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► **To cite this version:**

Katharina Immel, Vu-Hieu Nguyen, Guillaume Haiat, Roger A Sauer. Long-term stability and debonding of cementless implants. Proceedings in Applied Mathematics and Mechanics, 2021. hal-03430340

HAL Id: hal-03430340

<https://hal.science/hal-03430340v1>

Submitted on 16 Nov 2021

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Long-term stability and debonding of cementless implants

Katharina Immel^{1,2}, Vu-Hieu Nguyen^{3,4}, Guillaume Haiat², and Roger A. Sauer^{1,5*}

¹ Aachen Institute for Advanced Study in Computational Engineering Science (AICES), RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany

² MSME, CNRS UMR 8208, Université Paris-Est Créteil, Université Gustave Eiffel, 94010 Créteil, France

³ Université Paris-Est Créteil, CNRS, MSME, 94010 Créteil, France

⁴ Université Gustave Eiffel, MSME, 77454 Marne-la-Vallée, France

⁵ Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, ul. Narutowicza 11/12, 80-233 Gdańsk, Poland

This work presents a three-dimensional FE frictional contact formulation with NURBS-enriched contact elements for the debonding of partially osseointegrated, cementless implants. The contact model is based on a modified Coulomb's friction law [1] that can model the tangential debonding of partially osseointegrated implants. Here, a smooth transition function between the two friction coefficients is used to model the decrease of friction due to debonding of the implant. The model is applied to simulate the debonding of a hip implant to determine the influence of partial osseointegration on the stability of the implant.

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1 Introduction

Cementless implants are widely used in orthopedic and oral surgery. This type of implant achieves initial stability during the surgery through a press-fit in the host bone, while long-term stability is obtained by bone growing around and into the porous surface of the implant, a process called osseointegration. As debonding of the bone-implant interface (BII) due to loosening and insufficient osseointegration still occur and may have dramatic consequences, predicting osseointegration, implant stability and failure are major goals in implant research. Especially in terms of friction, adhesion, and debonding at the BII of partially osseointegrated implants at the macroscale, there is a lack of experimental data and reliable numerical models. In this work we model long-term stability and debonding of a partially osseointegrated acetabular cup implant (ACI). A modified Coulomb's friction law (MCFL) is used, which can model the tangential debonding of partially osseointegrated implants [1]. A NURBS-enriched contact discretization is used for an efficient modeling of the curved geometries of the hemispherical ACI and hip cavity and their contact, especially during the debonding process [2]. The long-term stability in terms of removal force and torque is assessed with regards to the influence of the degree of osseointegration.

2 Methods

For classical Coulomb's friction, the tangential sliding traction is given by

$$\mathbf{t}_t = -\mu p_c \frac{\dot{\mathbf{g}}_s}{\|\dot{\mathbf{g}}_s\|}, \quad (1)$$

where $\mu = \text{const}$ is the friction coefficient, p_c is the contact pressure, and $\dot{\mathbf{g}}_s$ denotes the relative tangential sliding velocity between the two bodies in contact. In contrast to a constant friction coefficient, we model μ as a function of the scalar state variable ϕ [1], as

$$\mu := \mu(\phi) = \phi \mu_{ub} + (1 - \phi) \mu_b, \quad \phi(g_s) = \phi_0 \cdot \begin{cases} 1 & \text{if } \frac{g_s}{a_s} < 1, \\ \frac{1}{2} - \frac{1}{2} \sin\left(\frac{\pi}{2b_s} \left(\frac{g_s}{a_s} - b_s - 1\right)\right) & \text{if } 1 \leq \frac{g_s}{a_s} \leq 1 + 2b_s, \\ 0 & \text{if } \frac{g_s}{a_s} > 1 + 2b_s. \end{cases} \quad (2)$$

where μ_{ub} and μ_b are the friction coefficient for the unbroken (initial) and broken state, respectively, that are weighted according to the state variable ϕ . The state variable ϕ determines whether a point is in an unbroken ($\phi = 1$), partially broken ($0 < \phi < 1$) or fully broken/sliding state ($\phi = 0$). Here, ϕ is considered to depend on the accumulated deformation of the BII in tangential direction g_s , according to the smooth function $\phi(g_s)$ (2.1). $\phi_0 \in [0, 1]$ denotes the initial bonding state ($\phi_0(\mathbf{x}) = 0$ denotes no initial bonding and $\phi_0(\mathbf{x}) = 1$ denotes perfect bonding). This approach enables us to use homogeneously distributed osseointegration over the BII, as well as pre-defined or pre-computed osseointegration patterns, e.g., based

* Corresponding author: sauer@aices.rwth-aachen.de,

on osseointegration and remodeling algorithms. The parameter a_s represents the sliding threshold up to which tangential adhesion takes effect ($\mu = \mu_b$ for $g_s \leq a_s$), while b_s defines the size of the transition zone between the two friction coefficients. As this is a local friction model, where ϕ and thus μ can change pointwise, it allows for the description of locally varying bonding states, such as occur in crack propagation and partial osseointegration.

