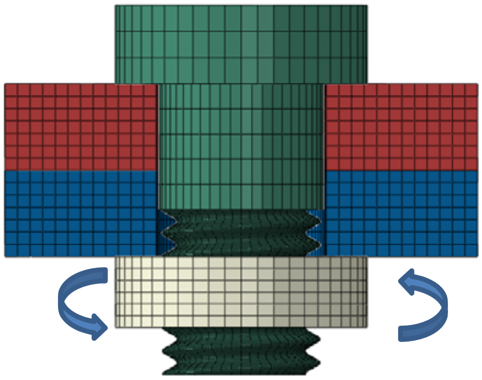

Fig. 5 The loading diagram

In this simulation, the bolt head is fixed, the nut is applied a torque for tightening. The size of bolt is M10x1.5, the thickness of each plate is 10 mm, the value of torque is in the range 0 ~ 60 Nm. The contact set up in Abaqus is surface-to-surface contact, finite sliding formulation, penalty friction formulation and Augmented Lagrange constraint enforcement method. The simulation investigates the friction coefficients being 0.1, 0.12, 0.14, 0.16. The relation between torque and clamping force is extracted to compare the simulation and experiment result. The data of experiment are from [2] with the same installation and dimension. Fig. 6 shows the good agreement between simulation data and experiment data of the relation clamping force – torque. This alignment proves that the model of dimension, contact condition and boundary condition is reliable.

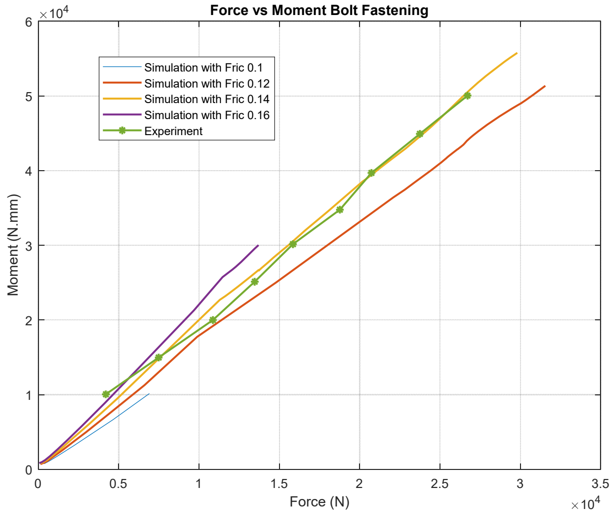

Fig. 6 The comparison between experiment and simulation of the relation clamping force – torque

IV. Bolt Self-Loosening Simulation

The full process of simulation consists of 3 steps:

Step1. Bolt is tightened to create clamping force

Step2. Torque application is stopped to release bolt

Step3. Transverse vibration is applied to lead bolt self-loosening phenomenon

The clamping force is varied through three steps. In the last step, the magnitude of clamping force in simulation is compared to that of experiment. In this simulation, the bolt size is M8 with the clamp length being 25 mm.

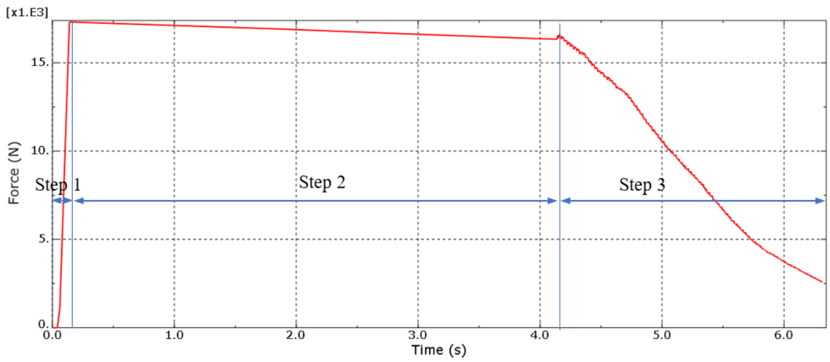

Fig. 7 The magnitude of clamping force varying through 3 steps

The third step is set up based on the Junker test [6]. The bolt head is constrained 1 degree-of-freedom which is the rotation around Z axis. The transverse vibration is applied to upper clamped part. The amplitude of vibration is 0.3 mm and the frequency is 40 Hz.

