

FEM-based wear simulation for fretting contacts

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Summary. This article presents a robust Finite-Element-Method-based wear simulation method, particularly suitable for fretting contacts. This method utilizes the contact subroutine in a commercial finite element solver Abaqus. It is based on a user-defined contact formulation for both normal and tangential directions. For the normal contact direction, a nodal gap field is calculated by using a simple Archard's wear equation to describe the depth of material removal due to wear. The wear field is included in the contact pressure calculation to allow simulation of wear and contact stress evolution during the loading cycles. The main advantage of this approach is that all contact variables are accessible inside the routine, which allows full coupling between normal and tangential contact variables. Also, there is no need for mesh modifications during the solution. This makes the implementation flexible, robust and particularly suitable for fretting cases where friction and tangential contact stiffness play an essential role. The method is applied to the bolted joint type fretting test case. The methodology is also fully applicable to complex real component simulations.

Key words: finite element method, wear, fretting, friction, contact mechanics

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Introduction

Clamped metal contacts are very common in modern machine industry as almost all products are divided into sub-assemblies due to practical reasons for easier manufacturing and better serviceability. Many of the contact interfaces are experiencing cyclic loading caused by vibrations, inertia forces, thermal expansions, etc. Especially high-strength materials, performance demands and weight savings have increased the utilization of fatigue strength of materials, consequently increasing the cyclic loading of the contact interfaces. The plain fatigue of metals is relatively well understood, and there are many fatigue criteria that can be used with modern simulation methods to ensure the fatigue safety of components [4, 19, 18, 14, 10, 3]. However, there is a dangerous damage phenomenon called fretting [5] that can cause an unexpected failure of a contact interface at relatively low nominal stress levels. Generally, fretting consists of two main damage phenomena: fretting fatigue and fretting wear. Fatigue in this context means surface cracking due to high local shear tractions, and wear may redistribute contact pressure and consequently change slip and

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shear traction distributions. This paper concentrates on the latter one by describing a FEM-based approach suitable for industrial applications. Fretting wear has been investigated by many research institutes. Both experimental and modeling studies have been made. A commonly used theory to describe material removal due to wear is the Archard's equation [1] or its modifications. Lehtovaara et al. in Tampere University of Technology (TUT) have developed a numerical model for fretting wear in rough point contacts [13]. University of Nottingham has made pioneering research with the FEM-based wear modeling by using Abaqus and a subroutine to modify the contact mesh according to material removal. They have shown that wear has a significant effect on the evolution of contact stresses [17, 15]. In studies found from literature, wear modeling is usually applied with a constant friction coefficient. Very recently, also a time-dependent coefficient of friction in wear simulation has been studied [20].

The method described in this article is based on the Archard's wear model, local solution dependent friction coefficient and, in addition, the wear model is implemented inside the contact formulation. This allows user-defined contact physics in both normal and tangential directions, which makes the method numerically robust also easily applicable to large scale industrial problems. The same method has been applied in a fretting analysis of a large connecting rod in [16], but in that specific case the wear itself did not play any significant role so it was not considered. A robust contact algorithm is needed on the component level analyses of large combustion engines as the models are usually big and boundary conditions are coming from a flexible multibody simulation in a time domain [12, 2].

A contact interface under pressure and cyclic loading can be in three different conditions: In a gross slip condition, the whole contact interface is sliding, which usually means relatively large slip that causes global wear and contact loosening in dry initially clamped situations. In a partial slip condition, a part of the contact is sliding, which limits the slip amplitude and may likely to cause fretting damage, local wear and contact stress redistribution. A full stick condition can be obtained initially but also due to increasing friction or local wear. Contacts can evolve between these conditions depending on the loading, friction, wear and cracking, which makes realistic simulation of such contacts very complicated. Figure 1 shows the bolted joint under investigation and its different possible contact conditions. This article focuses on the wear part of the process. A full-stick condition of an unworn contact of this type is not possible as the contact pressure drops to zero at some distance from the bolt and some sliding always occurs near the contact border. The purpose of the suggested simulation method is to predict if there is a stabilized situation in the contact condition. The method is applied to a bolted joint used in a fretting experiment and also simulated by finite element method in [11].

