An Efficient Computational Approach for Frictional Analysis in ABAQUS

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FEA contact modeling with severe interfacial friction is often associated with computational challenges to obtain converged solutions. The challenges may increase for problems with significant non-linear deformation (e.g., hyperelastic materials) and more sophisticated laws of coefficients of frictions (COF). Thus, objectives of the present paper are to propose an efficient FEA-based approach to model frictional behavior and demonstrate its implementation in ABAQUS. Major idea of the proposed approach is based on an iterative process where several contact frictionless problems are considered instead of an initial frictional model. Frictional behavior is modeled for each iteration in form of given boundary conditions (BC) at the interface. Here, the BCs are calculated using corresponding FEA predictions obtained at previous iteration according to known constitutive law of COF. The iterative process continues until desired accuracy is satisfied. Implementation of the approach in ABAQUS is considered in detail. Extremely robust nature of the approach is computationally illustrated on several simple representative examples. Validation with available exact analytical solutions is presented and high accuracy of FEA predictions is emphasized.

Keywords: Friction, Contact, Constitutive Model, Convergence.

1. Introduction

FEA of frictional behavior is believed to be one of the most challenging issues in non-linear computational mechanics. In general, successful convergence of a frictional problem is much more difficult to obtain than convergence of a similar frictionless contact model. Computational challenges of frictional FEA could have different natures. However, one of the major reasons is associated with strong interdependent character between normal (contact) and shear (frictional) stresses or so-called “stick-slip” behavior. Thus, a significant probability of non-uniqueness of frictional solutions (along with corresponding convergence difficulties) can exist in principle in FEA. The complexity of the issue was aphoristically summarized (HKS, 2000, p.L7.2) as “… do not use friction unless it is physically important to do so …”, and this caution is perfectly understood.
There are, however, problems where friction cannot be ignored due to expected significant effect on stress/strain distributions. Moreover, there are numerous problems where frictional behavior is the major focus of analysis, and its accurate prediction is a fundamental output of FEA modeling. It is important to emphasize that there are also certain specific friction-based problems where modifications of existing computational algorithms may be especially helpful. Thus, to mitigate computational challenges for certain types of frictional problems, an efficient FEA-based approach to model frictional behavior is proposed in this study. Implementation of the approach and demonstration of its robust nature is considered using ABAQUS/Standard Version 6.3, although, potentially, it may be also used for other versions and/or FEA codes.

2. Concept of the approach

To minimize a challenge, one of the ways (and, perhaps, the best one) is to avoid the challenge. This philosophy is used in the proposed approach where direct (i.e., “conventional”) frictional analysis is not applied. Instead, one original frictional problem is substituted by several similar but frictionless problems. These frictionless problems possess exactly the same parameters (materials, loading, geometry, mesh, etc.) as the original model with only one exception: there are additional loading conditions at contact surfaces to mimic actual frictional behavior. These loading conditions are kept constant during every single problem and are given in terms of forces.

These forces are assumed to compensate friction and, therefore, should be applied in the tangential direction of contact surfaces against expected movement of contact surfaces. Since absolute values of the forces are not known, the following step-by-step iterative procedure is proposed:

a) initially \((k = 0)\), some preliminary values of the forces, \(F(k)\), are suggested (the simplest way is to consider \(F(0) = 0\));

b) frictionless contact FEA is carried out to predict corresponding contact output, such as contact pressure, \(\sigma(k)\); slip; etc.

c) more accurate predictions of tangential stresses \(\tau(k + 1)\) are calculated according to previously obtained contact stresses and known coefficient of friction (COF), \(\mu\), as

\[
\tau(k + 1) = \sigma(k)\mu(k)
\]

(note that COF may be, in general, a complex function of pressure, slip, etc., i.e., depends on iterations);

d) more accurate predictions of forces \(F(k + 1)\) are calculated as

\[
F(k + 1) = \tau(k + 1)\Delta S
\]

where \(\Delta S\) is the contact length or area per considered node depending on 2- or 3-D statement of analysis.
e) finally, if difference between $F(k)$ and $F(k + 1)$ is less than specified accuracy criteria, the iterative process continues from step “b” at $k = k + 1$ and $F(k) = F(k + 1)$. Otherwise, the analysis is completed.

A possible generalization of the approach is also proposed for especially complex problems with sophisticated patterns of deformation. Here, application of the approach is performed for several specified levels of loading history. Calculated values of forces $F(k)$ at every level are used as initial suggestions for FEA at the next level.