The variation of clamping force in simulation correlates well with that of experiment, especially in the first period. In this period, the pace of reduction is the most significant and it corresponds to the most severe failure. The good matching indicates that the modelling and installation of full process is reasonable. The further investigation is carried out with different transverse vibrations.

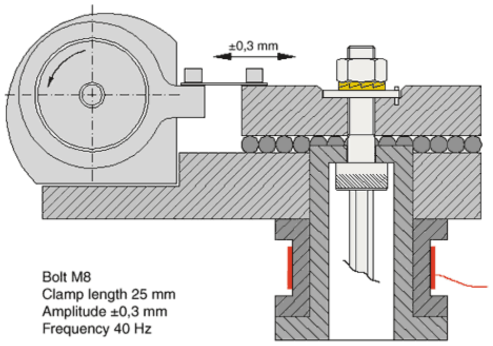

Fig. 8 The Junker test diagram [5]

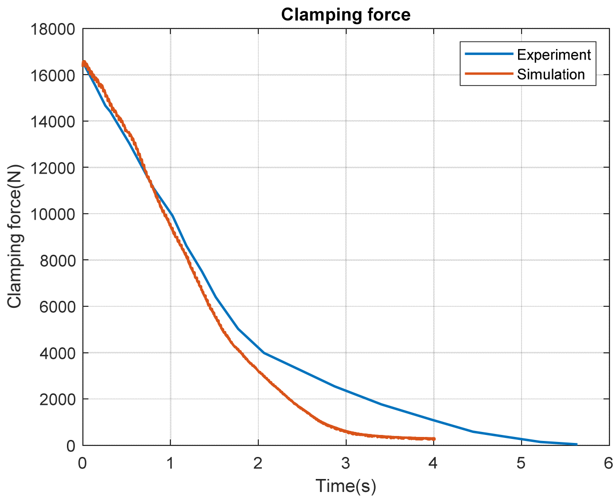

Fig. 9 The correlation of clamping force between simulation and experiment

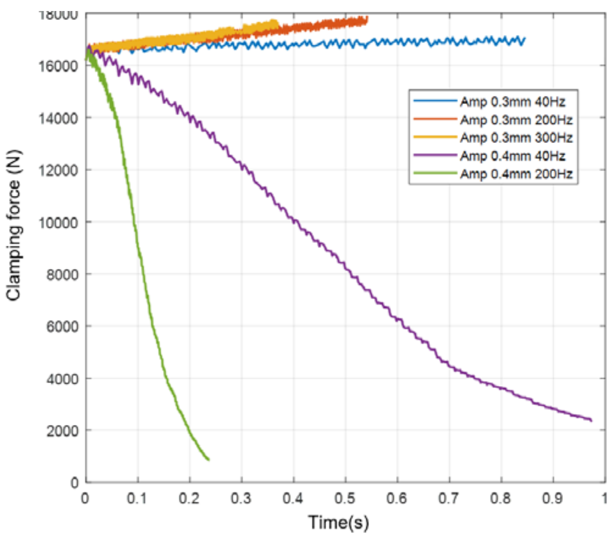

Fig. 10 The bolt self-loosening under different level of transverse vibration

Fig. 10 shows three patterns of clamping force under different transverse vibrations: reduction, increase and stabilization. The two factors inducing the difference are amplitude and frequency of transverse vibration.

Energy of harmonic excitation is

$$E = \frac{1}{2} m \omega^2 A^2 = \frac{1}{2} m (2\pi)^2 f^2 A^2 \tag{3}$$

The energy of harmonic excitation with frequency being 300 Hz and amplitude being 0.3 mm is greater than that of frequency being 40 Hz and amplitude of 0.4 mm, but the former does not lead to bolt self-loosening phenomenon whereas the latter does. Hence, it is stated that the magnitude of amplitude is more dominant than that of frequency in inducing bolt self-loosening failure. In the case the magnitude of amplitude is large enough, the pace of failure is proportional to the value of frequency.

V. Conclusion

The comprehensive self-loosening process of bolt joints under transverse vibration is investigated in the paper. The unified FEM with complete hexahedral elements is created. The accuracy of FEM result and contact definition is verified by the good agreement between simulation result and experiment result of the relationship between torque and clamping force. The reliability of comprehensive self-loosening simulation process is proved by the reasonable matching between the simulation result and experiment result of clamping force variation under transverse vibration. The research also indicates the amplitude is more dominant than the frequency in leading to bolt self-loosening failure.

Acknowledgment

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