Methods

As the target of the simulation is to find the stabilized contact condition (if it exists), the rate of change in wear depth is not the main interest. The size of the wear depth increments need to be limited so that the strong history dependency of the phenomenon is captured. What comes to friction, it has been measured that the evolution of the coefficient of friction is very fast in the beginning of fretting tests, much faster than the wear [7, 8]. Therefore it is assumed that the wear happens after the fully developed friction. In practise, the rate of friction evolution is defined so that the maximum allowed friction coefficient is reached before any wear occurs. The friction evolution model is described in more detail

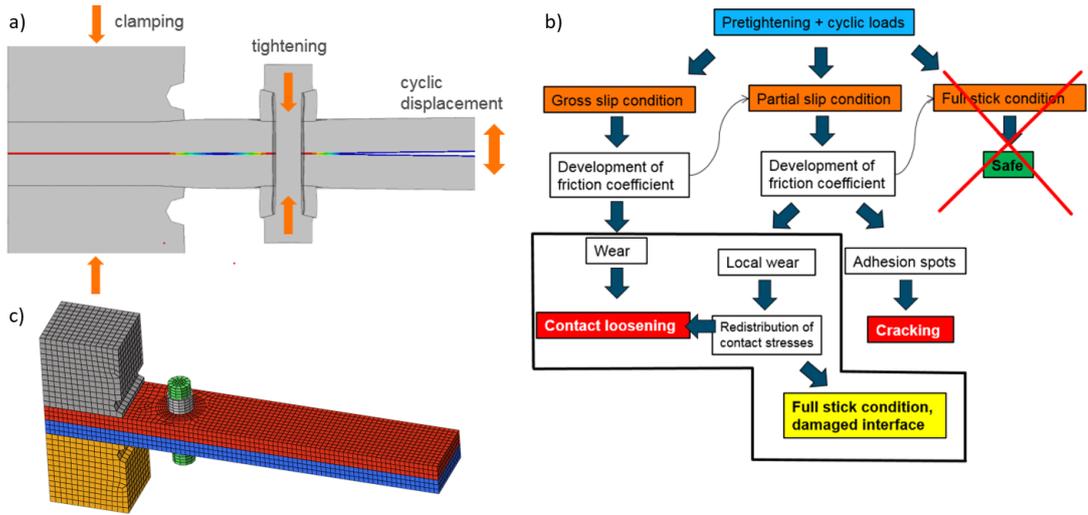


Figure 1. a) Bolted joint, b) different contact condition and c) finite element model.

in [16]. Finite element model is shown in Figure 1c. Linear hexahedral elements C3D8I are used due to their robustness in contact problems. Element size in the contact zone is 1mm that is enough to capture accurate slip and contact pressure distributions but for fatigue assessment, finer mesh would be needed. Surface to surface discretization with finite sliding formulation is used. Implicit analysis (quasi-static) in Abaqus/Standard is used and the coefficient of friction for increment n is defined as

$$\mu_{n+1} = \begin{cases} \mu_n + k \cdot \Delta\gamma_{eq} \cdot \tau_{eq} & \text{if } \mu_{n+1} < \mu_{max} \\ \mu_{max} & \text{if } \mu_{n+1} \geq \mu_{max}, \end{cases} \quad (1)$$

where $\Delta\gamma_{eq}$ is an equivalent slip increment, τ_{eq} is an equivalent frictional shear stress and k is a constant regulating the rate of change. Friction coefficient is also limited by its maximum allowed value of 0.8, that is based on the stabilized friction measurements in [9, 6].

The effect of material removal due to wear can be simulated by using subroutine UINTER with the commercial finite-element solver Abaqus. The subroutine is written in Fortran, and the solver calls it for each iteration. Inside the routine, the solver gives a suggestion of the displacement increment in normal and tangential directions and the user has to define the contact condition, contact stress tensor, and its derivatives. The working principle of the subroutine is illustrated in Figure 2. The result variables like wear depth, its increment, contact pressure, frictional shear stress and equivalent slip increment are defined as nodal state variables for post processing. Also iteration control is affected by the routine to define how the solver treats the next iteration, for example, if it will be an equilibrium or a severe discontinuity iteration according to the changes in the contact condition at each node.

The surface to surface discretisation of Abaqus with finite sliding formulation is used. Material removal is simply defined as an additional gap at each node, which is considered in the contact pressure calculation. In practice, the wear is seen as an allowed penetration of the initial surfaces of the bodies. For the relatively small amount of wear, some hundredths of millimeters, it is assumed that the update of the geometry is not needed, which removes the need of mesh modification. The wear depth is defined according to Archard's law as