3. Implementation in ABAQUS

ABAQUS, as the state-of-the-art FEA code with advanced and robust capabilities of non-linear contact analysis, provides extremely favorable opportunity for implementation of the approach. There are several ways to do it depending on how much efforts could be spent on the implementation and how specific/general it is expected to be. Also, ways of implementation may depend on programming expertise of an analyst and availability of programming tools (C/C++, Fortran, etc.). The best solution, of course, would be its implementation as an available standard option in the basic code of ABAQUS. (The authors hope to enjoy the standard option in future versions of ABAQUS).

The simplest and the least time-consuming way of possible implementation is schematically described below. It can be done by practically everyone even with very limited background in programming. First, output of contact frictionless analysis is expected for every iteration as

*CONTACT PRINT, NSET = node set name or
*CONTACT FILE, NSET = node set name

It provides information on node number, status, contact pressure ($CPRESS$), shear stress ($CSHEAR1 = 0$), etc. of considered node sets. Then, for every node with actual contact ($STATUS = CL$ or $CPRESS > 0$), concentrated forces $F(k)$ are calculated according to the algorithm described in Section 2. Finally, a file combining information on these forces is created and used in the next iteration as

*INCLUDE, INPUT = file name

The described methodology was realized in a code written in Microsoft Visual C++ 6.0. Examples considered below were analyzed using this code and ABAQUS/Standard 6.3.

4. Possible applications

Although the approach seems to be very close to a “conventional” frictional analysis, it does not require frictional analysis at every load increment and de facto eliminates the interdependent nature between normal (contact) and shear (frictional) stresses. Correlations between these stresses are taken into consideration in a more robust computational form. Among others, it can be especially beneficial for the following issues.
4.1. Steady-state analysis

There are numerous dynamic problems where inertia effects may be ignored. Thus, a steady-state (or quasi-static) statement of analysis can be used for their structural models. ABAQUS does offer very advanced capabilities of “Steady-State Transport Analysis” including numerous important options, e.g., inertia effects. However, this analysis is used to model primarily an interaction between a 3-D deformable rolling object and different rigid surfaces. The proposed approach, on the other hand, is not limited by this statement and can be successfully used for analysis of

a) interaction between a deformable rolling object and deformable surface/media;

b) constant sliding movement of several deformable bodies with respect to each-other (e.g., models of “infinite” conveyor belt in contact with deformable bodies; advanced tribology modeling; models of tests for frictional/abrasive characterization; etc.).

It seems the proposed approach may be helpful in modeling of such quasi-static problems.

4.2. Complex COF

COF, in general, may be sensitive to contact pressure, slip, slip velocity, temperature, etc. Models based on constant values of COF may be too approximate (and, sometimes, even incorrect) for numerous engineering applications involving rubber, polymers, composite, leather, etc. More sophisticated definitions of COF (e.g., pressure-dependent functions) are available in ABAQUS. However, probability of convergence challenges, associated with “stick-slip” behavior, will significantly increase for non-linear correlations between shear and normal stresses. Also, FEA with constant COF is usually very insensitive to local non-uniformity (computational “noise”) of contact stresses. In case of non-linear COF, effect of this non-uniformity is important and may provide, in general, considerable error. The proposed approach can significantly mitigate this challenge.

4.3. Control of stick-slip behavior

ABAQUS provides advanced tools to predict stick-slip behavior even for very complex problems. Fully automatic nature of FEA-based frictional analysis does not require “manual” input from the researcher during the analysis. Nevertheless, certain possibilities to control contact analysis can be very helpful, especially if the expected physical behavior is not captured by available standard options. This issue is important for certain contact problems with high probability of instability, when solutions may converge to significantly different results depending on model accuracy (e.g., mesh density, time increment, tolerance criteria), geometry of contact surfaces, and loading conditions. Again, the proposed approach seems to be helpful here.

5. Representative example

To illustrate the proposed approach, consider a problem shown in Figure 1a. A long metal roller is pressed into elastomeric pad, and torque, $T$, is applied to the roller to provide rotation. The
objective of the problem is to predict torque at steady-state rotation, if COF, $\mu$, between surfaces is known. (Without discussing physical details, note that such models may represent, for example, experimental characterization of friction. The characterization, however, is usually based on an inverse statement to evaluate COF if the torque is experimentally measured).