3 Application

The MCFL is applied to the debonding of a 3D acetabular cup implant. Geometry and material parameters are chosen according to [3]. An ancillary is rigidly fixed to the ACI and all loads are applied to the upper surface of the ancillary. The hip is represented by a cylinder with a hemispherical cavity. Here, the difference between the diameter of the implant and the cavity is 1.4 mm to ensure a sufficient press-fit. The hip block is rigidly fixed in all directions at the bottom surface. Before the insertion, the ACI and hip cavity are close but not in contact. All materials are assumed to be non-linear elastic, homogeneous and isotropic. The parameters for the MCFL are chosen to be $a_s = 128 \mu\text{m}$, $b_s = 1.84$, $\mu_{ub} = 0.44$, and $\mu_b = 0.3$ based on [1]. The implant is first inserted into the hip cavity until a normal reaction force of -2500 N is reached. Then instantaneous, homogeneous osseointegration is applied to the BII. Last, the implant is pulled out or rotated until the BII has fully debonded. Figure 1 a) shows the mesh of the implant-bone system and the numerical setup.

Figure 1 b) and c) show the normal reaction force F_z obtained during normal pull-out, and the torque M_z obtained during the rotation of the ancillary. Compared to pure Coulomb's friction ($\phi_0 = 0\%$) the MCFL only affects the magnitude of the peak in normal reaction force/torque. The magnitude of the peak in F_z and M_z increases almost linearly with increasing ϕ_0 . The largest effect of MCFL can be seen for the pull-out case, with an increase in F_z of up to 221 N, while the increase in torque is only up to 6.5 Nm.

This model can be coupled with, e.g., pressure- or micro-motion-based osseointegration and remodeling algorithms to study the effect of implant design changes on osseointegration and stability. An extension to adhesion and debonding in normal direction and respective adhesive friction will be considered in future work.

Acknowledgements This work has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No 682001, project ERC Consolidator Grant 2015 BoneImplant). This work was also supported by the Jülich Aachen Research Alliance Center for Simulation and Data Science (JARA-CSD) School for Simulation and Data Science (SSD). Simulations were performed with computing resources granted by RWTH Aachen University under project ID rwth0671.

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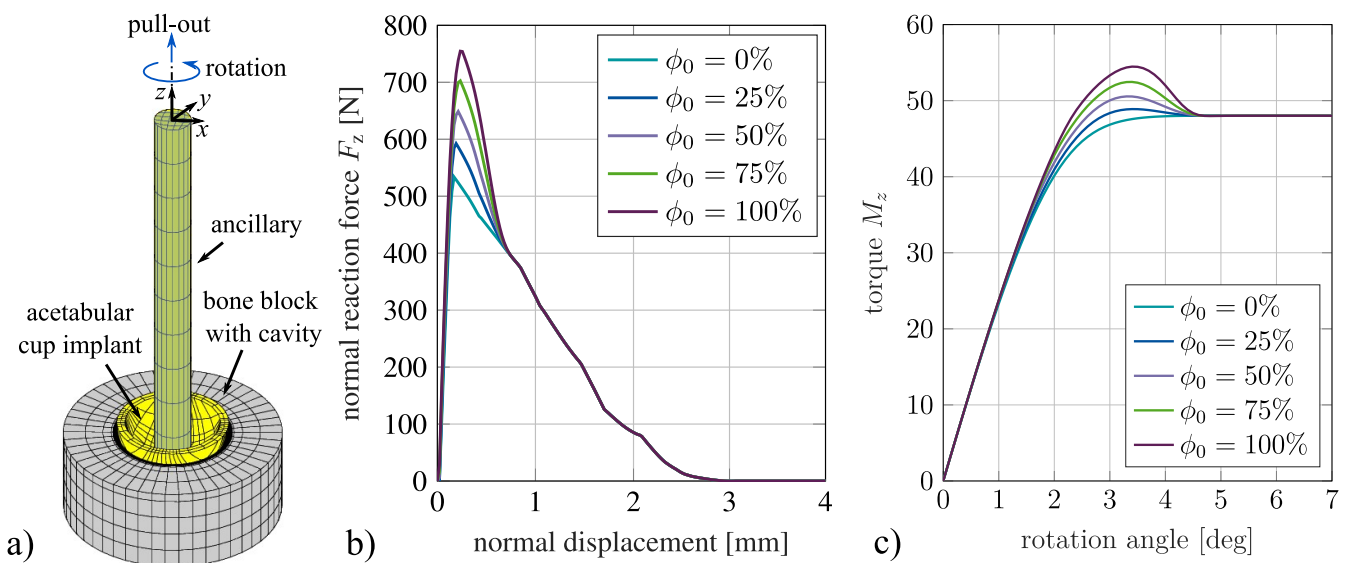


Fig. 1: Debonding of an acetabular cup implant: a) FE mesh. b) normal reaction force F_z as a function of the initial degree of osseointegration ϕ_0 . c) torque M_z as a function of the initial degree of osseointegration ϕ_0 .