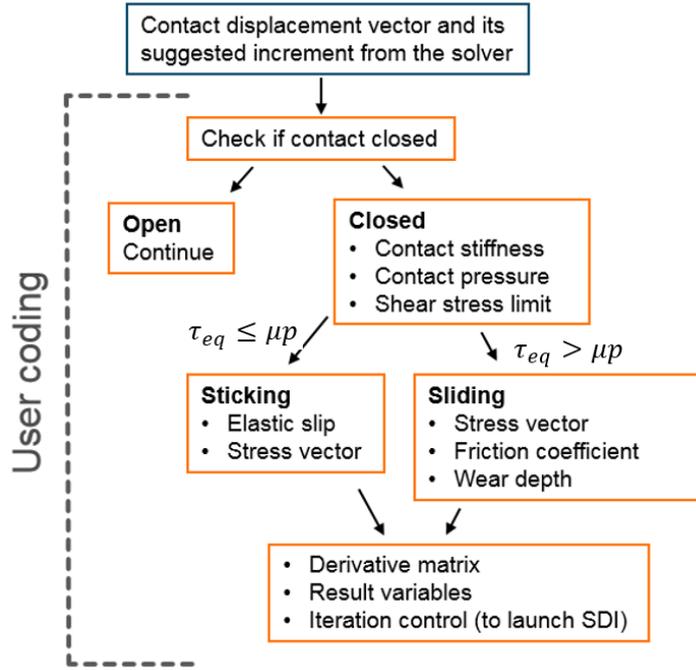


Figure 2. Working principle of the UINTER subroutine in Abaqus

$$h_{n+1} = \begin{cases} h_n + w \cdot \Delta\gamma_{eq} \cdot p_n, & \text{if } p_n > p_{lim} \\ h_n, & \text{otherwise} \end{cases} \quad (2)$$

where w is a constant, p is a nodal contact pressure and p_{lim} is the limit value above which the wear occurs. The limit pressure, in this case, is chosen to be 1 MPa.

In reality, there is a layer of wear particles that remain in the contact and that are carrying some part of the load. These particles may leave or stay in the contact, and therefore the presented method is a conservative approach as it assumes full material removal from the interface.

Results and discussion

The double beam fretting apparatus simulates a realistic bolt joint in a relatively large scale. Two beams are clamped together with a bolt, and the shear force and sliding can be created by enforced cyclic displacement at the end of the beams. Two different loading cases are simulated, one with a higher bolt tightening of 30 kN and another with a lower tightening level of 20 kN. The cyclic nominal bulk stress amplitudes at the center of the bolt hole are 130 MPa for the higher tightening case and 205 MPa for the lower tightening case. For the friction coefficient and wear simulation the parameters are $\mu_{max} = 0.8$, $k = 0.1$ mm/N and $w = 5.0 \times 10^{-4}$ mm²/N. The contact condition after a fully developed friction coefficient in the unworn situation is important, as it defines the initial area where the wear starts to evolve. The unworn stabilized contact conditions for both cases are illustrated in Figure 3 by showing the sticking area and frictional dissipation energy during one loading cycle. Slip area before wear corresponds well with the results in [11], although friction coefficient distribution with maximum value of 0.8 is used instead of constant value of 1.0 in [11].

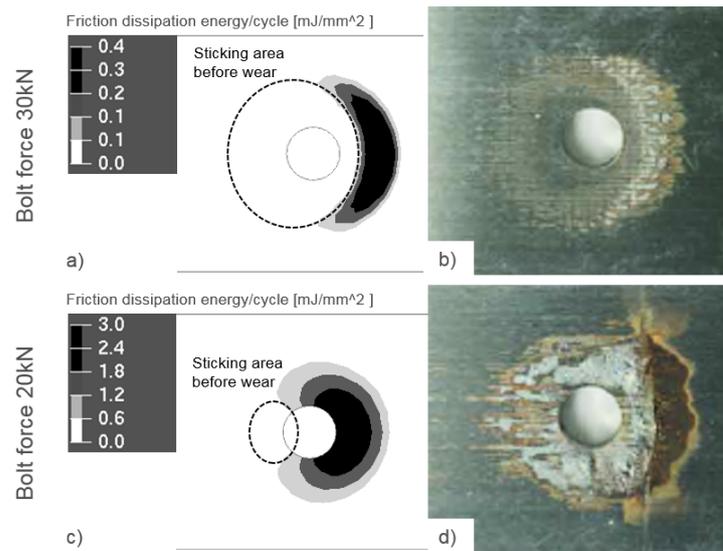


Figure 3. Simulated contact condition and experimental fretting scars at the end of test with higher bolt load (a,b) and with lower bolt load (c,d).

With the higher bolt tightening force, the unworn contact is in the partial slip condition where only a small area is sliding. With the lower bolt tightening force, the unworn contact stabilizes also to a partial slip condition but only a small area stays stuck. The corresponding experiments show the adhesion spots in approximately the same area where the contacts stay sliding. This area of sliding has caused material adhesion as described in [11] and may nucleate cracks and decrease the fatigue strength of the contact. In the experiment with the lower bolt force, a large crack was observed in the front of the bolt hole. This macroscopic crack has affected to the contact condition based on the different types of surface scars in different sides of the crack. This could be further investigated but from engineering point of view, it is not very interesting.

The next main interest was to simulate the effect of material removal due to wear. Redistribution of contact pressure and shear traction and some change in the bolt force were expected. The contact may evolve either to a fully stuck condition or loosen and develop to a gross slip. The results are shown in Figure 4.