For a very long roller, 2-D plane strain statement of the problem (Figure 1b) may be applied. The roller is considered as a rigid body. Lower edge of the rectangular pad is fixed. Elastic properties of the pad are described by Neo-Hookean law with ideal incompressibility ($C_{10} = 1$). Vertical displacement of the roller is defined by displacement $\Delta$, which is kept constant during the rotation. The following numerical parameters are used in this example: $L = 1.5$; $H = 0.5$; $R = 0.25$; $\Delta = 0.15$; COF = 0.20.

FEA model (ABAQUS/Standard 6.3) with refined mesh is developed for the problem (Figure 1c). Hybrid elements CPE4H are used to model hyperelastic behavior and large deformations of the pad. Analysis is performed in two steps. The first one is static vertical displacement $\Delta$ of the roller with no rotation. The second step is analysis of steady-state rotation assuming unchangeable vertical displacement $\Delta$. The first step is considered frictionless for simplicity, while full friction is modeled in the second step according to the proposed approach. For illustrative purposes, calculated distributions of Mises stresses are shown at the end of the first (Figure 2a) and the second (Figure 2b) steps. Significant non-linear deformation may be noted.

Extremely robust character of convergence process is illustrated in Figure 3a for the second step (rotation). Predictions of torque are achieved with computational error less than 1% after only 5 iterations. Here, the torque is calculated at each iteration as

$$T(k) = R \sum F(k)$$

for all contact nodes. Computational error is characterized by comparison with the asymptotic solution ($T = 0.067656$) at $k \to \infty$. Similar fast convergence is shown for contact stresses (Figure 3b). Practically asymptotic distributions are achieved after 4 iterations (node #0 represents the center of the contact).

It is interesting to compare these results with similar predictions based on “conventional” scheme of frictional analysis. Here, the analysis is also performed in two steps. The first step is exactly the same as in the previous solution. The second step, however, is actual rotation of the roller with “conventional” definition of friction given by option *FRICTION.

A challenge here is to mimic the steady-state nature, which is achievable only at very large (theoretically, infinite) rotation. Approximately steady-state behavior may be achieved at rotation close to 0.8 as illustrated in Figure 4a. Here, predicted average values of COF, $\mu_0$, are compared with expected COF = 0.2 during the rotation. As soon as average value of COF reaches expected level of $\mu$, conditions of steady-state behavior are considered to be achieved. Values of $\mu_0$ are calculated as

$$\mu_0 = \frac{\sum \tau dS}{\sum \sigma dS}$$
assuming integration (summation) in the contact area. Calculated distributions of Mises stresses, shown in Figure 4b, are practically identical to predictions according to the proposed approach (see Figure 2b).

6. Accuracy of the approach

To evaluate accuracy of the proposed approach in detail, consider a representative problem with known analytical solution, for example, a wedge shown in Figure 5a. The wedge is a symmetric 2-D linear elastic body located between two rigid surfaces and compressed by force $P$. Frictional properties between the wedge and surfaces are defined by constant COF, $\mu$. Reactions of surfaces are characterized by frictional force $F$ and normal force $N$ (see Figure 5a). These reactions may be easily calculated as

$$N = \frac{P}{2(\sin \alpha + \mu \cos \alpha)}; \quad F = \mu N = \frac{\mu P}{2(\sin \alpha + \mu \cos \alpha)},$$

according to equilibrium analysis in the $y$–direction and assuming a) symmetry of the problem and b) correlation between the forces defined by COF.

Corresponding FEA model is shown in Figure 5b for a symmetric part of the wedge with the following representative parameters: $\alpha = 30$ deg; $H1 = H2 = 1$; $P = 5$; $\mu = 0.3$. Boundary conditions at the left edge are defined according to conditions of symmetry (no displacements in the $x$–direction). Boundary conditions at the right edge are defined by frictional contact and modeled by the proposed approach. External compression (force $P$) is uniformly distributed at the top edge.

Results of the iterative analysis are presented in Figure 6. Extremely fast and robust convergence may be noted. FEA predictions within 1% of error with analytical solution ($F = 0.987092$) are achieved in 7 iterations. This analysis indicates high level of accuracy of the proposed approach.

7. Reference


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Figure 1. Scheme, 2-D model and FEA mesh of the roller problem.
Figure 2. Distributions of Mises stresses calculated by the proposed approach at the end of step 1 (a) and 2 (b).
Figure 3. Convergence of solutions for the roller problem.
Figure 4. Predictions of average COF (a) and Mises stresses (b) according to the “conventional” approach.
Figure 5. Scheme and FEA model of the wedge problem.
Figure 6. Convergence of the wedge problem.