With the higher bolt load, the contact evolves to fully stuck state where the loading is carried by the area around the bolt hole. Contact pressure of this case is shown in Figure 4c. This area is approximately similar to the undamaged area in Figure 3b. In this case, the contact condition is stabilized and only a small amount of the bolt force is lost. Bolt force is plotted in Figure 4a. This is a logical result as the clamping force decreases only by 3%, meaning also that the joint's capacity to carry the frictional shear force remains almost unaffected.

With the lower bolt force, the contact pressure starts to drop over a large sliding area and, finally, the small sticking area tries to remain stuck. However, the bolt force and clamping force drop so much that the sticking area cannot carry the shear load and, eventually, the contact develops into a gross slip condition. This can be seen in the contact pressure development in Figure 4d. After this, the wear continues, the bolt force keeps dropping (Figure 4b) and, therefore, the contact loosens and there is no stabilized contact condition in this case. There is no reason to simulate this unstable situation further.

It has to be noted that the bolted joint experiment with the 20 kN bolt force did

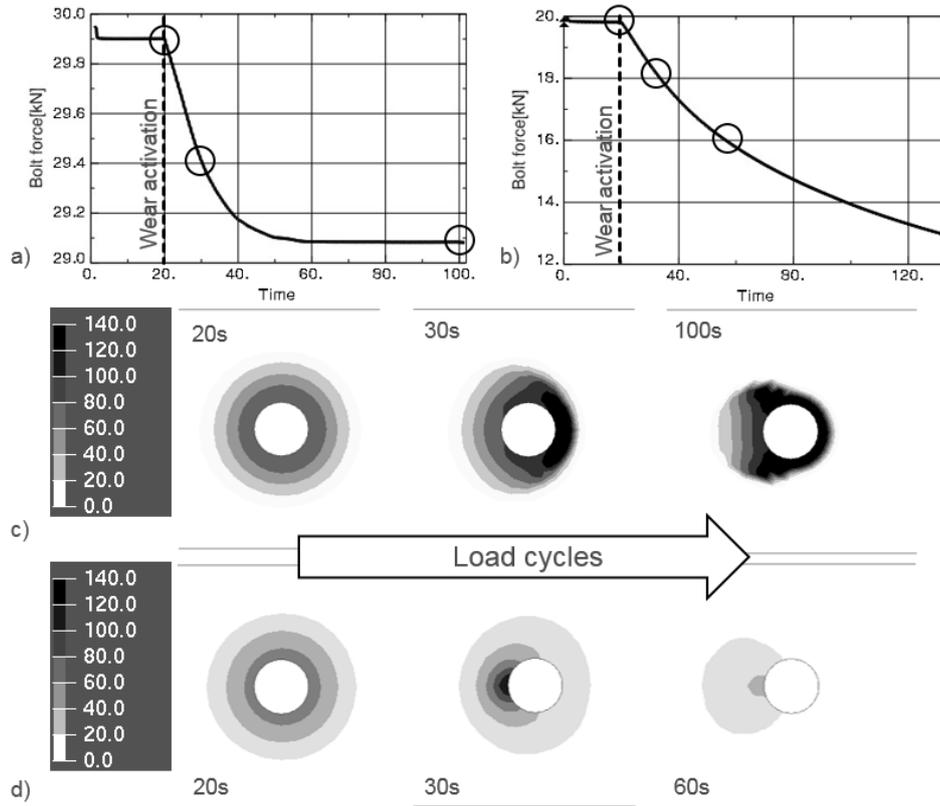


Figure 4. Bolt forces at 30kN load (a) and 20kN load (b), and corresponding contact pressure evolutions (c,d) respectively.

not show loosening, at least not before fatigue failure at about one million cycles. One possible explanation is that the slip amplitude was so small compared to the contact size that the wear debris could not escape from the contact. Naturally, this tells about the limitations of this simple wear simulation approach. Of course, the question remains what would happen if there were no fatigue failure and the test was run for much longer time. It is also notable that the surface damage in Figure 3d reaches the bolt hole.

Conclusion

A FEM-based wear simulation was presented to study the effect of wear in the clamped dry metal contacts. The main target of the study was to demonstrate a methodology to investigate if a clamped metal joint has a stable contact condition when the effect of wear is considered. The developed approach allows to simulate the effect of contact stress redistribution and contact condition evolution due to wear. It allows the investigation of possible contact loosening due to the reduction of clamping force. Two fretting test cases were used as an example, one with a higher and another one with a lower tightening force and shear load. The first case shows how wear redistributes the contact pressure to a smaller area and the contact shakes down to a fully stuck stable condition. In the second case, the reduction of the clamping force causes a gross slip situation and there is no stable contact condition but the joint loosens. The method is robust for industrial applications as it does not require any mesh modifications.

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